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Open-source Simulation Study for Direct Use Geothermal Systems

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ABSTRACT

Simulation of Direct Use Geothermal Systems can provide guidance for geothermal resource assessment, where the energy production, geothermal system's lifetime and heat recovery ratio are used as performance indicators. The energy recovery ratio within the expected influence area is a function of a geothermal system's lifetime. In this work we present reference examples on the design of a DUGS simulation model using the open-source software Delft Advanced Research Terra Simulation (DARTS). The DARTS platform enables accurate and efficient sensitivity and uncertainty analysis. We identify an optimal cartesian grid resolution to forecast the real thermal response of a 3D homogeneous model in a computationally efficient way for a typical reservoir domain and discharge rate. Subsequently, we identify the optimal number of confining layers ensuring a sufficient heat recharge without boundary layer interactions that remains computationally efficient. The models with optimal resolution and number of confining layers are used to define the influenced reservoir volumes within a 3D domain and to calculate the energy recovery factor. The optimal parametrization and computational efficiency of the open-source DARTS platform is used as a basis for research on project feasibility, risk management, and system optimization.

1. INTRODUCTION

Greenhouse gas (GHG) emissions together with the high demand for energy have long been a concern in contemporary society. The application of renewable sources such as wind energy and geothermal energy can contribute to mitigate GHG emissions. Geothermal energy is the heat stored in the Earth's interior. It has been developed and exploited for a long time to generate electricity or for direct heating. Direct Use Geothermal Systems (DUGS), which are also known as low enthalpy geothermal systems, are typically found in conduction-dominated geological settings (Moeck, 2014). In these systems, one injection well and one production well are used to produce energy. The design and operation of DUGS is governed by subsurface multi-physics, geomechanical and chemical processes. There is no simple analytical solution that can be applied to describe these complicated processes. The design and development of a geothermal project at an early stage might have limited subsurface information and uncertainty at this stage is quite high. Simulation of DUGS can provide guidance for geothermal resource assessment and quantify the uncertainties at various stages of a geothermal project, where the energy production, geothermal system's lifetime and heat recovery ratio are used as performance indicators. Simulation can be meaningful for educational, research and development.

Numerical simulation is employed to provide crucial inputs for DUGS studies of feasibility and risk at essential phases of geothermal projects. It provides a long-term and reservoir-scale understanding of the fluid flow in porous media and the interaction of the injected fluid with rock and in-situ fluid (Pandey et al., 2018). Significant studies have been carried out to investigate and quantify the challenges in the numerical simulation of geothermal systems. Homogeneous, stratified, and heterogeneous geological models are created to investigate the dynamic thermal response of geothermal production (Daniilidis et al., 2016, 2021; Major et al., 2023; Poulsen et al., 2015). A high-fidelity 3D heterogeneous geological model gains more attention in geothermal modeling (Wang et al., 2021, 2023). These models are constructed by multiple grid cells. The size of the grid cell can affect the characterization of subsurface hence will influence the accuracy of simulation result. Depending on the availability of input data and the trade-off between computational cost and accuracy, it is a crucial decision that reservoir engineers and geoscientists make to choose an appropriate model resolution.

In this work, the log data of geothermal wells in West Netherlands Basin is applied to construct conceptual homogeneous, stratified, and heterogeneous models to investigate the optimal resolution for DUGS. Confining layers above and below the reservoir body is important in geothermal modeling; confining layers are typically geological formations consisting of low-permeable or impermeable rocks that have limited convective flow but provide conductive thermal recharge to the reservoir (Daniilidis & Herber, 2017; Saeid et al., 2013). Previous studies (De Bruijn et al., 2021) on the effect of confining layers prove the positive effect of these layers on heat production and the simplification of the reservoir characterization probably weaken the positive effect (Wang et al., 2021). With a sufficient and computationally efficient resolution, it will be meaningful to quantify the effect of the confining layers on the simulated thermal response. However, confining layers add computational overhead by increasing the numerical problem size;. It is crucial to model the right amount of heat recharge from confining layers without boundary interactions during simulation in a computationally efficient way.

Once a geothermal reservoir with a sufficient resolution and a minimum number of confining layers is determined, it is desired to estimate the potential energy produced from the given geological model. The United States Geological Survey (USGS) developed a volumetric methodology to predict the Heat In Place (HIP) which is subject to different sources of uncertainties (Garg & Combs, 2015).

The recoverable heat in place is defined as heat stored in the reservoir which can be harnessed and for power generation or direct use. Heat recovery factor is known as one of quality indicators to assess a geothermal project. It is the ratio between the produced heat from the wellhead and recoverable heat in place (Garg & Combs, 2015). An operating DUGS is considered to be a forced-convection thermal system, which means the fluid conveys most of the heat produced from the production well. It is meaningful to quantify the fluid sweeping area hence to evaluate the reservoir volume where fluid can flow through. Flow diagnostic analysis is applied to evaluate the hydraulically connected area during the simulation, between the injection well and production well (Møyner et al., 2015). Based on the combined fluid sweeping volume and thermal cold plume volume, the effective Influence Area (IA) of a geothermal project is determined. The effective IA is utilized to compute the volumetric recoverable heat in place and subsequently the heat recovery factor in a standardized way across different geological settings.

In this study, Delft Advanced Research Terra Simulator (DARTS) (DARTS Team, 2023) is used to develop the open-source geothermal simulation. DARTS is a robust and efficient reservoir simulator which can be used to model various energy transition problems. DARTS is implemented using the state-of-arts Operator-Based Linearization (OBL) (Voskov, 2017). Meanwhile, Matlab Reservoir Simulation Toolbox (MRST) (Lie et al., 2012; MATLAB, 2020) is applied to perform the flow diagnostic to determine the fluid convection influence area.

2. NUMERICAL AND GEOLOGICAL MODELS

Mass and energy conservation equations are applied to describe the thermal multiphase flow in a geothermal production system.

$$\frac{\partial}{\partial t}\left(\varphi\rho_w\right)-\nabla\left(K\frac{\rho_w}{\mu_w}\left(\nabla p_w-\gamma_w\nabla D\right)\right)+\rho_w q_w\sum_{j=1}^{n_p}\rho_j q_j=0 \quad (1)$$

$$\frac{\partial}{\partial t}\left(\varphi\rho_w U_w+(1-\varphi)U_r\right)-\nabla\left(Kh_w\frac{\rho_w}{\mu_w}\left(\nabla p_w-\gamma_w\nabla D\right)\right)+\nabla\left(\kappa\nabla T\right)+\rho_w q_w h_w=0 \quad (2)$$

where: φ is porosity [-], ρ_w is water molar density [kmol/m^3], U_w is water internal energy [kJ], U_r is rock internal energy [kJ], h_w is water enthalpy [kJ/kg], κ is thermal conductivity [kJ/m/day/K], K is permeability tensor [mD], μ_w is water viscosity [cp], p_w is pressure [bar], γ_w is water gravity vector [N/m^3], D is depth [m]. The governing equations are solved by applying Operator Based Linearization (OBL) in Delft Advanced Research Terra Simulation (DARTS) framework implicitly. The detailed geothermal formulation in DARTS is described in the work (Khait & Voskov, 2018; Wang et al., 2020).

Three diverse types of conceptual geological models are considered (Figure 1): i) homogeneous 3D reservoir model, ii) stratified 3D reservoir model and iii) heterogeneous 3D reservoir model. For all reservoirs we investigate the optimal Cartesian resolution and the minimum number of confining layers for geothermal simulation without boundary interaction.

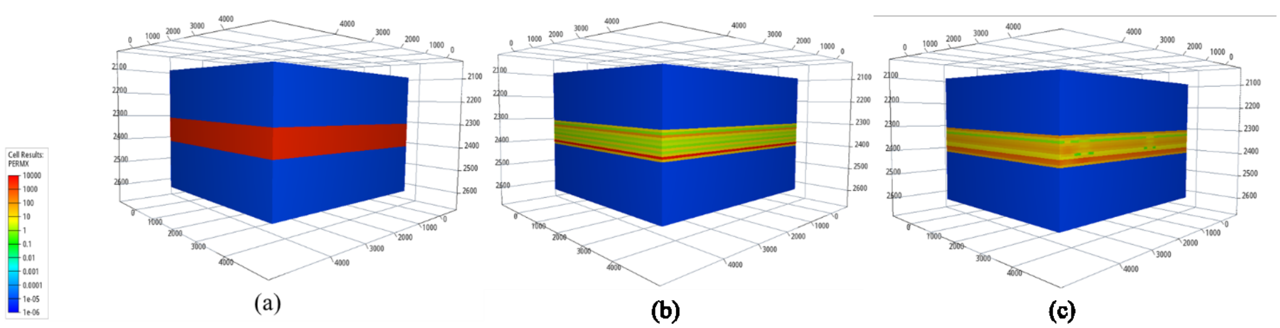

Figure 1: 3D geological models: (a) homogeneous model; (b) stratified model; (c) heterogeneous model

All models have the same reservoir domain extending horizontally 4500 m × 4200 m and vertically by 100 m. A single doublet, operating on constant mass rate control with uniform pressure and temperature initial conditions is used. The injection well and production well locate in the middle of the domain for all three types of the model. For the heterogeneous model, well log data from seven Dutch geothermal wells located in the West Netherlands Basin at a depth from 2000 m to 2100 m is used to derive the effective porosity, while for the stratified model, the log data of PNA-GT-01 well is used; permeability is defined using the porosity-permeability correlation derived by Perkins (2019). For the heterogeneous reservoir model, we use a universal kriging interpolation method to generate porosity and permeability fields. Tabel 1 summarizes the hydraulic and design parameters of the models.

Tabel 1: The simulation parameters for different models

Parameters	Unit	Values of different reservoirs		
		Homogeneous	Stratified	Heterogeneous
Porosity	-	0.2	0.11-0.24	0.01-0.25
Permeability	mD	3000	150-2000	1-2400
Shale heat capacity	$kJ/m^3/K$	2300		
Sandstone heat capacity	$kJ/m^3/K$	2450		
Shale conductivity	kJ/m/day/K	190.18		
Sandstone conductivity	kJ/m/day/K	259.20		
Initial temperature	K	350		
Initial pressure	bar	200		
Discharging rate	kmol/day	417000		
Simulation time	years	30		
Well spacing	m	1300		

3. SWEEPING AREA AND COLD PLUME

Figure 2 is a schematic for a 2D homogeneous reservoir with a streamline-defined sweeping area and a cold plume. A streamline is the trajectory of fluid flowing from the injection well to the production well, where the tangential direction of the points on streamlines is the same to the velocity vector (Datta-Gupta & King, 2007). After defining a threshold of Time of Flight (TOF) as 100 years in this study for streamlines, the sweeping area can determine. The grid cells within the sweeping area and the cold plume are used to compute the effective IA to calculate the recoverable heat in place and compute the energy recovery ratio within the effective IA.

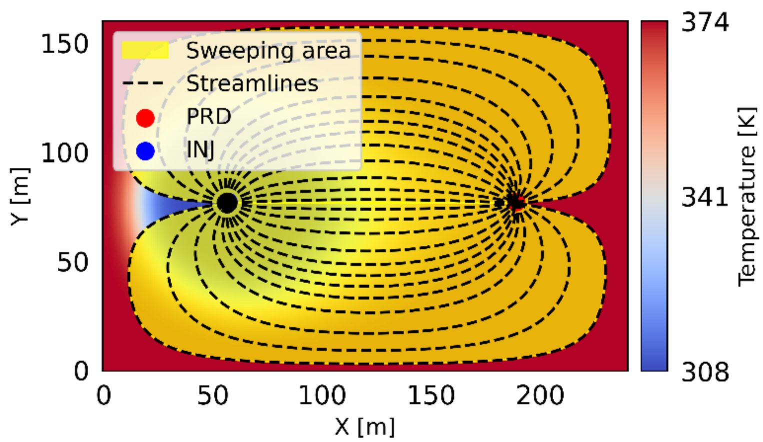

Figure 2: 2D streamline-defined sweeping area and cold plume

4. RESULTS

4.1 Optimal Cartesian resolution

The production temperature is used as an indicator to evaluate the optimal Cartesian resolution of a homogeneous, a stratified and a heterogeneous reservoir. The following Figure 3 (left) demonstrates the production temperature in 30 years by varying resolutions in different directions for a homogeneous reservoir.

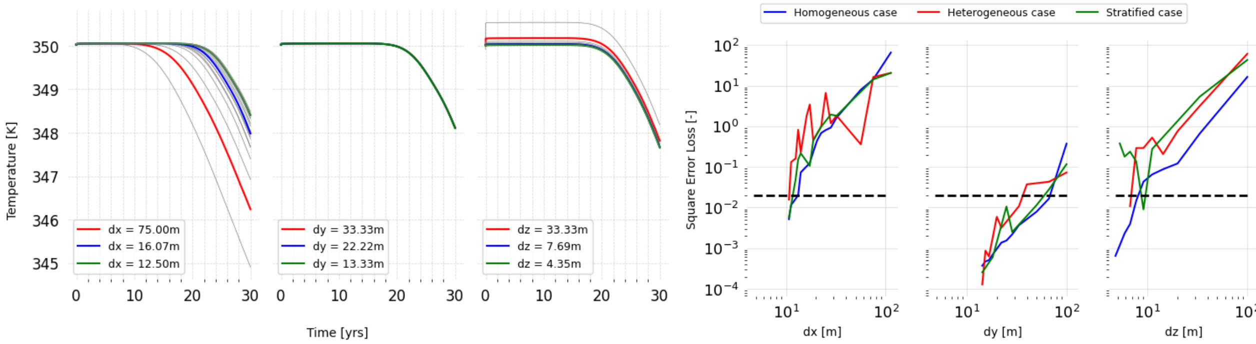

Figure 3: The production temperature (left) and the RSS of different dx, dy and dz for different types of reservoirs (right)

The residual sum of squares (RSS) of production temperature is used to quantify the difference between two sets of consecutive production temperature values for the given consecutive resolutions. If RSS is less than 0.02 which is the square of the relative difference between injection and initial reservoir temperature, the optimal resolution of a reservoir is determined. Based on above criteria, an optimal Cartesian resolution for a homogeneous reservoir is determined which is dx =15 m, dy = 70 m, and dz = 8 m. We also varied dx, dy, and dz values for a stratified and a heterogeneous reservoir to investigate an optimal Cartesian resolution. However, the RSS of production temperature for a stratified and a heterogeneous reservoir fails to converge to an optimal resolution value because of the combination of resolution changing and geological properties upscaling while creating a new model. The RSS of production temperature with varying dx, dy, and dz for stratified and heterogeneous reservoirs are shown in Figure 3 (right) in green and red respectively. It is worth noting that dz is requires a smaller value, less than 10 m, compared with dx and dy values. Although the non-convergence of RSS is present in stratified case and heterogeneous case, this study can still provide a general guidance on the creating of conceptual stratified and heterogeneous models.

4.2 Minimum thickness of confining layers

The models with the optimal Cartesian resolution are used to investigate the minimum number of confining layers required to avoid boundary interaction. The optimal number of the confining layers is decided if the variation of the maximal temperature and minimal temperature of the top confining layer is less than 0.05 K. We find that if the number of confining layers is larger than 50, which is equivalent to 400 m thickness on the top and the bottom of the pay zone respectively, the temperature variation is within 0.05 K. The top graph in Figure 4 exhibits the cold plume distribution after 30 years at the xz plane. The bottom graph in Figure 4 gives the corresponding permeability distribution to show the thickness comparison of the confining layers and the reservoir layer.

The dz of the confining layers is then upscaled to improve the computational efficiency while the thickness of the confining layers is preserved. If the confining layers have uniform dz which is the same as the dz at reservoir layers, the simulation time is about 7 minutes, while the simulation time of the non-uniform dz is around 3 minutes, which is more than two times faster. Checking the cross section of the reservoir layers at xz plane which is parallel to the well plane, the top of Figure 5(a) and Figure 5(b) shows the temperature and pressure when the confining layers have uniform dz, while the middle two graphs of Figure 5(a) and Figure 5(b) demonstrate the case with non-uniform dz.

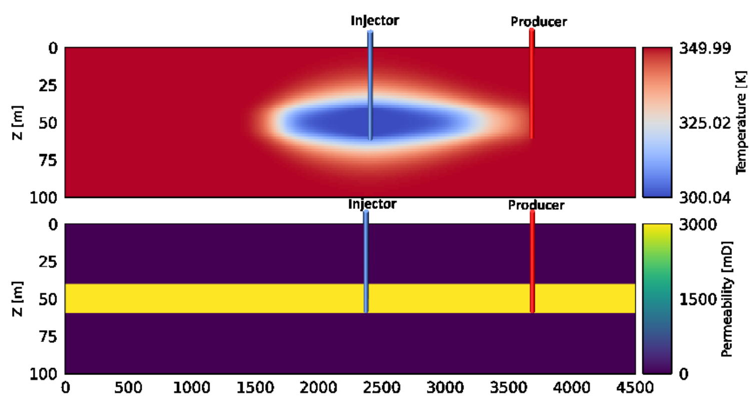

Figure 4: Cold plume after 30 years and permeability distribution at xz plane parallel to the well plane

The reservoir temperature difference of the confining layers with uniform and non-uniform dz is less than 0.2 K after 30 years of simulation(Figure 5a). Meanwhile the pressure difference of the two cases is less than 5×10^{-4} bar(Figure 5b). The production temperature of the confining layers with the uniform dz and the confining layers with non-uniform dz in 30 years is also in Figure 5(c). The RSS of production temperature is 2.7×10^{-4}.

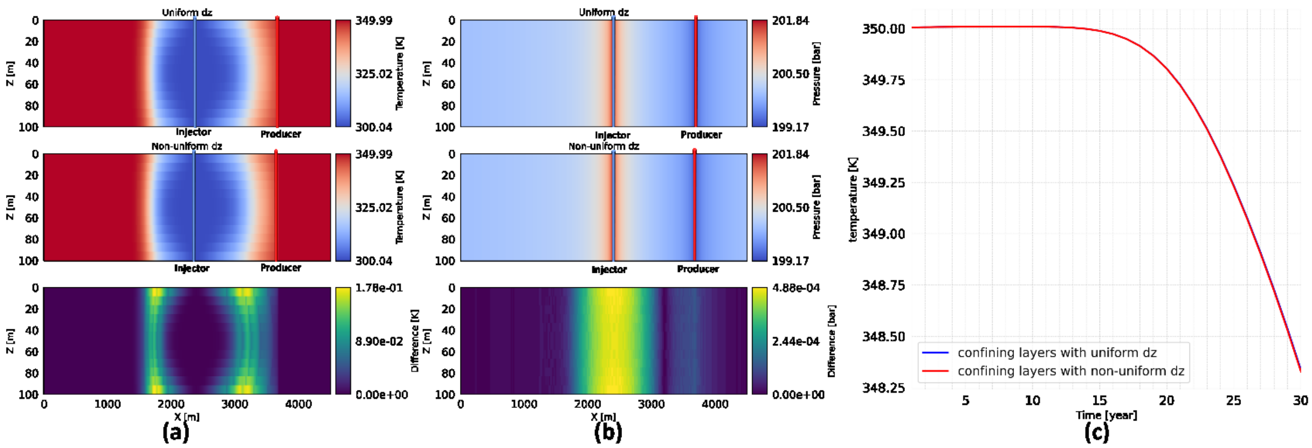

Figure 5: Temperature (a) and pressure (b) distribution of confining layers with uniform and non-uniform dz at the well plane; the production temperature for cases with uniform and nonuniform dz at the confining layers (c)

Based on the optimal Cartesian resolution which is dx =15 m, dy = 70m, dz = 8 m, and the minimum number of confining layers, following plots show the 2D cold plume and pressure distribution at the 2 layers above the middle of the reservoir after 30 years' simulation,

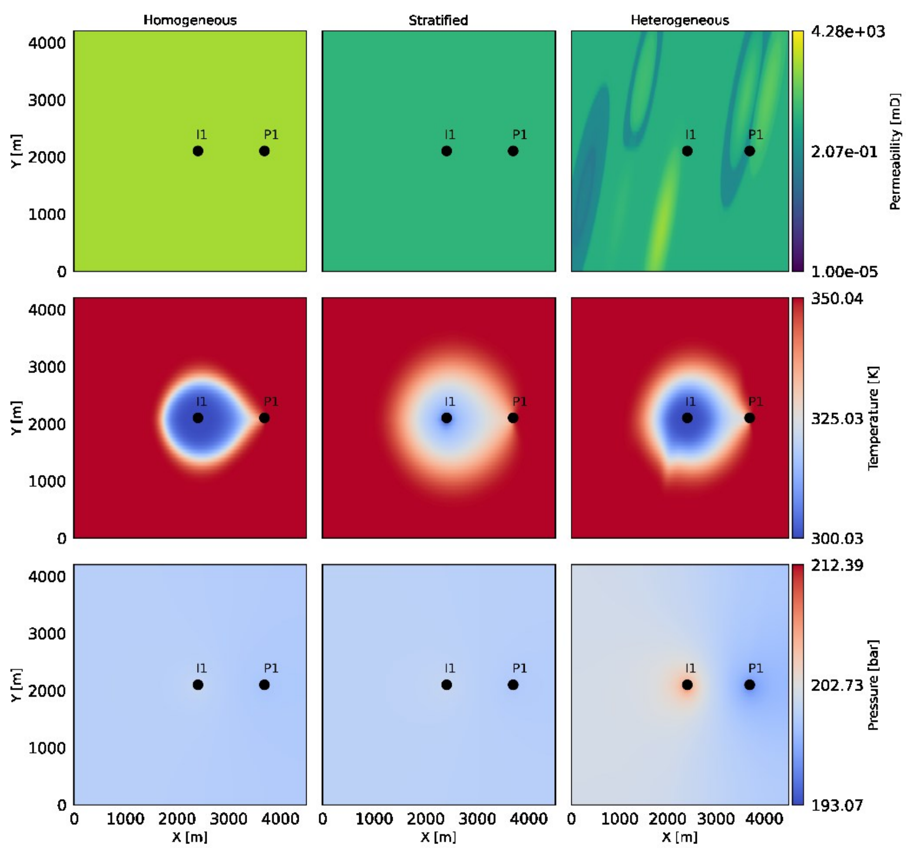

Figure 6: Permeability, temperature and pressure distribution of layer 15 for homogeneous, stratified and heterogeneous reservoirs with optimal resolution and the minimum number of confining layers

We evaluate the sweeping area using the parameters from Table 1 with the same geological settings which are defined in 4.1 Optimal Cartesian resolution and 4.2 Minimum thickness of confining layers. 100 years is used in this study as a rule-of-thumb Time of Flight (TOF) to determine the sweeping area for a geothermal project. Figure 7 shows the sweeping area for three types of reservoir models with the TOF equivalent to 100 years. Figure 7 shows the sweeping area of a homogeneous reservoir is smaller than two other cases and the shape of sweeping area of a homogeneous model remains restricted. The heterogeneity of the model allows the fluid flow along the high permeable channels. Therefore, the sweeping area remains irregular for a stratified and a heterogeneous model.

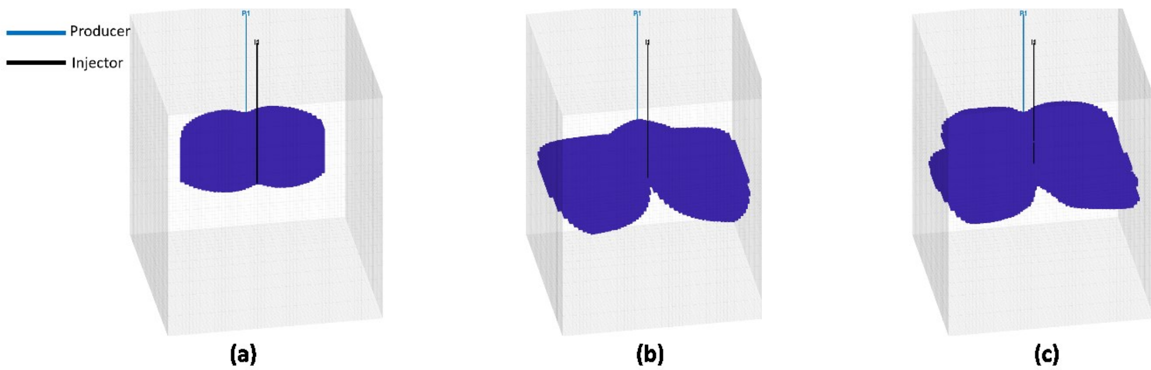

Figure 7: Sweeping area for different types of reservoir models with TOF = 100 years: (a) homogeneous model, (b) stratified model, (c) heterogeneous model

5. CONCLUSIONS AND DISCUSSIONS

In this work, we provide guidance and examples on geothermal simulation using open-source software for both educational and research activities. This study focuses on the energy production and system lifetime of DUGS. All simulation models will be constructed on the open-source Delft Advanced Research Terra Simulation (DARTS). Matlab Reservoir Simulation Toolbox (MRST) is introduced to investigate the thermal Influence Area (IA). We have following conclusions and discussion from this study:

We utilize production temperature at the production well to quantify if the reservoir model is sufficient and computationally efficient to describe a geothermal production. In this work, we identified the optimal Cartesian resolution for a geothermal simulation is dx=15 m, dy = 70m, dz = 8 m. After the determination of the optimal Cartesian resolution, a minimum thickness of confining layers which will suffice correct amount of heat during simulation without interacting with the boundaries and represent a real geological setting is obtained. The equivalent thickness of confining layers for a geothermal simulation is > 400 m, which is four times thicker than the reservoir layers. We also found that compared with the confining layers with uniform resolution in vertical direction (dz), non-uniform dz has subtle effect on the thermal response, but it is more than two times faster to simulate.

With the optimal Cartesian resolution and the minimum thickness of the confining layers, if the maximum Time of Flight (TOF) is set to 100 years, the sweeping area of a homogeneous, a stratified and a heterogeneous model is determined after deploying the same geological models and specifying the same production parameters in MRST. The 3D distribution of the sweeping area for three types of the models delineate that the heterogeneity will affect the flow behavior of injection fluid, thereby affect the thermal response.

In future work, we would like to compute the heat recovery factor using the recoverable heat in place defined by sweeping area and cold plume to assess geothermal projects which are based on different types of reservoir models. In addition, we will utilize models with the optimal Cartesian resolution and the minimum thickness of confining layers to perform comprehensive sensitivity analysis for direct-use geothermal systems. Then, the sweeping area will be employed together with the cold plume to compute the recoverable heat in place for different types of reservoir models.

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