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Thermo-Hydraulic Performance of an Enhanced Geothermal System Under Different Spatiotemporal Heterogeneous Conditions

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ABSTRACT

The purpose of this study is to evaluate the effect of permeability heterogeneity in a hydraulic fracture of an Enhanced Geothermal System (EGS). It is common practice that a single homogeneous permeability value is assumed for the hydraulic fracture. However, in reality, the permeability distribution in the HF is more likely to be fully spatially heterogeneous. Also, during EGS operation (injection/production) geomechanical stresses in the reservoir induce permeability changes that alter the initial permeability distribution in the HF. Therefore, the heterogeneous permeability distribution in the HF becomes more dynamic, and also as a function of time. The thermo-hydraulic behavior of the EGS will be investigated under different types of heterogeneity distributions of the hydraulic fracture permeability, as a function of space and time compared to a homogeneous HF permeability. This numerical simulation study is conducted with the TOUGH+RealGasBrine V1.5 code. The cooling front propagation (in the HF and into the rock matrix), optimal production rates, and produced heat flow (MW_{th}) are the main criterion for the thermo-hydraulic evaluation of the performance of the EGS. The results showed a significant effect of these changes on the overall performance of the EGS. The exact heterogeneity distribution of the HF permeability/conductivity will play a big role on the injected fluid trajectory, thus the cooling front propagation rate. Pressure build-up concerns may become an issue at some point for a given permeability distribution, especially if low permeability "damaged" zones are considered.

1. INTRODUCTION

In recent years, geothermal energy has been attracting a lot of attention as a sustainable energy source. Its capacity to tap into the Earth's natural heat, provides a source of clean, dependable, and baseload energy. Nonetheless, the effectiveness and economic viability of geothermal systems rely on various factors. In the natural context of geothermal systems, particularly hydrothermal systems, three fundamental components—heat, fluid, and permeability—are indispensable for generating electricity. According to the U.S. Department of Energy (2016), numerous regions have hot underground rock but lack adequate natural permeability or fluids. In such scenarios, Enhanced Geothermal Systems (EGS) come into play, establishing artificial reservoirs to harness heat for energy generation.

The main difference between EGS and Conventional Geothermal Systems (hydrothermal systems) is the permeability enhancement technique via hydraulic fracturing in EGS. According to SLB Glossary (2023), hydraulic fracturing is performed by pumping engineering fluids at high pressure and rate into the reservoir interval to be treated, causing a vertical fracture to open. This fracture is kept open by the use of a proppant such as fine sand. This enhanced permeability enables the fluid to circulate through the fractured hot rock. Consequently, operators introduce colder water into the reservoir from an injection well and draw out significantly warmer water to the surface via a production well (Figure 1). An EGS, is implemented as follows: 1. Drill the injection well, 2. Perform the hydraulic fracturing operation, 3. Drill the production well that intercepts the hydraulic fracture, and 4. Inject cold water from the injection well and produce hot water from the production well.

EGS technology encompasses several essential components, including exploration, drilling, hydraulic stimulation, subsurface heat extraction, wellbore flow, geomechanics, surface thermodynamic processes etc. (Tester et al., 2006). This study focuses on the subsurface heat extraction. This involves the flow of fluid and heat in the reservoir, including the thermal and hydraulic interaction between the hydraulic fracture and the native rock matrix. This numerical simulation study is conducted with the TOUGH+RealGasBrine V1.5 code, with high-resolution 3-D Cartesian grids (Sfeir et al., 2023). This paper will investigate the effect of introducing different types of heterogeneities into the hydraulic fracture permeability, compared to a homogeneous distribution.

2. OVERVIEW

2.1 EGS Heat Extraction

The EGS begins with the injection of cold (surface temperature) water into the reservoir through an injection well. Then, the injected cold fluid starts seeping into the reservoir. Since the fluid will flow into the path of least resistance, most of the flow is concentrated within the hydraulic fracture (HF), with inevitable fluid exchange with the low-permeability rock matrix. As the fluid travels from the injector to the producer, it gradually heats up due to the contact with the hot rock. The heat exchange process is facilitated by the large temperature difference between the injected cold water and the hot rock in the subsurface reservoir. This hot water is then pumped back to the surface through the producer.

Over time, due to the constant injection of cold water, the reservoir starts to cool down. There is a cooling front that is initiated at the injection well and propagates from the injector into the reservoir. The cooling front propagates mainly towards the production well, but also into the rock matrix to a certain extent. When this cooling front reaches the production well, the temperature of the produced fluid starts declining, and this is referred to as a thermal breakthrough. How fast the cooling front propagates, and the magnitude of the thermal decline rate depend on multiple factors.

Those factors may be reservoir properties, which cannot be controlled (permeability, porosity, thermodynamic conditions etc.) or operational parameters that are human-designed (injection rate, well spacing, working fluid etc.). Proper reservoir management is needed for the sustainability of the EGS over many years of operation. Indeed, EGS are typically planned to operate for 30 years. The injected cold water initially cools the reservoir rock, especially near the injection spot. Understanding the cooling effects and their extent is critical for predicting heat exchange efficiency. Higher flow rates can enhance heat transfer but must be balanced with reservoir sustainability and seismic risks. Heat transfer within the reservoir occurs primarily through conduction and convection. Conduction involves the transfer of heat through the solid rock, while convection involves the movement of hot fluids through fractures and fissures, carrying heat with them.

A common method for predicting thermal depletion of the EGS can be done via proper reservoir modeling and numerical simulation. However, the accuracy of reservoir simulation is highly dependent on the quality of the available data and the uncertainty around the parameters used.

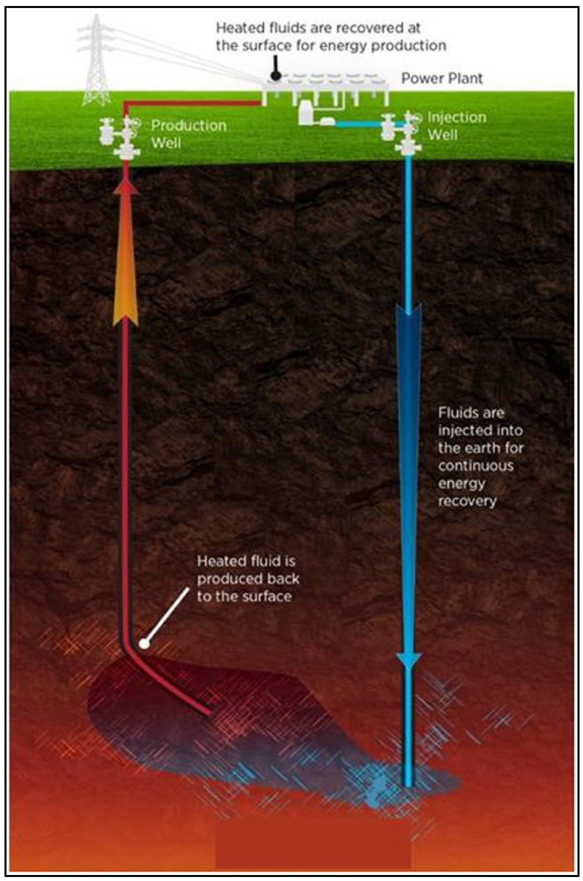

Figure 1 EGS Reservoir (US Department of Energy, 2016)

2.2 Knowledge gap

It is very common in reservoir simulation practice to assign a single given value for the hydraulic conductivity or permeability of the hydraulic fracture. This would make a smooth homogeneous permeable path for the fluid in the hydraulic fracture. However, this is very unlikely in reality. The reservoir rock's heterogeneous and anisotropic properties, the geomechanical stress regime, the injection-induced thermal stresses, the injection of proppants to keep the fracture open, and many other factors make it less accurate to assume a homogeneous permeability for the HF. Another factor that also affects the permeability distribution in the reservoir is chemical reactions, as shown in Li et al. (2023) where they experimentally analyzed the effect of mineralization of CO_2 in EGS reservoirs and showed that it reduces reservoir permeability. Geothermal reservoirs often exhibit complex and heterogeneous subsurface conditions, including variations in rock types, fractures, and fluid properties. The over-simplification of assuming uniform permeability neglects the inherent heterogeneity of the reservoir, leading to inaccurate predictions of fluid flow patterns and temperature distribution. Ignoring this heterogeneity may result in underestimated or overestimated reservoir performance, hindering the effectiveness of geothermal energy extraction strategies. To enhance the precision of reservoir simulations, it is crucial to incorporate realistic heterogeneous permeability distributions in hydraulic fracture models, thereby providing a more accurate representation of the complex subsurface dynamics associated with geothermal systems.

2.3 Objective

This paper will assess the effect of permeability heterogeneity and anisotropy in the hydraulic fracture, on the overall behavior of the system. Different types of permeability heterogeneity distributions will be considered and compared to a homogeneous distribution case. The studied cases are: Homogeneous case (base case), regional heterogeneity, stochastic heterogeneity, and time-dependent stochastic heterogeneity. The specifics of each will be discussed in section 4.

Emphasis will be placed on the optimization of operation for maximization of heat recovery and of the productive lifetime of the system, managing the inevitable cool water injection without depleting irreversibly the heat of the rock (quenching the fire). The evaluation of these influencing factors will be based on the overall thermal and hydraulic performance of the EGS by monitoring all relevant thermodynamic quantities globally in the simulation domain and regionally at areas of interest (production well), as a function of time (Sfeir et al., 2023).

This analysis will be able to assess how big of an impact can the assumption of a homogeneous permeability distribution have on overpredicting/underpredicting EGS reservoir metrics (temperature distributions, production rates, temperature of produced fluid, and the thermal energy produced).

3. RESERVOIR MODEL

Numerical Simulator. This reservoir simulation employs TOUGH+RealGasBrine ((Moridis and Pruess, 2014; Moridis and Freeman, 2014; Song et al., 2023a,b; Huang et al., 2023) , a code developed at the Lawrence Berkeley National Laboratory. This code can simulate all known processes inherent in the non-isothermal, multicomponent, multiphase flow of fluids and heat through porous and/or fractured geologic media (Moridis et al., 2010). The primary physics governing fluid and heat transport in porous media are dictated by the Mass Balance and Energy Balance equations. Following the approach presented by Pruess et al. in 1999, mass balance considerations are applied to each subdomain (gridblock) formed by the integral finite difference method, as the simulation domain is subdivided. Further details on this subject can be found in Moridis and Freeman's work (2014) in the T+RGB Core Manual.

Simulation Aspects. The examined EGS comprises a pair of vertical wells (one injector and one producer), a hydraulic fracture (HF), and the rock matrix subdomain (Figure 2). A highly refined 3-dimensional Cartesian discretization is employed (148,353 gridblocks). Because of the symmetry on either side of the vertical plane of the HF, the 3D simulation domain represents only half of system. This domain is referred to as the minimum repeatable element (stencil/domain) that can describe an EGS (Sfeir et al., 2023). The simulation spans a period of 5 years.

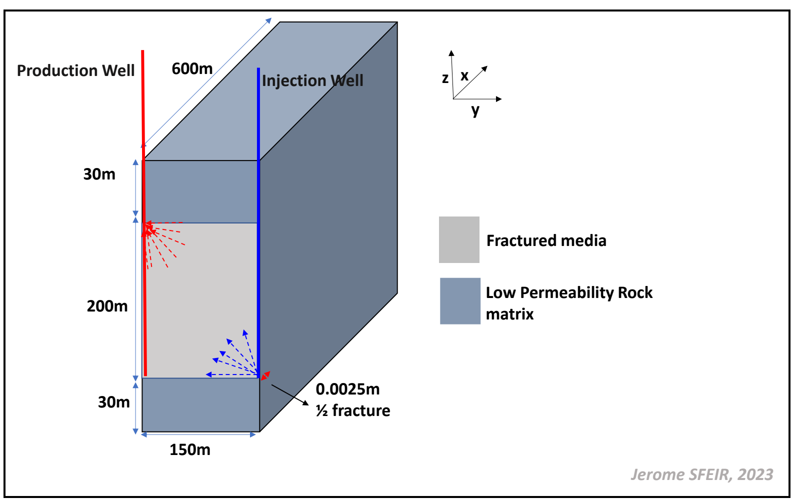

Figure 2 Simulated Domain Geometry (Sfeir et al., 2023)

Reservoir Properties. The properties of the rock matrix are configured to replicate those of a tight media, having low porosity and permeability. Emphasizing the predominant flow within the hydraulic fracture (HF) with some fluid exchange with the rock matrix. Table 1 provides in-depth information on reservoir rock properties, as well as specific simulation computational parameters. For the initial conditions of the system, an initialization simulation, spanning thousands of years, is conducted to achieve hydraulic and thermal stability before commencing injection/production. Production is governed by a constant bottomhole pressure constraint, acting as a boundary condition, while the back x-boundary (x=600 m) serves as a no-flow (impermeable) boundary. Extensive testing of boundary condition dimensions has been carried out to minimize interference with EGS operation. The initial pressure and temperature of the reservoir are 20 MPa and 200°C, respectively. The injection of 8 kg/s of 55 °C water occurs at the bottom right of the HF (see Figure 2), with production taking place at the top left.

Table 1 Reservoir Properties and Simulation Parameters (Sfeir et al., 2023)

Reservoir Parameters and Conditions	
Parameter	**Value**
Rock Density	2650 kg/m^3
Rock Porosity	0.05
Rock Permeability	0.1 mD
Wet Thermal Conductivity	4.5 W/m/°C
Specific Heat	1000 J/kg/°C
Compressibility	1.0E-9 (Pa-1)
Klinkenberg parameter	1.0E+05 (Pa)
Relative Permeability Equations	Van Genuchten-Mualem model
Capillary Pressure	Van Genuchten function
Composite Thermal Conductivity	Somerton Model
Hydraulic Fracture Permeability	5 Darcy
Hydraulic Fracture Aperture	5 mm
Hydraulic Fracture Porosity	0.5
Initial Pressure	20 MPa
Initial Temperature	200 °C
Simulation Time	5 years
Convergence Criterion	5.00E-05
Max. Newton Raphson Iterations	10
Maximum Time-Step	10 days
Injection Temperature	55°C
Injection Rate	8 kg/s
Producing Bottomhole Pressure (P_{bh})	5.5 MPa

4. HETEROGENEITY DESCRIPTIONS

Homogeneous case. This reference case considers a homogeneous permeability in the hydraulic fracture, of 5 darcies. It also considers the presence of proppants by assigning a 50% porosity for the hydraulic fracture subdomain.

Regional Heterogeneity. This case refers to a permeability distribution in the hydraulic fracture by subdividing it into different regions. This is a user-defined discretization of the HF. Different combinations of HF permeability and porosity are assigned, as seen in Figure 3. This is done in a way to replicate the non-uniformity of a HF with potential damaged zones in the HF, where permeability is low or where there is a high proppant density compared to other regions.

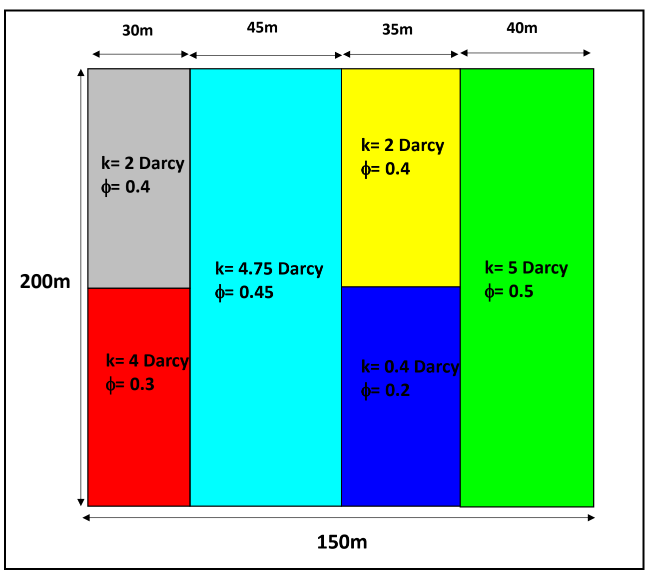

Figure 3 Regional Heterogeneity Permeability Distribution

Stochastic Heterogeneity. This case refers to a random permeability distribution based on a log-normal distribution of the HF permeability. This is performed by assigning a random permeability value for each of the 3500 gridblocks in the HF. This is not a feature in the simulator, it was performed externally by the user. A MATLAB code was written that goes into the Initial Conditions file (INCON) of the T+RGB input files and assigns a random value for each of the permeabilities in the x-y-z directions, based on a log-normal distribution of permeability values. This makes the HF permeability stochastically heterogeneous and anisotropic. The pool of values used is within a range of 2 to 9 Darcy, with an arithmetic mean of 5 and arithmetic standard deviation of 0.7. The mean value is selected to match the permeability value of the homogeneous case. The same workflow is applied for the rock matrix permeability. Now the system is fully heterogeneous and anisotropic (Figure 4).

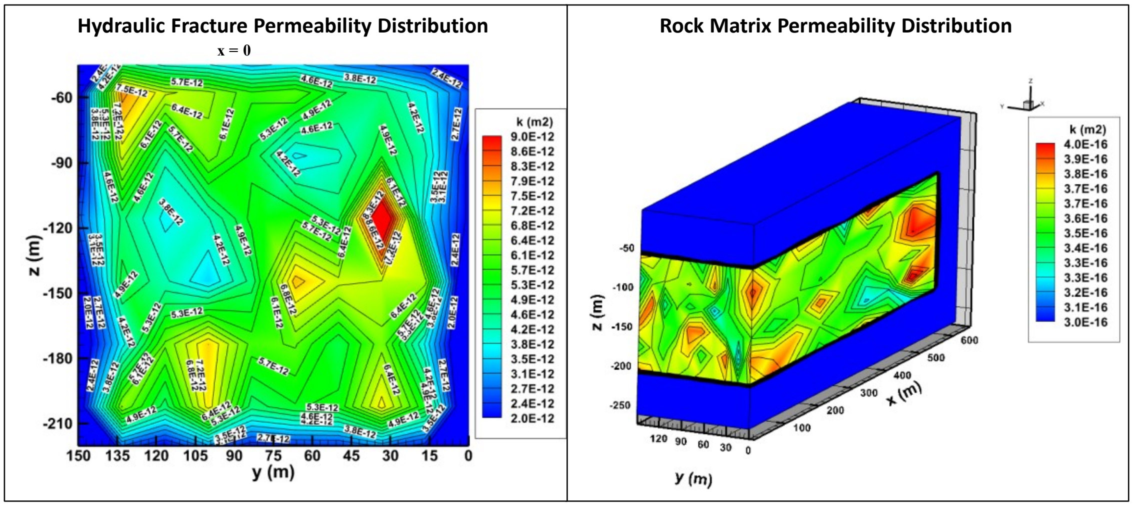

Figure 4 Stochastic Permeability Distribution

Time-Dependent Stochastic Heterogeneity. This case follows the same conditions as the previous one (stochastic heterogeneity). The only difference is that the effect of time is incorporated. At each year, new random permeability values are assigned for each grid block, based on the same log normal distribution discussed in the previous case. This replicates a similar effect that would occur in the reservoir with changes in thermal and mechanical stresses, deformations, and potential proppant transport (Figure 5).

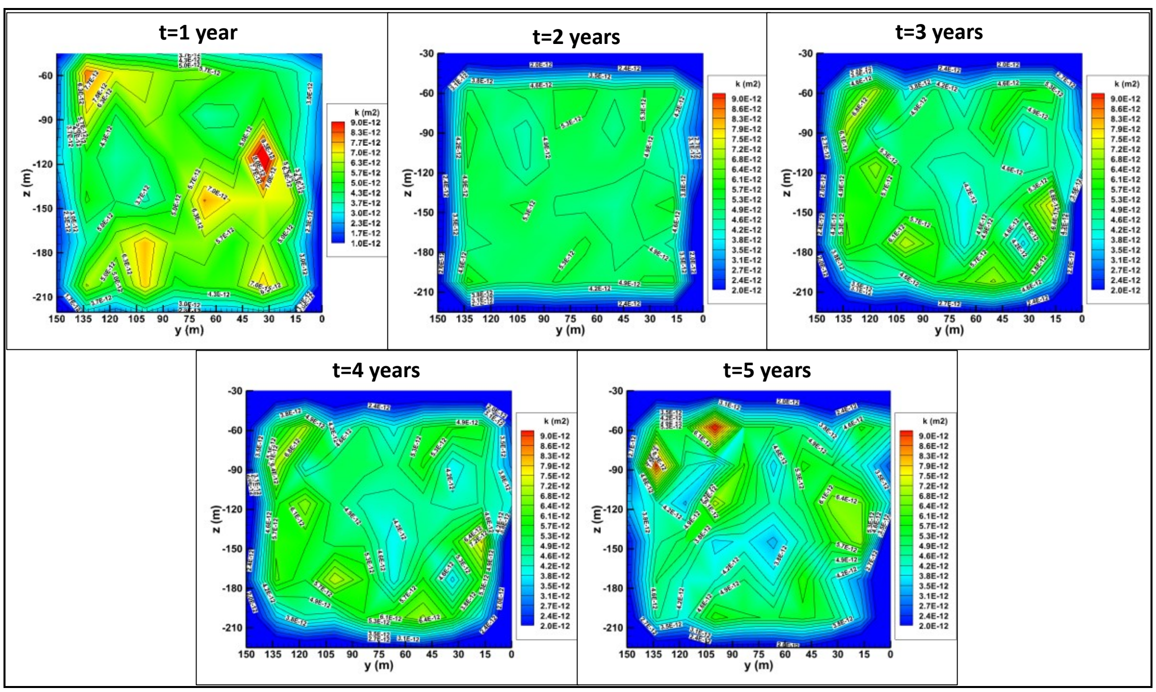

Figure 5 Time-Dependent Stochastic Distribution

5. RESULTS AND DISCUSSION

Temperature distribution. Figure 6 shows the temperature distribution at t = 5 years for all four simulated cases. In EGS, the propagation of the cooling front within the hydraulic fracture is a critical aspect that directly impacts energy extraction efficiency. As time progresses, the cooling front within the hydraulic fracture begins to propagate away from the injection well towards the production well. The optimal target for such a system is to delay the propagation of the cooling front as much as possible. The major difference in the cooling front propagation can be seen only in the regional heterogeneity case. This case is a user-defined distribution of different permeability zones within the HF. The stochastic heterogeneity cases are randomly assigned permeability values based on a log-normal distribution; it shows no significant difference compared to the homogeneous case. It can also be seen that there is a cooling front that propagates into the rock matrix (along the x-axis) which shows the thermal and hydraulic communication between the HF (hydraulic fracture) and the rock matrix.

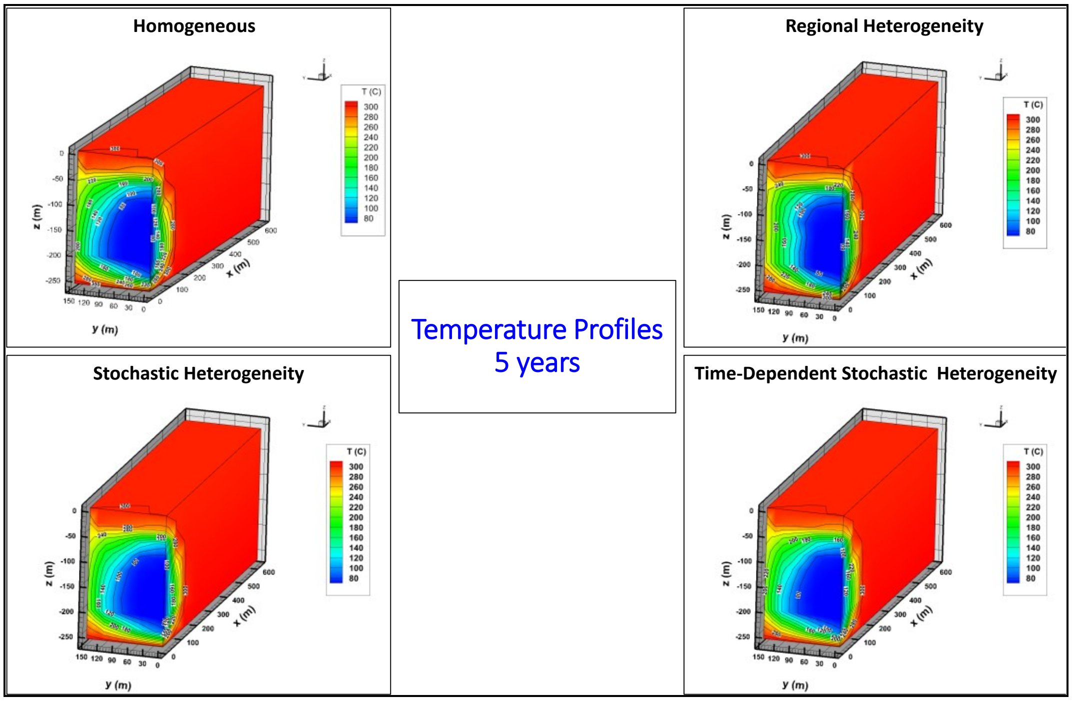

Figure 6 Temperature Distribution t= 5 years

Production Rates. Figure 7 shows the production rates curve as a function of time. As 8 kg/s is injected in the system, the production rate should asymptote around this value, while accounting for inevitable losses to the rock matrix. There are some minor differences in the first 1.5 years of the simulation (<1%). This is the period where the system is trying to accommodate the injection-production operation, in order to reach a quasi-stable state. This is highly dependent on the permeability, therefore a change in the distribution, would affect this behavior. After 5 years, the production rates are all the same, thus showing no effect of the heterogeneity on the production rates. However, the stochastic distribution cases show some "noise" in the data, this shows that the stochastic heterogeneities (assigning each gridblock a random permeability value) can make the problem numerically challenging. The discontinuity of flow patterns and pressure gradients due to random permeability values at each gridblock can make the problem numerically challenging.

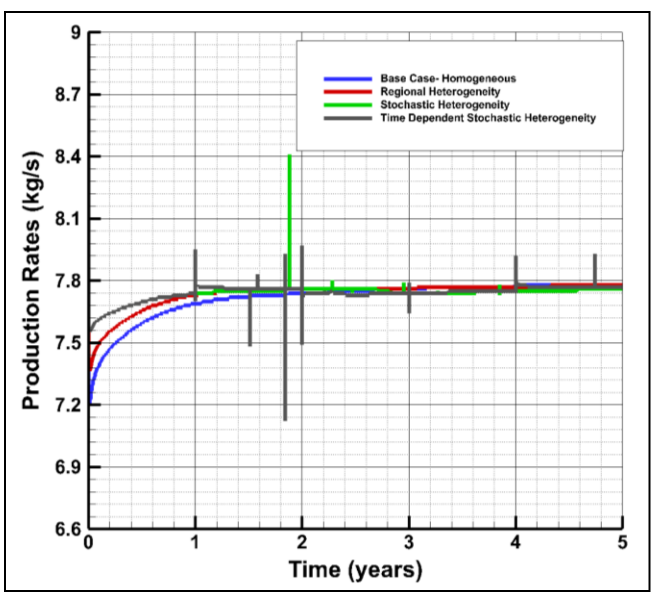

Figure 7 Production Rates as a function of time

Fluid Temperature at the production well. Figure 8 shows the temperature of the produced fluid for the four simulated cases. When the cooling front reaches the production well, a drop in the temperature of the produced fluid will be experienced, referred to as thermal breakthrough. Thermal decline starts at 1.7 years for the homogeneous case. This figure shows that the homogeneous permeability distribution in the HF slightly underpredicts the temperatures after 5 years (242°C compared to 248°C for the stochastic heterogeneity case and 250 °C for the regional heterogeneity case). The stochastic and time-dependent stochastic heterogeneity show no difference. Therefore assuming a homogeneous distribution underpredicts the temperature of the produced fluid by 2.4%. This may or may not be relevant depending on the complexity of the heterogeneity of the system, and the user's accuracy interest.

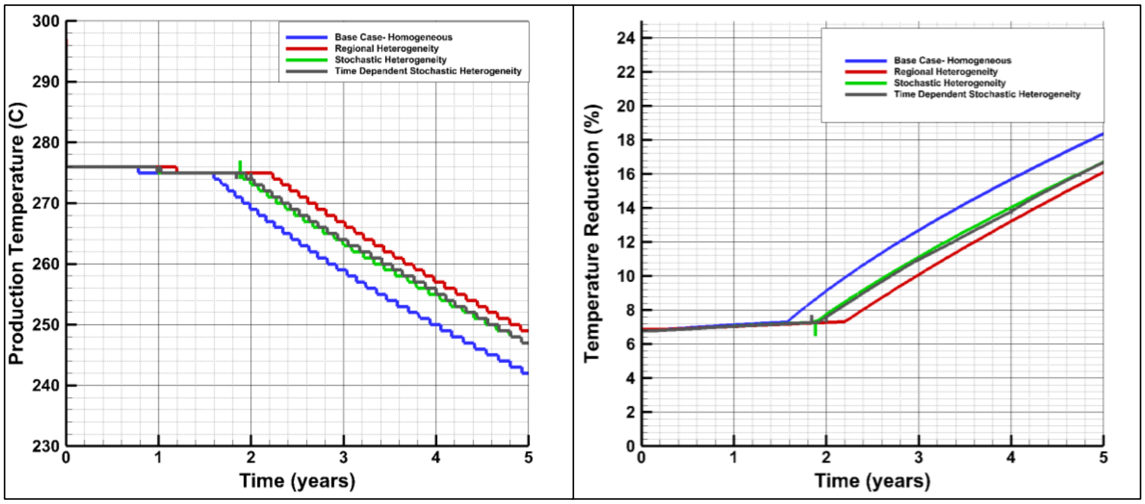

Figure 8 Temperature of the produced fluid (left) and temperature reduction (right)

Produced Heat Flow. This is the major product of the EGS: the thermal energy produced. This metric reflects both the hydraulic and thermal subsurface performance of the EGS. It is mainly governed by the advective heat flow, beeing the product of mass rates and enthalpy of the produced fluid. Combining the hydraulic and thermal aspects, Figure 9 shows the produced heat flow. After 5 years, the homogeneous EGS produces 8.15 MW_{th}. The hydraulic performance (production rates) is almost identical for all cases. The thermal performance showed small changes. The trend of the heat flow decline is similar to the thermal decline shown earlier. The homogeneous system slightly underpredicts the thermal energy produced (8.15 MW_{th} compared to 8.4 MW_{th}), similar to what was observed in the temperature of the produced fluid calculations.

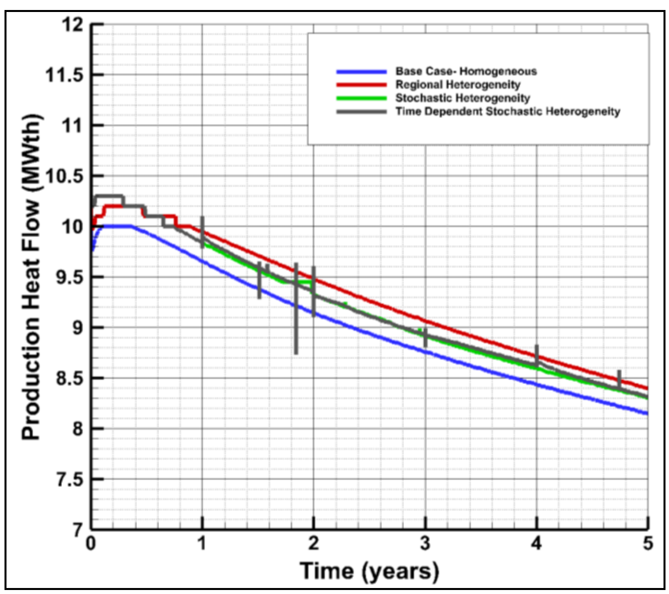

Figure 9 Produced Heat Flow

Tracer Test. A tracer test is a diagnostic technique used in geothermal energy exploration and production to better understand the flow of fluids within a geothermal reservoir. This method involves injecting a small amount of a detectable substance, known as a tracer, into the geothermal fluid circulating within the reservoir. The behavior of the tracer is then monitored as it moves through the reservoir over time. By tracking the tracer's movement, researchers can gather essential information about the reservoir's physical characteristics, such as permeability, porosity, and flow pathways. The tracer substance itself is carefully chosen to be inert, non-reactive with the geothermal fluid, and easily detectable. Common tracers include hydrogen sulfide (H2S). A numerical tracer test is performed for this case to study the effect of the permeability heterogeneous distribution in the HF on the fluid trajectory and the residence time. Figure 10 shows the production rates of the tracer fluid for the simulated cases. It can be seen that the heterogeneity of the HF does play a role on the residence time of the fluid. The shortest residence time is for the homogeneous case, with about 13 hours. The stochastic heterogeneous case is at 18 hours and the regional heterogeneous case is at 20 hours. This is an observation based on the inflection point of the curve. However, this metric is more relevant in field testing, to ensure connectivity between the wells and residence time. Numerically, it highlights that heterogeneities can delay the fluid by changing its ideal trajectory considered in the homogeneous case.

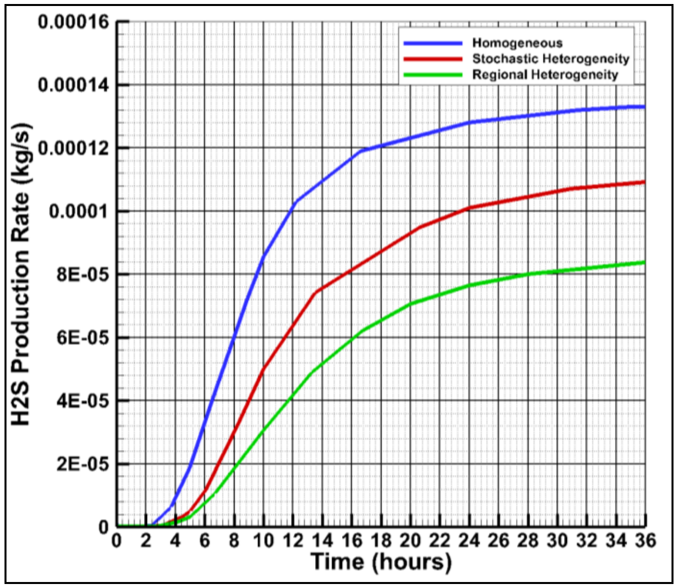

Figure 10 Residence time for simulated cases

Figure 11 shows the distribution of the tracer fluid in the HF from the injector (y=0) to the producer (y=150 m) at t = 24 hours for x=0. The stochastic case shows a disturbed trajectory of the fluid which is more realistic compared to the homogenous case showing a smooth idealistic trajectory taken.

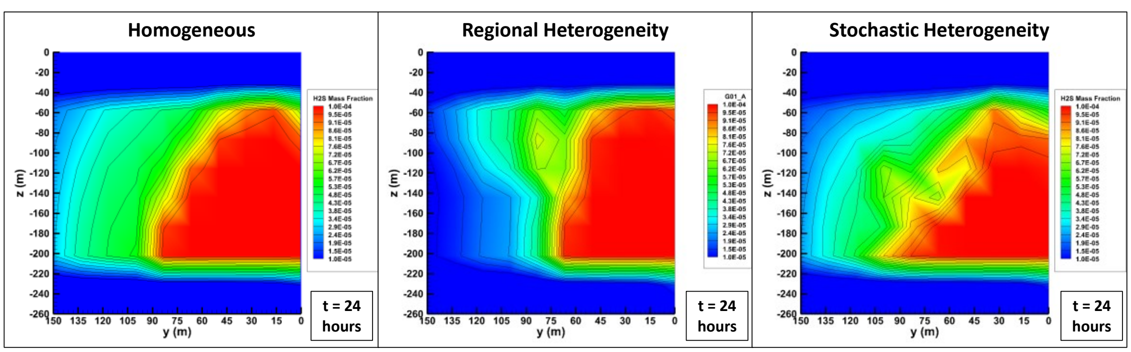

Figure 11 Tracer Distribution at t = 24 hours

6. DISCUSSION

It can be seen that there is a small difference in the homogeneous case compared to the stochastic case, i.e. the random distribution of permeability values for each gridblock. In reality, this reflects a scenario where the hydraulic fracturing operation on the field went as planned, meeting the designed permeability/conductivity of the hydraulic fracture. It will depend on the user interest of degree of accuracy, since a 2% difference is seen. There is a larger difference, yet not significant with the regional heterogeneity case. This case is based on a user-defined discretization splitting the HF into different regions, replicating a scenario where a “damaged” zone is present in the HF whether in terms of fracture propagation or proppant accumulation. This is common in reality when the HF operation doesn’t go as planned, and therefore induces deviations from the designed geometry or hydraulic performance. In conclusion, it is fair to assume that the HF is homogeneous, however one must not neglect the effect that the heterogeneity can have depending on the degree of accuracy desired, and the extent of the heterogeneity expected into the system. The degree of heterogeneity will depend on the quality control of the fracturing operation and monitoring, in order to assess if the actual HF properties, meets the designed-for properties as much as possible.

7. CONCLUSIONS

- It is common practice in reservoir simulation to assign a single value for the hydraulic conductivity or permeability of the HF. However, in reality, many factors make this assumption less appropriate, such as: rock properties, geomechanical stresses, the injection-induced thermal stresses, the injection of proppants to keep the fracture open, etc.

- This paper introduced and assessed the effect of permeability heterogeneity and anisotropy in the hydraulic fracture, on the overall behavior of the system.

- Different types of permeability heterogeneity distributions are considered: Homogeneous case (base case), regional heterogeneity, stochastic heterogeneity, and time-dependent stochastic heterogeneity.

- The analysis reveals a subtle difference between homogeneous and stochastic cases, indicating that in scenarios where hydraulic fracturing operations proceed as planned, with the designed permeability and conductivity, a relatively small 2% difference is observed. This underscores the importance of assessing the user's interest in accuracy, as this variance may be considered acceptable in certain contexts.

- In contrast, the regional heterogeneity case exhibits a larger but non-significant difference, simulating scenarios where the hydraulic fracturing process deviates from the intended design due to factors such as fracture propagation issues or proppant accumulation. This mirrors real-world situations where unexpected challenges arise during operations, leading to deviations from the planned geometry and hydraulic performance.

- The heterogeneity of the permeability distribution in the HF does affect both the hydraulic and thermal performance of the EGS. However, it can either affect it positively or negatively, depending on the exact heterogeneous distribution.

- A heterogeneous distribution would disrupt the flow path/trajectory of the fluid and increase parasitic loads. Especially if "damaged" zones or proppant clogged spots are considered when modeling a HF.

- While assuming homogeneity may be reasonable, it is crucial not to overlook the potential impact of heterogeneity based on the desired accuracy and the extent of expected deviations in the system.

- Quality control measures and monitoring during fracturing operations become paramount to assess whether the actual hydraulic fracture properties align with the intended design, emphasizing the need for effective control and assessment mechanisms in field.

ACKNOWLEDGMENT

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