

Simulation of Injected Flow Pathways in Geothermal Fractured Reservoir Using Discrete Fracture Network Model

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ABSTRACT

Understanding injected flow behavior through subsurface fractured media is important for successful energy production of enhanced geothermal systems (EGS). The injected fluid travels through stimulated and natural fractures; the fracture surface – matrix interaction leads to heat exchange and energy production. Since the natural and stimulated fractures provide fast paths for flow and fracture connectivity dictates the flow behavior and flow directions, understanding the effect of fracture network topology is important for flow predictions at reservoir sites. We used Discrete Fracture Network (DFN) model to generate fracture configurations, and to simulate flow and transport through fractures. The particle tracking tool was applied to follow particles trajectories travelling through fractures from injection source to production well. The DFN team at EGS Collab performed tremendous work on identification and characterization the fractures observed at wells and boreholes. The Common DFN (CDFN) model, based on deterministically defined fractures observed at boreholes, was generated on FracMan software. We transferred the CDFN to dfnWorks computational model and generated new DFNs where Common DFN is surrounded by stochastic fracture networks, which provide a fracture connectivity for flow paths from stimulated fracture and injection well to the production well and the flowing fractures at monitoring boreholes. We simulated flow and particle tracking through the generated DFNs, and show how flow tortuosity and particles travel distance depend on natural fracture networks intensities. The presented new modeling workflow has a high potential for reproducing exact flow paths observed at the experimental sites with understanding fracture network topology of geothermal reservoirs at large scale.

1. INTRODUCTION

Enhanced geothermal systems (EGS) offer enormous potential as a renewable energy resource, which supports the energy reliability of the United States. EGS Collab project was initiated to extend and clarify our understanding of rock mass response to applied stress for stimulation and provide a testbed at local scale for the validation of thermal-hydrological-mechanical-chemical (THMC) modeling capabilities as well as novel monitoring tools (Kneafsey et al., 2018). The Sanford Underground Research Facility (SURF) was selected as a site for EGS Collab Testbed. The SURF is established as a dedicated underground research facility using the extensive network of tunnel systems developed over a century of gold mining activities as Homestake Gold Mine in Lead, South Dakota (Heise, 2015).

The EGS Collab Experiment-1 (E1, 4850 Level) testbed consists of eight HQ-diameter (9.6 cm), continuously cored sub-horizontal holes with nominal lengths of about 200 ft. Each hole was steel-cased to a depth of 20 ft from top (collar). Six of the boreholes (E1-OT, E1-OB, E1-PST, E1-PSB, E1-PDT, and E1-PDB) were heavily equipped with various equipment for seismic, temperature, electrical resistivity monitoring, and grouted with a mixture of ground blast furnace slag, ground pumice, and Portland cement. The remaining two holes E1-I and E1-P were left open and being used as injection and production wells, respectively. Five notches were created at different

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depths along the E1-I to facilitate stimulation and guide initiate intended hydraulic fracturing (Neupane et al., 2019). Our simulations were focused on the stimulated fracture at the 164' notch. The boreholes and a conceptual depiction of the stimulated fracture are shown in Figure 1.

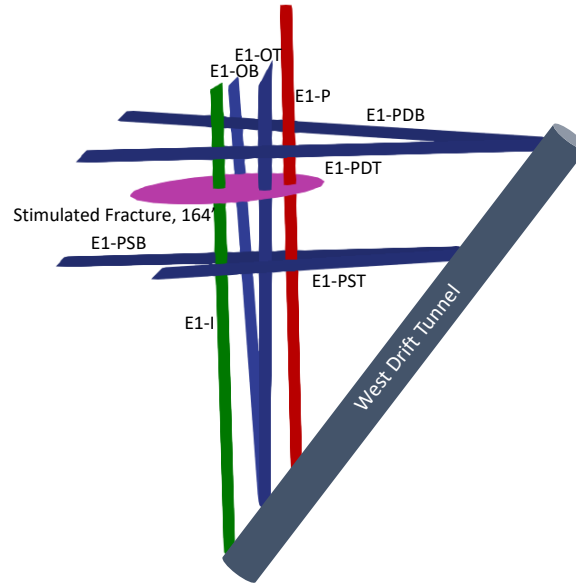


Figure 1: EGS Collab Experiment-1 Testbed: injection well E1-I (green), production well E1-P (red), six monitoring boreholes (blue), and stimulated hydraulic fracture (magenta disk) at 164' notch. The drift tunnel is shown in gray color.

During the drilling, the subhorizontal boreholes intersected a number of natural fractures. The observed natural fractures along the boreholes were identified using acoustic and optical televiewer logging. These fractures were verified by core inspections and hydraulic characterization efforts (e.g., Roggenthen and Doe, 2018; Ulrich et al., 2018; Singh et al., 2019; Neupane et al., 2019). To simulate natural fractures at EGS Collab site, the advanced three-dimensional Discrete Fracture Network (DFN) model has been used by EGS modeling team (Neupane et al., 2019; Singh et al., 2019). The discrete fracture network simulation method (Dershowitz, 1984), which, as opposed to the traditional continuum approach, explicitly represents individual fractures. In 3D DFN approach, two-dimensional fractures are placed in a three-dimensional domain, intersecting each other and forming fracture networks. Model generates fractures according to fracture network characteristics, such as fracture size, aperture, and orientation, extracted from site-specific geological observations. The DFN model is chosen as one of the most advanced computational approaches for modeling fractured media, where fractures provide the fastest path for flow.

The study of Roggenthen and Doe (2018) presented a first DFN model of flowing fractures, potential flow conductors and identified drip and weep zones at EGS Collab E1 site. The observed fracture network was generated at FracMan software (Dershowitz, 2014) and used in later studies to recreate the natural fracture network at the site (Neupane et al., 2019). The main goal of the current research is to develop the new modeling workflow that will extend the presented DFN simulation capability (Neupane et al., 2019) to flow paths modeling, where the flow, injected at stimulated fracture, travels through a natural fracture network and is collected at defined drip zones. We used variable stochastic fracture network intensity to show how flow paths directions, tortuosity of released particles, and particles travel distances are affected by existence of natural fractures. To perform the flow path simulations, we used dfnWorks parallelized computational suite, developed for simulations of flow and transport in three-dimensional discrete fracture networks. dfnWorks (Hyman et al., 2015a) has been successfully applied to the problems associated with contaminant transport in nuclear waste repositories (Hyman et al., 2015b; Makedonska et al., 2016); natural gas production from fractured reservoirs (Karra et al., 2015; Hyman et al., 2016); and the modeling of CO₂ migration at CO₂ sequestration sites (Makedonska et al., 2018). dfnWorks was used in Jafarov et al., (2020) study to generate fracture networks, which were transferred to continuum volume mesh. This mesh was used to perform the heat-flow simulations and tracer modeling, where the EGS Collab experimental design was applied (Jafarov et al., 2020). dfnWork's parallel framework is computationally efficient allowing for a broad range of length scales (from mm to kilometers) to be simulated, and to model large scale reservoir site in a reasonable computational time.

2. METHODOLOGY

In this section, we describe the new workflow developed to perform discrete fracture networks generation, to obtain steady state pressure solution and to model particle tracking through DFNs, applied to EGS Collab experimental design.

2.1 DfnWorks Workflow

DfnWorks represents individual fractures as two-dimensional planar objects, placed in a three-dimensional domain, that intersect each other and form fracture networks (Hyman et al., 2015a). Each fracture in the network is assigned a shape, location, aperture, and orientation. The individual fractures are generated using the Feature Rejection Algorithm for Meshing (FRAM) (Hyman et al., 2014),

which ensures that the DFN computational mesh does not have any small features. For instance, the algorithm ensures that the length of intersections between fractures and distance between lines of intersection of a fracture are smaller than a user-defined minimum length scale. This restriction provides a firm lower bound on the required mesh resolution, and special care is taken so that prescribed geological fracture network statistics are not affected by this restriction. The final DFN mesh is a conforming Delaunay triangulation, which provides a framework for control volume flow solutions that obey mass conservation law and prevent non-physical sources, sinks or stagnation points. Once the DFN is generated, the isolated fractures are removed from the network since they do not participate in the flow simulations. The parallel multiphysics code PFLOTRAN (Lichtner et al., 2015) is used to obtain steady state pressure solution for fully saturated flow on a DFN with prescribed pressure boundary conditions. The flow Darcy velocities are evaluated at the center of every computational cell. The mesh of intersecting fractures is coincident along fracture intersection lines, where control volumes are split into four pieces. The transport velocity is reconstructed independently on each piece representing flow direction on fracture intersection explicitly. This method supports Lagrangian particle tracking modeling (Makedonska et al., 2015) using flow velocities given by the PFLOTRAN flow solver. We adopt a Lagrangian approach and represent a non-reactive conservative solute as a collection of indivisible passive tracer particles. Particle tracking methods (a) provide a wealth of information about the local flow field, (b) do not suffer from numerical dispersion, which is inherent in the discretization of advection–dispersion equations, and (c) allow for the computation of each particle trajectory to be performed in an intrinsically parallel fashion if particles are not allowed to interact with one another or the fracture network. The flow solutions obtained from PFLOTRAN are locally mass conserving, so the particle tracking method does not suffer from the problems inherent in using Galerkin finite element codes, such as stuck in cells that exhibit unphysical stagnant regions because the flow solution does not conserve mass locally (Hyman et al., 2015). The details on particle tracking technique in dfnWorks can be found in (Makedonska et al., 2015).

The overall DFN modeling workflow can be summarized as follows: 1) generate discrete fracture network according to given fracture characteristics; 2) produce high quality computational mesh with conforming Delaunay triangulations; 3) define pressure boundary conditions and obtain steady state pressure solution for fully saturated flow; 4) simulate transport through the fracture network using Lagrangian particle tracking.

2.2 Discrete Fracture Network Generation

The fracture networks were generated according to the workflow proposed in Neupane (et al., 2019). The fracture locations and orientations were adopted from the FracMan model of the Common DFN (CDFN) characterized by Schwering et al. (2018). In our model the fractures of the CDFN were generated as deterministic fractures since their location and orientation were directly observed from borehole imagery/logging and core inspections. While the borehole intersections of fractures were observed during cores inspections and their location and orientation were determined, the extents of those fractures into the rock mass are estimated, and then modeled in the CDFN as circular disks. The hydraulic stimulated fracture was defined deterministically as well, since its location and orientation are defined. In our model we assume that stimulated fracture has a circular shape, centered at injection well on 164' notch, where the stress was applied and stimulated fracture was initiated. The hydraulic fracture crosses production well, E1-P, and has a radius of 15 meters ($R=15\text{m}$). The distance between injection well and production well along the stimulated fracture is ~ 10 meters. The deterministically defined CDFN and hydraulic fracture with boreholes are shown in Figure 2.

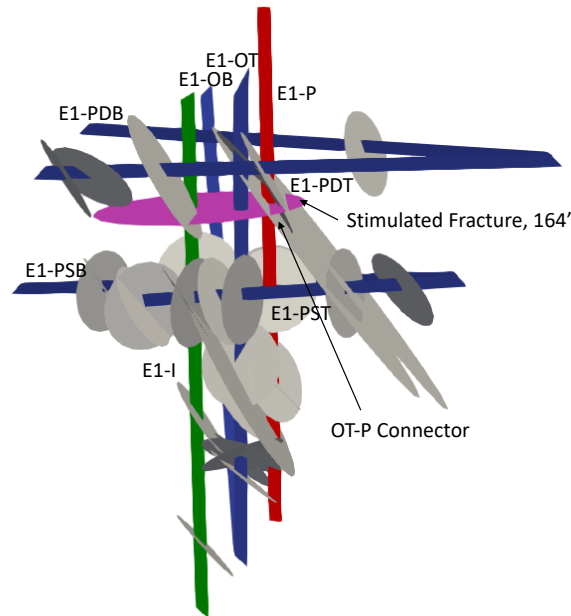


Figure 2: Common DFN, where fracture locations and orientations were defined from boreholes inspections at EGS Collab testbed. Initially CDFN was generated at FracMan, then it was reproduced into dfnWorks.

In order to simulate flow paths through natural fractures we needed to add stochastically defined fracture network to the CDFN. The role of stochastic fractures is to create the fracture network connectivity between injection source of flow and the locations of flow collections and to represent existing fractures at the site that were not observed directly. We defined two fracture sets; the fractures size follows truncated power law distribution (circular shape); fracture's orientation follows Fisher distribution, which parameters were chosen in the way to fit the same tendency of fracture orientations defined in the CDFN. The fracture network parameters are shown in Table 1. Locations of stochastically defined fractures (centers of circular polygons) were chosen randomly in the simulation domain.

Table 1: Input parameters of stochastic distributions of fracture sizes and orientations.

Fracture Set	Fractures Orientation, Fisher Distribution			Fractures Size, Truncated Power Law Distribution		
	$\Theta, ^\circ$	$\Phi, ^\circ$	κ	R_{min}, m	R_{max}, m	α
1	90	70	11	2.0	10.0	2.4
2	90	110	12	2.0	10.0	2.4

The fracture network intensity, P_{32} , dictates the number of fractures in stochastically generated DFNs and is calculated as a ratio between total area of fractures surface over volume of the simulation domain. We used the nomenclature of (Dershowitz & Herda, 1992), where P_{32} represents the total area of the fracture network per volume of rock. In the current study, the size of the simulation domain (volume of the fractured rock) is $80 \times 80 \times 40 \text{ m}^3$. We considered three different fracture network intensities of stochastic DFNs: low intensity, $P_{32}=0.2 \text{ 1/m}$ (138 fractures); medium intensity, $P_{32}=0.3 \text{ 1/m}$ (429 fractures); and high intensity, $P_{32}=0.4 \text{ 1/m}$ (745 fractures). The listed number of fractures in each case is the final number of stochastically generated fractures, after isolated fractures were removed from the network, since they do not participate in the flow. The final fracture network combined Common DFN, stimulated fracture and stochastically defined fracture network. The three DFNs of three different intensities are shown in Figure 3.

It is important to note that the current DFN modeling does not include any rock matrix, the computational mesh is focused on fractures only, which are presented as circular polygons. The considered flow here is the flow through fractures only. Also, the injection and production wells, as wells as monitoring boreholes, do not participate in the flow modeling and are not presented at the computational mesh. Wells and boreholes are shown in the Figures for visualization purpose only.

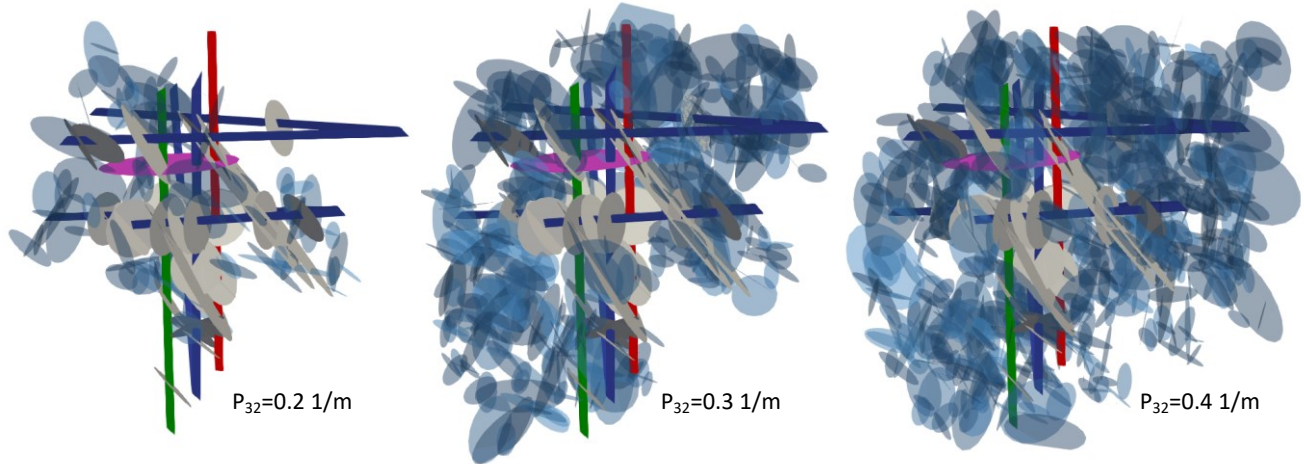


Figure 3: Three DFN configurations: low intensity, $P_{32}=0.2 \text{ 1/m}$ (138 fractures) on left panel; medium intensity, $P_{32}=0.3 \text{ 1/m}$ (429 fractures) in the middle plot; and high intensity, $P_{32}=0.4 \text{ 1/m}$ (745 fractures) on right panel. The stimulated fracture has a circular shape (magenta), fractures of CDFN are shown in light gray color and the generated stochastic fracture network is visualized in transparent blue color.

The conforming Delaunay triangulation meshes were produced in generated DFNs using LaGriT software (Los Alamos Grid Toolbox, 2018). The computational DFN mesh provides a foundation for control volume flow solutions that obey mass conservation law. The DFN fragment with conforming Delaunay triangulation is shown in Figure 4.

2.3 Flow Parameters and Steady-State Pressure Solution

The flow parameters in DFNs, such as fracture apertures and fracture transmissivity should be assigned to each fracture in the network. Fracture aperture and fracture transmissivity were calculated for every fracture and assigned to each computational cell center of the mesh. Those parameters were defined as function of the fracture size and were not varied within each fracture. The fracture transmissivity, σ , was calculated using a power-law relationship:

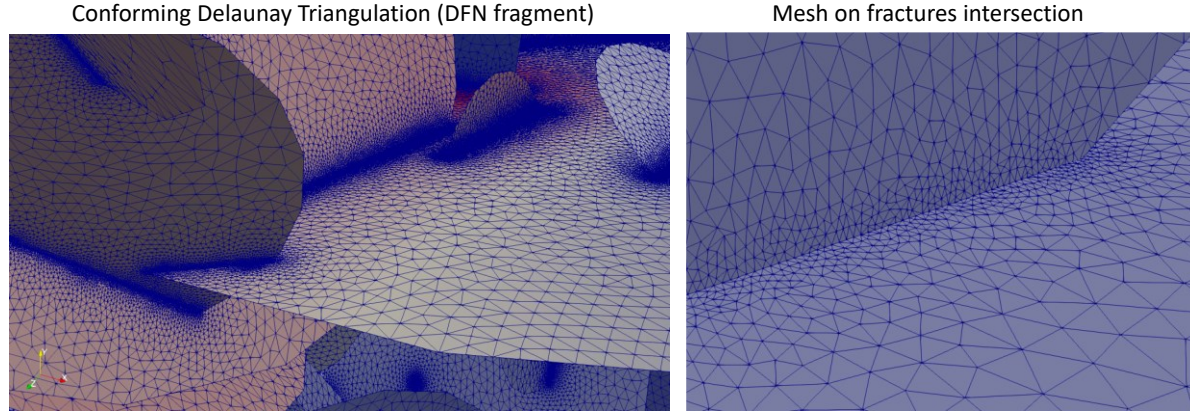


Figure 4: The fragment of DFN with produced conforming Delaunay triangulation is shown on left panel. The right panel shows the zoom in fragment on fracture intersection line. The computational grid coincides along fracture intersections. The mesh is fine near fracture intersections and gets coarser moving far from intersections.

$$\log(\sigma) = \log\left(3.1 \cdot 10^{-7} \cdot R^{1/2}\right) \quad (1)$$

where R is the fracture radius. The fracture aperture, b , is correlated to fracture radius and calculated using the cubic law (Adler et al., 2013):

$$\sigma = \frac{b^3}{12} \cdot \frac{\rho g}{\mu}, \quad (2)$$

where ρ is a water density, g is gravity acceleration, and μ is a water viscosity.

The steady state pressure solution for fully saturated flow was then obtained for each individual DFN realization. The solved governing equation is a result of balance of mass and Darcy's model, which is numerically integrated using a two-point flux finite volume method, subject to pressure boundary conditions at the inflow and outflow zones. The subsurface flow solver PFLOTRAN (Lichtner et al., 2015) is used to obtain pressure solution.

In our model we defined one inflow zone and four outflow locations, assuming that flow and simulated particles will be injected at one source point and collected in four different locations (drip and weep zones). The inflow zone corresponds to the location of the stimulated fracture center, where the flow was injected from injection well (E1-I) into hydraulic fracture. In our model, the initial high pressure, 4.0 MPa, was assigned to all the nodes of the computational mesh in the inflow zone. There are four outflow locations were defined in the current study. The first outflow location was defined at the intersection of stimulated fracture and the production well (E1-P). In this case we assume that flow will travel along the stimulated fracture only: released at the injection well and collected at the production well. Two additional outflow locations were defined along a major conducting fracture, designated the OT-P connector, because it connects the OT-161 fracture (in the OT monitoring well) to the and P-122 fracture in the production well. The fourth outflow zone was defined at the weep zone, observed at the production well, defined as primarily weep zone at E1-P collar. A low pressure, 1.0 MPa, was assigned to computational nodes at all outflow zones. We have to make it clear to the reader, that the chosen outflow locations not necessary correspond to the flow leaking positions observed at the EGS Collab E1 site. The outflow zones are defined in the way to represent ability of the simulation workflow to define several outflow boundary conditions - close to the stimulated fracture as well as far away from the expected location of flow collection zone. The model did not include the mine drift (tunnel) as a boundary, and the overall network was assumed to have a no flow boundary and not connect to far-field water sources. Thus, the fracture network does not have any flow sources other than the stimulation zone at the 164' notch in the injection well.

The example of the obtained steady state pressure solution for fully saturated flow in DFN is shown in Figure 5. The zoom in frame on hydraulic fracture with obtained flow pressure solution is shown in Figure 6.

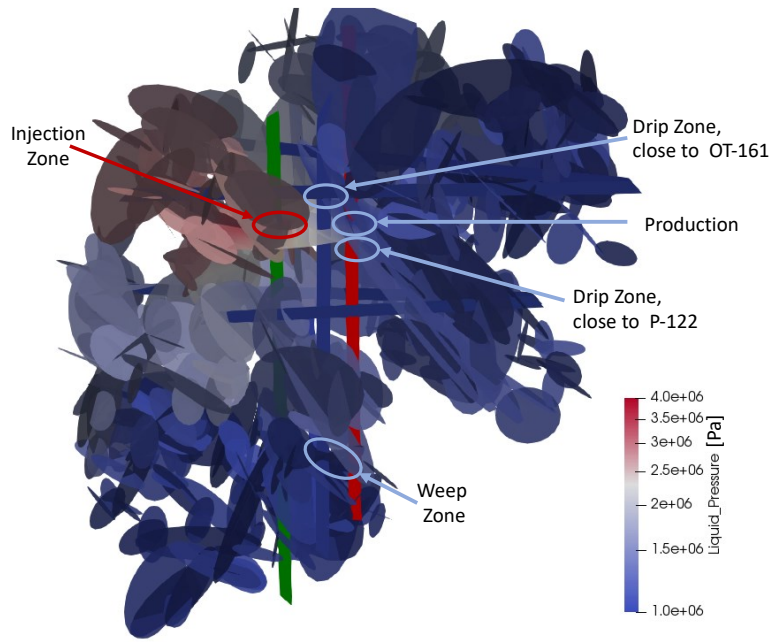


Figure 5: The steady state pressure solution for fully saturated flow in the DFN configuration with medium fracture network intensity. The inflow zone, the flow injection location at the injection well (E1-I) was assigned high pressure boundary flow condition, 4.0 MPa. The four outflow locations correspond to production well and stimulated fracture intersection, locations along OT-P connector, near OT-161 and P-122 natural fractures, the weep zone on E1-P collar. The low pressure, 1.0 MPa, was assigned to computational nodes at outflow zones.

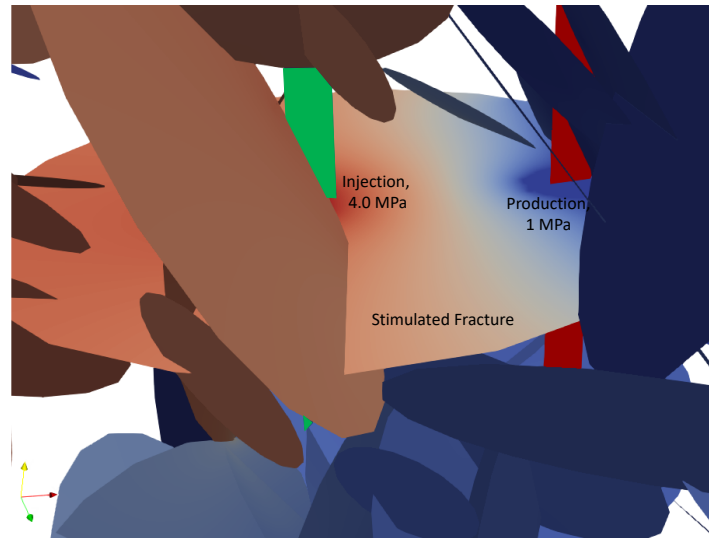


Figure 6: The zoom in fragment of steady state pressure solution on simulated hydraulic fracture, that connects injection and production wells. High pressure (red color) was assigned at injection zone and low pressure (blue color) was assigned at the production location. Flow pressure is gradually decreasing from inflow (injection) to outflow (production) zones along the stimulated fracture.

2.4 Lagrangian Particle Tracking

The particle tracking approach at dfnWorks is a method for resolving solute transport using control volume flow solutions obtained by PFLOTTRAN on the unstructured mesh generated DFN (Hyman et al., 2015). The particles were released at inflow zone, where high flow pressure was assigned. Moving along a fracture plane particle was driven by the flow, from high to low flow pressure. In order to move through fracture network, particle crossed fracture intersections. We used a complete mixing rule on fracture intersections: the probability to choose a next fracture to proceed was dictated by outflow fluxes at intersection line. With higher probability particles moved from one fracture to another carried by the main flow, however, there was a none zero probability to proceed along fractures with less active flow or to move to “dead end” fractures. We call “dead end” fractures, fractures with only one intersection, which are connected to the main fracture cluster but do not transmit the main flow. In this case, particle gets into fracture through the intersection, makes a loop along fracture and leaves it through the same intersection. As a result, the particle’s tortuosity, total travel distance, and travel time are increased.

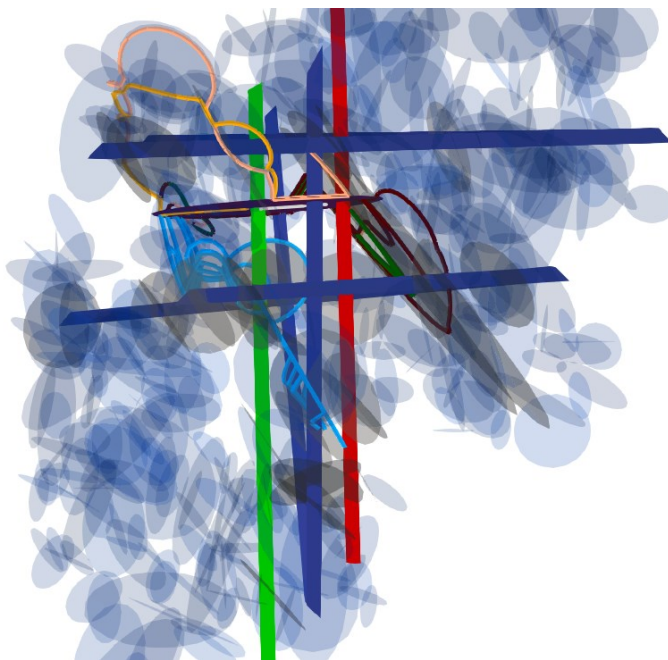


Figure 7: Examples of particle trajectories in DFN configuration with stochastic fracture networks intensity, $P_{32}=0.3$ 1/m. Particles were released from injection well and traveled to different outflow locations. CDFN is shown in light gray color, stochastically defined fracture network is shown in transparent blue color.

Figure 7 shows an example of a few particles’ trajectories in DFN configuration with stochastic fracture networks intensity, $P_{32}=0.3$ 1/m. Particles were released from injection well into stimulated fracture and then traveled to one of the defined outflow drip zones. Figure 8 shows a detail visualization of particles trajectories, where particles traveled to outflow locations (for simplicity, the only stimulated fracture and boreholes are shown). Figure 8a shows two sets of particle trajectories. Trajectories shown by light blue color correspond to those particles who traveled to weep zone at the collar of E1-OT and E1-P wells. When those particles were released, they chose to move along the stimulated fracture but in opposite direction from the production well, then they were continuing through natural fracture network and were collected at the weep zone. The distance from injection source to the weep zone is the longest comparatively to distance to other defined outflow locations; the pressure gradient over this distance is the smallest. This makes it a less likely scenario and only a few particles chose this path. The majority of particles moved straight from injection to production well along stimulated fracture. The white lines from injection to production well on stimulated fracture shows the trajectories of particles that reached outflow zone at production well without traveling through natural fractures (Figure 8a). However, they are not the only particles collected at this outflow location. Figure 8b shows the example of particles trajectories, where particles started at stimulated fracture, then moved through natural fractures, and were collected at stimulated fracture and production well. Those particles showed longer travel distance and higher tortuosity than those that travel directly from injection well to the same outflow point. The trajectories of particles collected at OT-P connector, near OT-161 fracture and close to P-122 fracture, are shown in Figure 8c and 8d, respectively. Those particles started at the stimulated fracture, moved to intersecting natural fractures, then, at some point, came back to the stimulated fracture and moved to natural fractures again. At the end, they were collected at OT-P connector, the deep fracture zone detected at EGS Collab site.

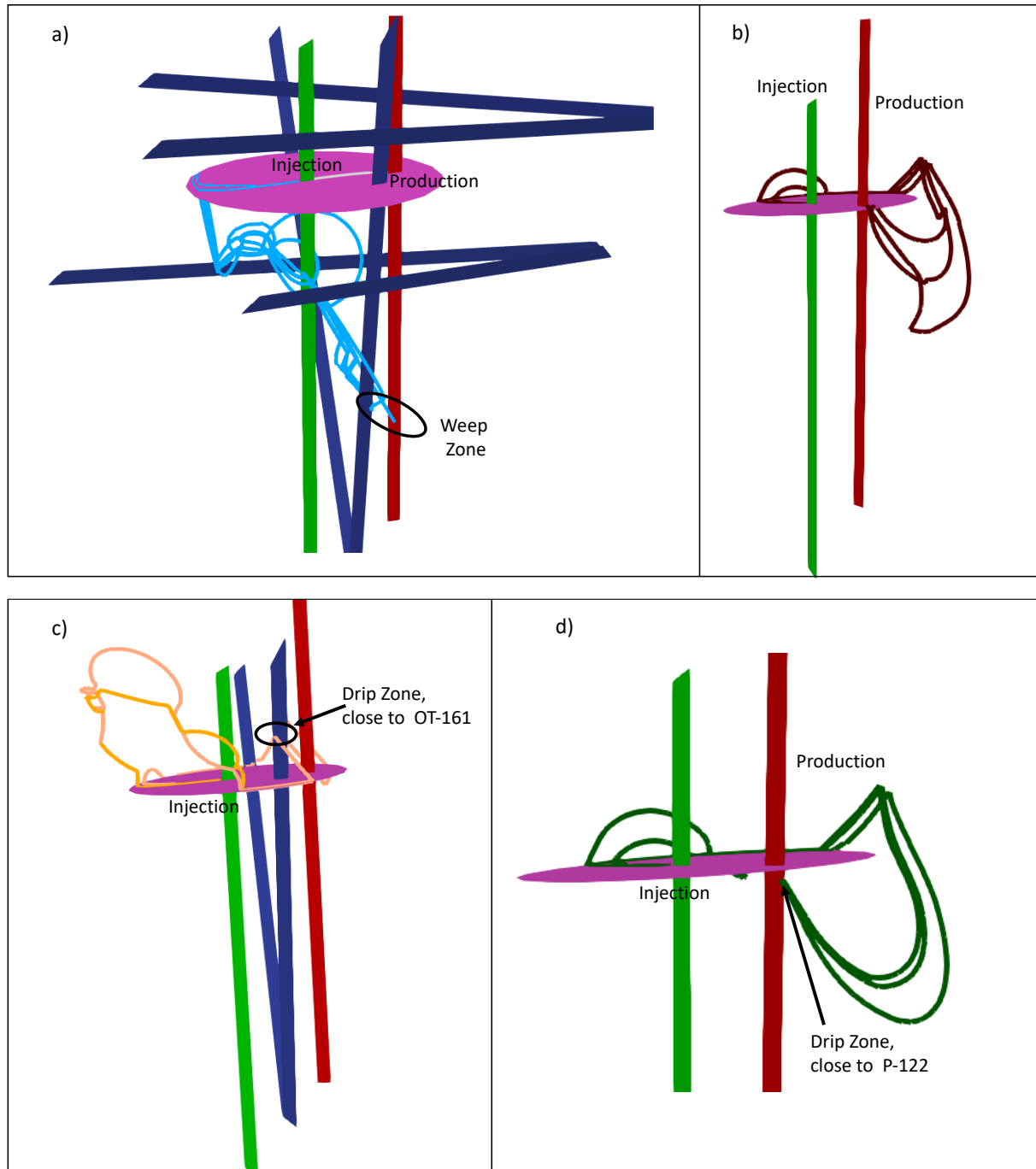


Figure 8: Examples of particles trajectories, where particles moved from injection source to outflow locations: a) particles were collected at weep zone (light blue); and particles collected at production well and stimulated fracture (white lines); b) dark red trajectories corresponds to particles that traveled through natural fractures and collected at production well and stimulated fracture; c) particles traveled (orange trajectories) from injection source through stimulated and natural fractures and were collected at OT-P connector near OT-161 fracture; d) particles moved (green trajectories) from injection well to drip zone at OT-P connector, and were collected close to P-122 fracture.

3. RESULTS AND DISCUSSION

Travel distance and residential time of the injected flow is important for flow heat exchange and geothermal energy production. Applied particles tracking modeling tool allowed us to measure and visualize trajectories of particles that are released at injection well and repeat

the flow paths through fractures. There are four characteristics of particles trajectories that were measured: 1) number of fracture intersections that particles crossed on their way from inflow to outflow zones; 2) the total travel distance of particles; 3) particles tortuosity; 4) residential time in the fracture network. In order to get statistical distributions of the calculated characteristics, one million particles were released from injection source and followed to their outflow locations in each of three DFN configurations with different fracture network intensity, P_{32} .

Figure 9 shows histogram plots of the particle's probability to cross certain number of fracture intersections, in other words, plots show how many fractures were participated by particles in order to get from injection source to one of the four defined outflow locations. In all three cases of considered fracture network intensity, the highest probability corresponds to the scenario when particles leaved injection well, traveled along stimulated fracture, and was collected at the production well, without crossing any fracture intersections. This scenario was dictated by the EGS Collab testbed design, where stimulated fracture connects injection and production wells and the flow is expected to be directed along stimulated fracture only. In other cases, when particles chose to move through natural fractures, it is clearly observed that increasing fracture network intensity increases number of fractures that particles moved through.

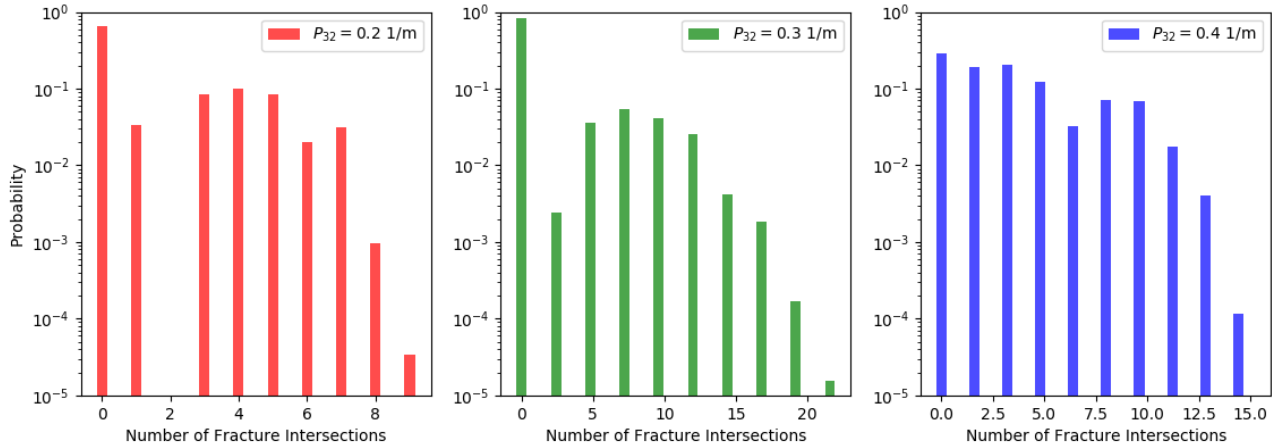


Figure 9: Histogram plots of particles probability to cross certain number of fracture intersection moving from injection source to outflow locations observed in DFNs with different fracture network intensities.

Figure 10 shows the probability histogram plots of particles travel distance for DFNs with different P_{32} . The majority of particles show the travel distance equal to the distance between injection and production well, ~ 10 m. This is the shortest distance that particles traveled. Moving from $P_{32}=0.2$ 1/m to $P_{32}=0.3$ 1/m (increasing number of stochastic fractures from 138 to 429 in the simulation domain) the longest detected travel distance almost doubled: from 75 m to 142 m. However, the probability for particles to show the longest travel distance is getting lower with increasing intensity in DFN configuration. Increasing DFN intensity by introducing more fractures into network creates larger variations of possible flow paths, and the probability for particles to travel through the same fracture path decreases.

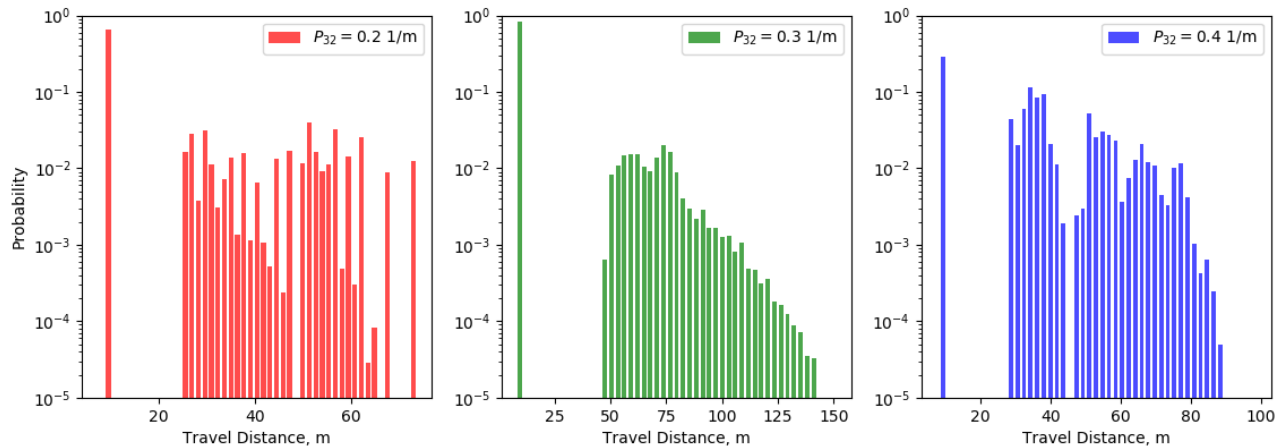


Figure 10: The probability histogram plots of particles travel distance for DFNs with different P_{32} .

Particle tortuosity, T , was measured as a ratio of total travel distance, D , m, (Figure 10) that particle traveled from injection inflow point to its outflow location through fractures, to the calculated length, L , m, of straight line that connects inflow and outflow particles positions: $T=D/L$. The probability histogram plots of calculated particles tortuosity in DFNs of different fracture network intensities is shown in Figure 11. The highest probability belongs to particles that traveled along stimulated fracture; their tortuosity is equal to 1.0 since particles actual trajectories resemble straight lines. In other cases, particles tortuosity increases with increase of number of fractures in the network. Figure 12 shows two examples of a few particle trajectories in low (Figure 12a) and high (Figure 12b) fracture network intensity in DFN, where particles were collected at the production well and OT-P connector. In spite of the fact that the short distance between inflow and outflow positions are the same in all considered DFN configurations, the tortuosity of particles in high intensity fracture network is larger due to larger number of fractures in the network and their improved connectivity with stimulated fracture.

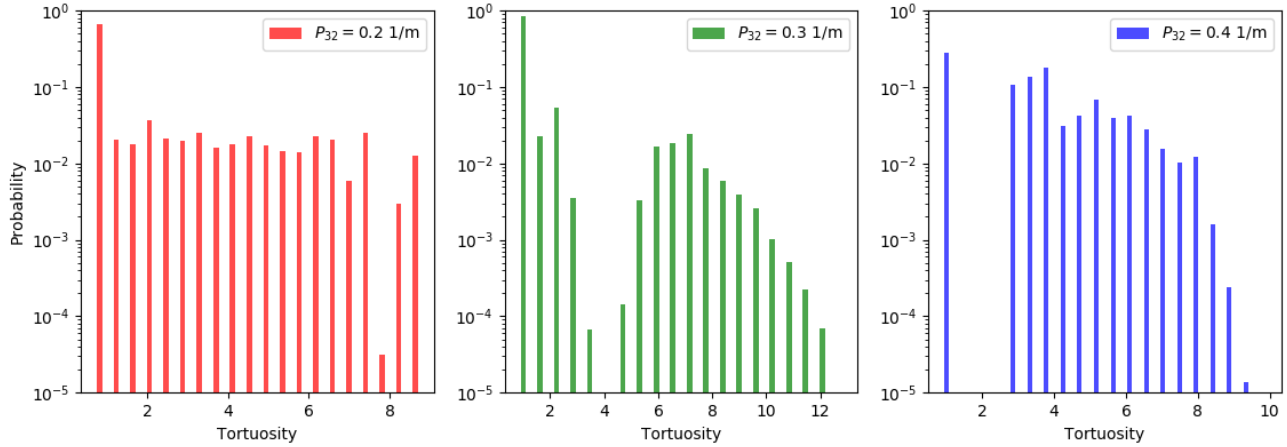


Figure 11: The probability histogram plots of calculated particles tortuosity in DFNs of different fracture network intensities.

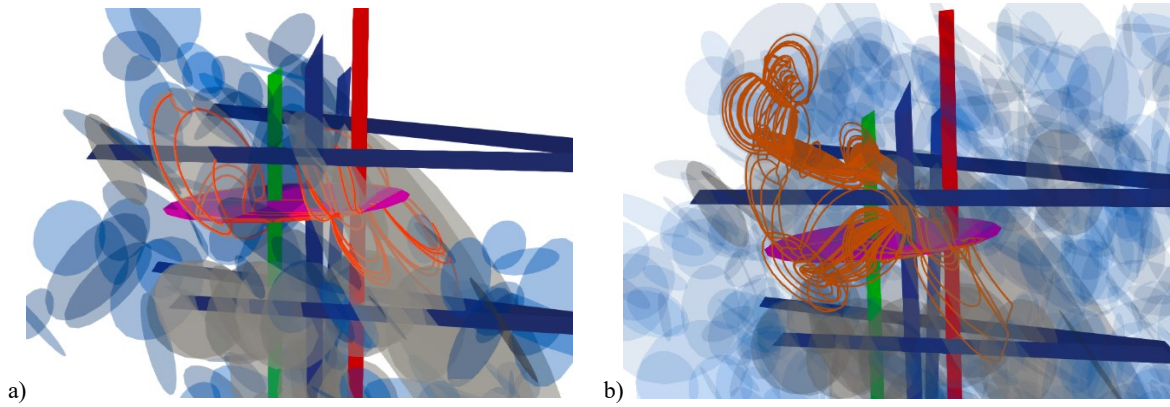


Figure 12: Two examples of particle trajectories in low (a) and high (b) fracture network intensity, where particles move from injection well to outflow locations at fractured zone in OT-P connector. The injection well is shown in green color, production well is colored in red, the monitoring boreholes are blue. The fractures of CDFN are shown in light gray transparent color, the stochastically defined DFN is shown in blue transparent color.

Figure 13 shows a probability histogram plots of particles residential time. The time is shown in hours, while the residence time of particles moving from injection to production well along stimulated fracture is less than a minute. The DFN configurations with higher fracture network intensity provides flow paths where particles spend significantly longer time than in case of low P_{32} ; the probability for particles to get there is also significantly low.

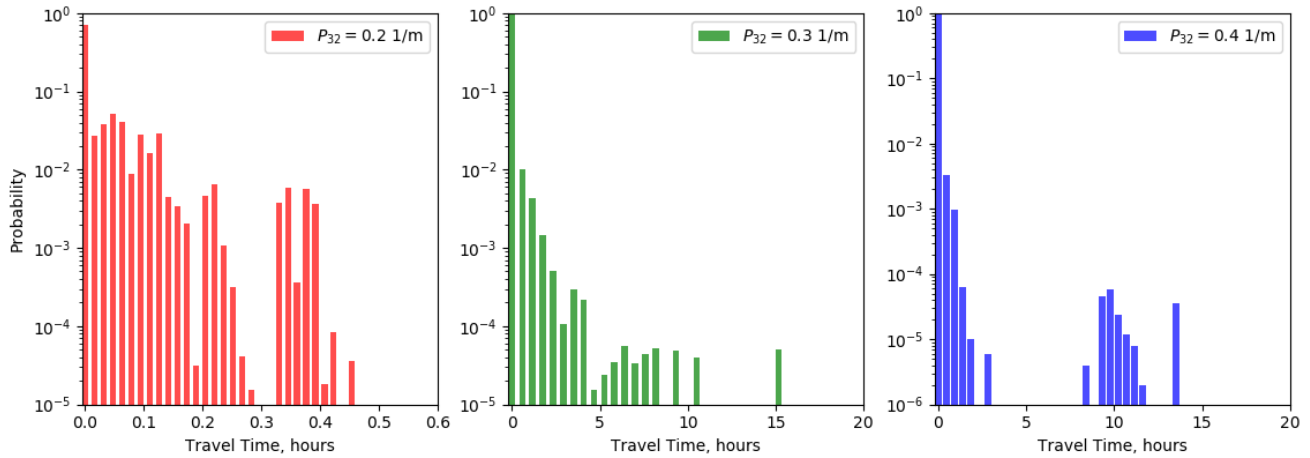


Figure 13: Probability histogram plots of particles residential time in DFN configurations with different fracture network intensity.

CONCLUSIONS

In the presented study, the discrete fracture network modeling was performed to simulate flow paths from injection source to outflow locations. The generated fracture network includes: Common DFN, deterministic fractures that were observed from logging and core inspections of boreholes at EGS Collab E-1 testbed; stimulated fracture of 164' notch; and stochastically defined natural fractures, which provide fracture network connectivity and were not observed at the site directly. The steady - state pressure solution for fully saturated flow in the fractures was calculated, where one injection location with assigned high pressure and four outflow zones with low pressure were defined. The Lagrangian particle tracking approach was applied to simulate particles that follow injected flow paths from injection well to drip zones. One million particles trajectories were simulated in three different DFN configurations with variable stochastic fracture network intensity.

We numerically showed that regardless of applied natural fracture network intensity, the majority of flow prefers to travel from injection well to production well along stimulated fracture, where released particles chose the shortest travel distance. This scenario is the most likely, and this was initially arranged and expected by EGS Collab Eperiemntal-1 design (Kneafsey et al., 2018; Roggenthen and Doe, 2018). The measured tortuosity of particles moving along hydraulic fracture is equal to 1.0 and the travel time calculated for those particles is faster than the time measured during tracer experiment at the site. The main reason is that no internal heterogeneity was included in this study. In our model each fracture had uniform aperture and was considered as two parallel plates. Wu et al. (2019) performed computer simulations of transport in hydraulic fracture, where multiple different scenarios of internal fracture heterogeneity was considered.

Our numerical simulations allowed us to visualize the possible flow paths through natural fractures from injection well to chosen as an example drip and weep zones. The existence of natural fractures near hydraulic fracture and injected source grant new, sometimes unpredictable, paths for injected flow, which then can be detected at different outflow locations of the site. Introducing larger number of fractures into simulation domain (increasing fracture network intensity, P_{32}) provides higher variety of flow paths through fractures. This results in enlarge tortuosity, travel distance, and travel time of the flow. At the same time, intense fracture network at geothermal sites, which provides multiple paths for injected flow and an increase of flow travel time, leads to effective heat exchange and energy production.

In the future work, the presented DFN modeling workflow will apply fracture network characteristics observed at the site and the outflow boundary conditions, which correspond to exact detected flowing locations. Then, the results of flow paths simulations can be compared with the tracer experiment performed at the EGS Collab E1 site.

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