

GEOFRAC AND ITS APPLICATIONS

Wei Li¹, Rita L. Sousa², Violeta M. Ivanova¹, Alessandra Vecchiarelli³, Herbert H. Einstein¹

¹ Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

² Masdar Institute of Science and Technology, Masdar City, UAE

³ Arup New York USA, New York, USA

Abstract

GEOFRAC is a 3D Discrete Fracture Network (DFN) model developed at MIT. Recent research developments based on GEOFRAC results in GEOFRAC-FLOW and -THERMAL, which simulate the flow and heat transfer in the DFN, respectively. This paper presents the development of GEOFRAC-FLOW and -THERMAL, and summarizes the inputs for the GEOFRAC package. A study on the Fenton Hill Project is used to demonstrate the applications of the GEOFRAC package in simulating the flow and heat transfer in a stimulated hot dry rock reservoir. A case study on the Námafjall geothermal field is used to show how GEOFRAC simulates the flow and heat transfer in a conventional geothermal reservoir. Both of the case studies provide reasonable results for flow rates and temperature in the reservoir.

1. Introduction

1.1 Modeling of fracture systems with GEOFRAC

GEOFRAC is a Discrete Fracture Network model developed at MIT based on work by Baecher et al. [1977], Veneziano [1979], Dershowitz [1985], Ivanova [1995]. Further work by Dershowitz [1985] led to Fracman [Dershowitz, 1989], while Ivanova's [1995] work led to GEOFRAC; the underlying concepts are analogous. GEOFRAC is a three-dimensional (3D), geology-based, geometric-mechanical, hierarchical, stochastic model of natural rock fracture systems [Ivanova et al., 2014] using MATLAB.

The model represents fracture systems as 3D networks of intersecting polygons, generated through spatial geometric algorithms that mimic the mechanical processes of rock fracturing in nature. Specifically:

1. The desired mean fracture size $E[A]$ and fracture intensity P_{32} in a region of volume V are given as input. $E[A]$ and P_{32} can be derived from field data; for example, methods for deriving P_{32} are described by Dershowitz and Herda [1992] and for deriving $E[A]$ by Zhang et al. [2002], Mauldon [2000] and Kulatilake [1993].
2. In the primary stochastic process, Poisson planes of intensity μ and a specified orientation distribution are generated in the volume V . The intensity of the Poisson plane process is computed as:

$$\mu = P_{32} \quad (1)$$

The orientation of the fractures can be simulated to follow the distribution observed in the field, for example Einstein et al. [1979] discussed possible orientation distributions and how to consider possible biases. GEOFRAC defines the orientation distribution with two parameters (m, k) and the mean orientation. The parameter m is the type of distribution, which from 1 to 4 represents: uniform distribution for all orientations, uniform distribution for a limited range of orientations, univariate Fisher distribution and bivariate Fisher distribution, respectively. The parameter k controls the distributions' parameters; for example in univariate Fisher, a higher k value indicates more concentrated orientations. The mean orientation of the pole of the fractures relative to the volume V is defined as (θ, ϕ) [Ivanova, 1998].

3. In the secondary stochastic process, a Poisson point process with intensity μ is generated on the planes, which are then divided into polygons by a Voronoi tessellation; where the intensity of the point process λ is computed as:

$$\lambda = \frac{1}{E[A]} \quad (2)$$

The development leading to this simplified expression compared to earlier ones is discussed in Ivanova et al. [2014].

4. In the tertiary stochastic process, polygons are randomly translated and rotated to represent local variations of fracture positions and orientations.

The fracture generation process is illustrated in Figure 1 below:

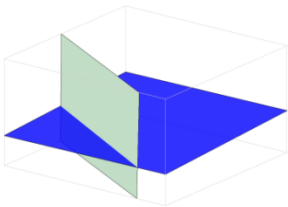
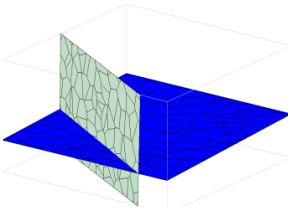
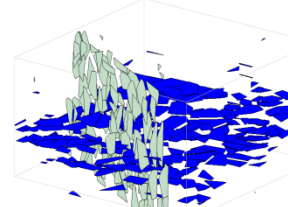
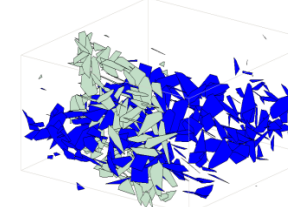
Primary Process: Generation of Planes	Secondary Process: Division of Planes into Polygons	Tertiary Process: Random Translation	Tertiary Process: Random Rotation
			

Figure 1 Three Fracture Generation Processes (Ivanova et al., 2014)

According to Zhang et al. [2002], natural fracture apertures follow a lognormal distribution based on field data. This is implemented in GEOFRAC by assigning the aperture values following a lognormal distribution to the fracture polygons in the fracture network.

With the help of built-in probability functions in MATLAB, these stochastic processes can be carried out easily. GEOFRAC produces the geometric information, such as the shape, location, orientation and aperture, for all the fractures. Detailed information can be found in Ivanova et al. [2014]. The results of GEOFRAC are in the form of three-dimensional fracture networks as shown in Figure 2, where each polygon represents a fracture.

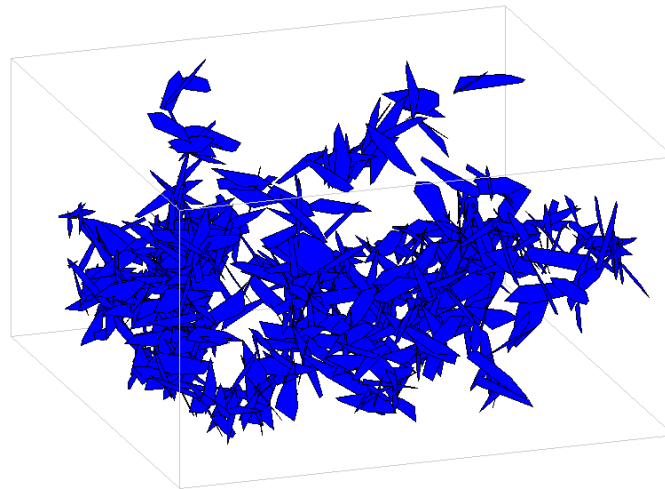


Figure 2 Graphic output generated by GEOFRAC

Fracture connectivity is important since it governs the behavior (stability, flow) of rock masses. For the purpose of computing interconnected paths, a fracture intersection algorithm was developed, implemented in GEOFRAC, and optimized. The algorithm follows these steps:

1. For every polygon, the radius R_i of the sphere that encloses it is computed.
2. For every pair of non-coplanar polygons, the distance D_{ij} between centers is computed. If R_i and R_j are the radii of two spheres, then the spheres intersect only if $R_i + R_j < D_{ij}$.
3. If two spheres intersect, the intersection, if any, between the polygons is computed. For this step, GEOFRAC implements the algorithms developed by Locsin [2005] to compute intersections between polygons. (See also [Locsin and Einstein, 2012])

Figure 3 shows an example of this process. The fracture intersection algorithm outlined above applies to the computation of fracture area intersections. Its purpose is to eliminate unnecessary computation: if two fracture “spheres” do not intersect, the fracture polygons will not intersect either. (Step 3 takes several calculations, while Step 2 takes only one.)

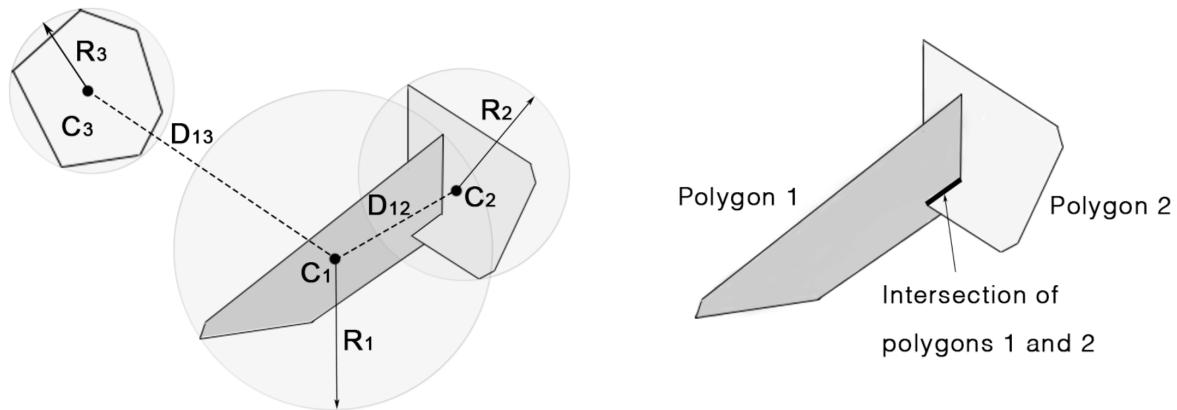


Figure 3 Fracture Intersection Algorithm (a) The spheres enclosing all polygons are computed and the intersections between spheres, if any, are determined. Two spheres intersect if the distance between their centers is smaller than the sum of their radii. Above the enclosing spheres of polygons 1 and 2 intersect, but neither of them intersects with the enclosing sphere of polygon 3. Therefore, polygons 1 and 2 might be intersecting, but neither of them could be intersecting with polygon 3. C_1 , C_2 , and C_3 : center of polygon 1, 2, and 3, respectively. R_1 , R_2 , and R_3 : radius of the enclosing sphere of polygon 1, 2, and 3, respectively. D_{12} : distance between the centers of polygons 1 and 2. D_{13} : distance between the centers of polygons 1 and 3. (b) For every pair of intersecting spheres, such as that of polygons 1 and 2, the intersection between the polygons, if any, is determined.

An additional process, called “clean fracture algorithm”, was implemented in GEOFRAC to determine and retain only those fractures that form an interconnected path [Sousa et al., 2012]. Namely, once all intersections between polygons have been determined, the clean fracture algorithm finds and retains only polygons that intersect either at least two other fractures, or one of the modeling volume boundaries and at least one other fracture. To further optimize the

computation, assigning apertures to fractures can be postponed until after the clean fracture algorithm. Validation of this fracture model was done by Sousa et al. (2012), who analyzed the connectivity of fracture networks.

2. Development of GEOFRAC-FLOW and GEOFRAC-THERMAL

2.1 GEOFRAC-FLOW

On the basis of GEOFRAC, a DFN flow model was developed by Sousa et al. [2013]. Since GEOFRAC provides geometric information for individual fractures, the flow problem can be solved explicitly. Since fractures are the major flow paths in the rock mass, only the flow in the fracture network is considered. The fluid flow through a single fracture is usually modeled using the cubic (Poiseuille) law [Witherspoon et al., 1980; Zimmerman and Bodvarsson, 1996], which is an analytical solution for laminar flow between two smooth parallel plates. To account for the surface roughness, surface contact and flow path tortuosity in a natural fracture, a friction factor f was introduced by Louis [1969] and modified by Jones et al. [1988]. This semi-empirical quantity is introduced into the cubic law to calculate the flow rate in a single fracture:

$$Q = \frac{w\delta^3\gamma\Delta H}{12f\mu_f\Delta L} \quad (3)$$

where Q is the flow rate in the fracture; w is the width of the fracture provided by GEOFRAC; δ is the fracture aperture; γ is the unit weight of the fluid; f is the friction factor introduced by Louis [1969] and Jones et al. [1988]; μ_f is fluid dynamic viscosity; $\Delta H/\Delta L$ is the hydraulic head gradient in the fracture.

According to Jones et al. [1988], the friction factor can be calculated as:

$$f = 1 + 6\left(\frac{\varepsilon}{\delta}\right)^{1.5} \quad (4)$$

where ε is the fracture surface roughness and δ is the fracture aperture, as shown in Figure 4.

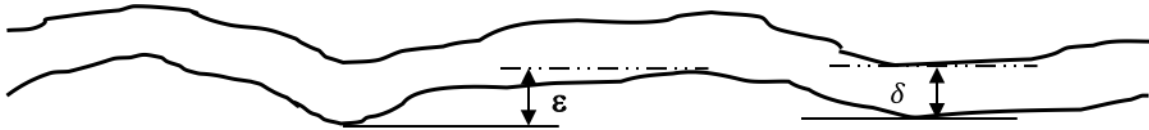


Figure 4 Sketch of fracture surface roughness

As shown in equation (3), hydraulic head loss is proportional to the length of the fracture, reciprocal to the width and the aperture cubed. Fluids tend to flow in the direction, which has the greatest pressure gradient, and it travels along the paths causing smallest head loss. In the model, paths are chosen as the shortest connection between the inlet fracture and outlet fracture. These connections can be found by using the Dijkstra's algorithm [Dijkstra, 1959]. After the paths are found, a flow path network is built as shown in Figure 5 below:

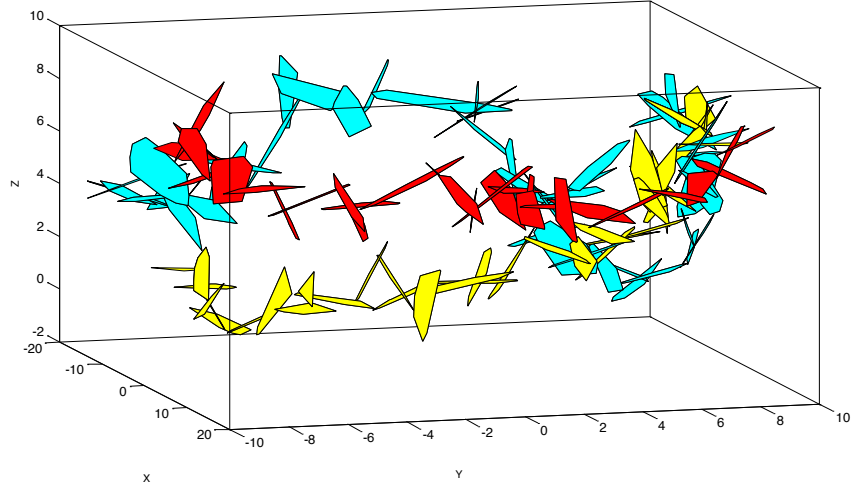


Figure 5 Example of flow network (Sousa, 2012)

To reduce computational cost, the fracture network is simplified by using one branch to equivalently represent the fractures from one node (intersection) to another. The equivalent fracture aperture, length, and width are expressed below.

$$\delta_{eq} = \frac{1}{\sqrt[3]{\sum_{i=1}^n \frac{l_i}{l} \left(\frac{1}{\delta_i^3} \right)}} \quad (5)$$

where l_i and δ_i are the length and aperture of the i^{th} fracture; l is the total length of the series of fractures.

$$l_{eq} = \sum_{i=1}^n l_i \quad (6)$$

$$w_{eq} = \frac{\sum_{i=1}^n w_i l_i}{\sum_{i=1}^n l_i} \quad (7)$$

where w_i is the width of the i^{th} fracture.

With the simplified flow network, the transmissivity between two fracture network nodes can be calculated. The hydraulic heads at the fracture network nodes H_i are formulated into the head vector $\mathbf{H}$. The mass conservation at each node can be formulated into the matrix form of linear equation system:

$$\mathbf{T}\mathbf{H} = \Delta\mathbf{V} \quad (8)$$

where $\mathbf{T}$ is the transmissivity matrix; $\mathbf{H}$ is the hydraulic head vector; and $\Delta\mathbf{V}$ is the volume accumulation vector. Except for the nodes at the inlet and outlet, $\Delta\mathbf{V}$ is zero. The linear equation system is solved and then the flow rate in each fracture is calculated. Validation of the flow model has been performed with parametric studies [Vecchiarelli et al., 2013].

2.2 GEOFRAC-THERMAL

Based on the GEOFRAC and GEOFRAC-FLOW, a heat transfer model was developed by Li et al. [2013] to model the heat transfer between the flowing fluid and the fractured rock mass. Based on the assumption of a uniform initial temperature in the rock matrix, the heat transfer model is intended to simulate the early stage of a geothermal reservoir development. In a single fracture, the heat transfer between the flowing fluid and the rock is through heat convection. The uniform wall temperature (UWT) heat convection equation for flow between two parallel plates is used:

$$q_h = h(T_r - T_f) \quad (9)$$

where q_h is the heat flux from the rock to the fluid; h is the heat convection coefficient; T_r is the temperature of the rock and T_f is the bulk temperature of the fluid. The heat convection coefficient h can be calculated as:

$$h = \frac{k_f Nu}{2\delta} \quad (10)$$

where k_f is the thermal conductivity of the fluid; Nu is the Nusselt number, which is the ratio of heat convection flux to heat conduction flux. Nu is related to flow state (laminar or turbulent) and the dimensions of the parallel plates. For laminar flow between two isothermal parallel plates, an analytical solution [Mills, 1995] is available for the Nusselt number as a function of the dimensionless length Z . The dimensionless length is defined as:

$$Z = \frac{k_f L}{2\delta^2 U \rho_f C_{pf}} \quad (11)$$

where L is the distance from the inlet; U is the flow velocity in the fracture; ρ_f is the density of the fluid; and C_{pf} is the heat capacity of the fluid.

The Nusselt number is higher in the thermal entrance region because of the high heat convection rate and asymptotically approaches 7.54 when Z is large. To account for the high heat convection rate in the entrance region, the average Nusselt number ($\overline{Nu}$) is used:

$$\overline{Nu} = 7.54 + \frac{0.03}{Z + 0.016Z^{1/3}} \quad (12)$$

As shown in Equation (12), the average Nusselt number is higher when Z is small and it approaches 7.54 when Z approach infinity.

With the above heat convection model for the heat transfer between the fluid and the rock in a single fracture, GEOFRAC-THERMAL explicitly calculates the fluid temperature in each branch. Assuming that the inflow at each node is well mixed, the temperature of each node can be calculated by weight averaging the temperature of the inflowing branches.

Figure 6 is an example of the results produced by GEOFRAC-FLOW and GEOFRAC-THERMAL. The example simulates the flow and temperature of the fluid in a $10*8*4 \text{ m}^3$ geothermal reservoir. To simplify the graphic output, the fracture branches are represented using lines and the intersections are represented using nodes. The indices are assigned in GEOFRAC before deleting the non-conductive fractures, so the indices of nodes and fractures are not continuous. The output of GEOFRAC-FLOW is the flow rate in each of the fracture branches, which is indicated in blue near the branches. The output of GEOFRAC-THERMAL is the temperature at each of the network nodes, which is indicated in purple near the nodes. The inlet fluid temperature is 70°C , while the rock temperature is 200°C . As shown in Figure 6, because of the high efficiency of heat convection between the rock and fluid, the temperature of the fluid reaches that of the rock at a distance not far from the inlet. This example also shows that GEOFRAC, as a discrete fracture model, calculates the flow rates and temperatures explicitly.

	ε	Fracture roughness [m]
GEOFRAC-FLOW	P_{in}	Inlet pressure [Pa]
	P_{out}	Outlet pressure [Pa]
	μ_f	Fluid dynamic viscosity [Pa·s]
GEOFRAC-THERMAL	k_t	Fluid thermal conductivity [W/(m·°C)]
	ρ_f	Fluid density [kg/m ³]
	c_{pf}	Fluid heat capacity [J/(kg· °C)]
	T_r	Rock temperature [°C]
	T_{in}	Injection fluid temperature [°C]

Systematic parametric studies have been conducted with the models to check the validity of the model, and to help the model user to better understand the models. Detailed results can be found in Vecchiarelli et al. [2013] and Li et al. [2014] on GEOFRAC-FLOW and -THERMAL respectively. The case studies described below also include some aspects of parametric studies.

3. Case studies using the GEOFRAC package

3.1 The Fenton Hill project

The project at Fenton Hill was the first attempt anywhere to work with a deep, full-scale hot dry rock (HDR) reservoir [Tester et al., 2006]. The site, – on the edge of the Valles Caldera at the northern end of the Rio Grande rift zone in north-central New Mexico– was chosen for its heat and rock characteristics, as well as its proximity to the Los Alamos National Laboratory where the project was conceived. The purpose of the project was to develop methods to extract energy economically from HDR systems located in crystalline, granitic/metamorphic basement rock of suitably high temperature. Useful data were found in the technical report written by Tester and Albright (1979). The plan view of the Fenton Hill site is shown in Figure 7. The Injection well EE-1 is at the top of the map and the production wells (GT) are at the bottom of the map.

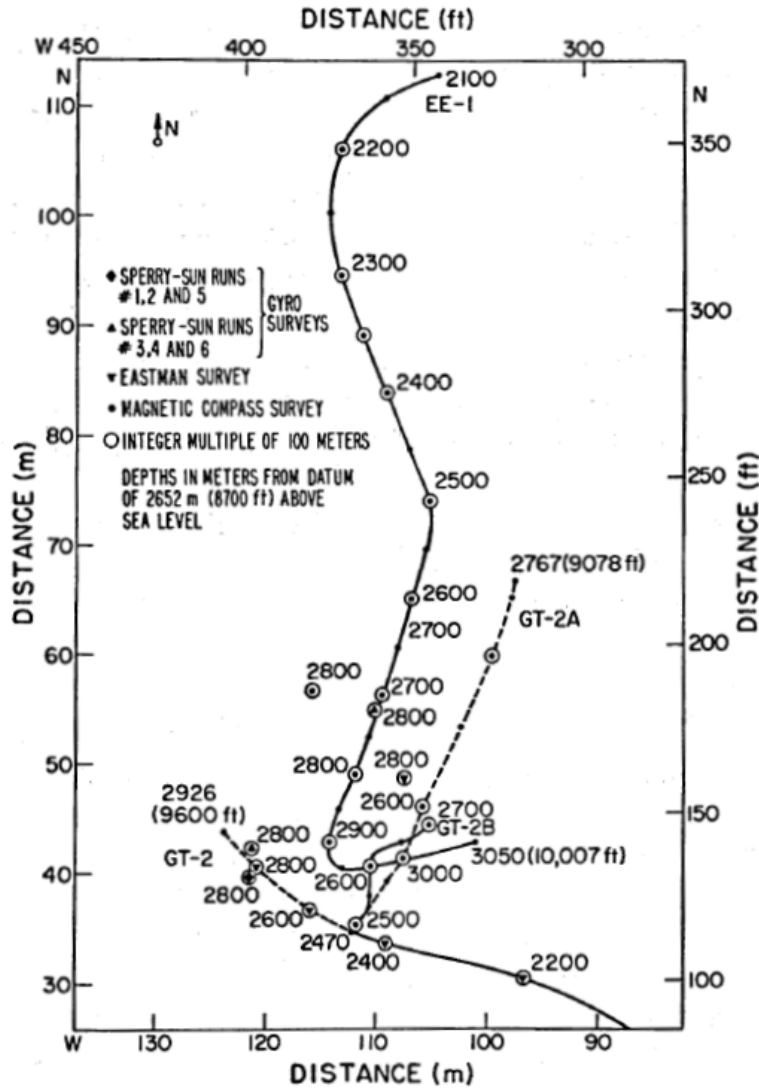


Figure 7 Plan view of the lower section of the GT-2 and EE-1 Wellbores

According to Tester and Albright, [1979], the main production well is GT-2B, where 90% of the hot fluid is produced. During the injection test, water loss was observed to decrease. One explanation was that the decrease of water loss was caused by saturation of the rock, so it is reasonable to assume that all the water injected is recovered from the production wells. The reservoir can be simplified as a two-well system, which can be modeled by the current GEOFRAC models. Rock temperature was not measured directly. However, the initial water temperature in the well was measured, and was close to that of the rock and could be used as rock temperature.

The horizontal distance between the injection and production wells was about 100m and the estimated effective heat transfer area was 8000m^2 [Tester and Albright, 1979]. No estimated

reservoir volume was reported. The flow rate was in the range of 5~30L/s. The impedance of the reservoir was in the range of 4~21bar-l/s. There were no data on fracture aperture; 0.2mm was assumed as the mean aperture in the simulation done by Tester and Albright [1979].

Using the above-mentioned information, GEOFRAC, GEOFRAC-FLOW and GEOFRAC-THERMAL were applied. Assumptions and estimations are made for some parameters that are not mentioned in the report by Tester and Albright [1979]. The parameters are summarized in Table 2, for which the definitions can be found in Table 1.

Table 2 Summary of the Input Parameter for GEOFRAC Simulation of Fenton Hill Project

X (m)	Y (m)	Z (m)	μ (m^{-1})	$E[A](\text{m}^2)$	m	k	$mPole$	rot
40	100	80	0.2	1000	4	20	$[\pi/2, 0]$	0
μ (m)	ε (m)	ΔP (Pa)	μ_f (Pa·s)	k_t (W/m·K)	ρ (kg/m^3)	C_{pf} (J/kg·K)	T_r ($^{\circ}\text{C}$)	T_{in} ($^{\circ}\text{C}$)
0.0002	0.001	1MPa	0.468×10^{-3}	0.6546	983	4185	180	60

Because of the stochastic processes used in GEOFRAC, the results are not deterministic. To draw reliable conclusions, a moderate number of simulations must be run. Here, 20 simulations are run and analyzed below. A statistical analysis has been done by Li [2014] to study the confidence level of averaging the results of 20 simulations. The analysis showed that 20 simulations were enough for drawing reliable conclusions. Figure 8 is a schematic representation of the possible flow paths in one of the simulations. Similar to the convention in the example shown in Figure 6, the flow rates and temperatures are calculated explicitly for the fracture network, as shown in Figure 8.

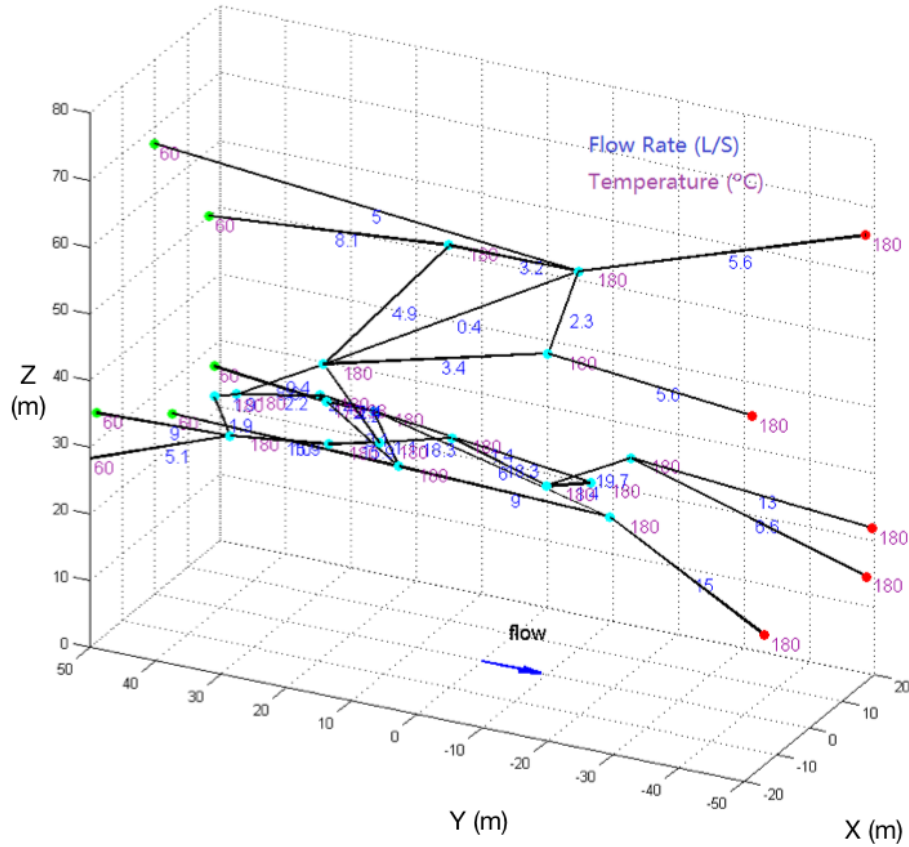


Figure 8 Schematic Representation of the Possible Flow Paths Obtained in One Simulation

The mean flow rate of the 20 simulations is 11.3L/s with a standard deviation of 9.05L/s. These values are in line with the flow rate of the production well, which indicates that GEOFRAC can provide results that do not deviate much from the real data. The Reynolds number of all the branches is checked to make sure that the assumption of laminar flow in the flow model is satisfied.

Because of the small apertures and large areas of the fractures, the heat transfer between the rock and the flow is very efficient. As shown Figure 8, the temperature of the water reaches that of the rock at the first node after the injection boundary. One should keep in mind, however, that the thermal model in GEOFRAC assumes a constant rock temperature, so the results can only model the beginning stage of the injection. Still, the results indicate that the large area and small apertures of fractures provide effective heat extraction from the underground.

This case study with GEOFRAC shows that it can be used to model the heat and mass transfer in a geothermal reservoir. However, the constant temperature assumption for the rock limits the

capability of this model to simulating only the beginning stage of the injection. While the Fenton Hill case is a HDR (EGS) application, the following case is a hydrothermal application.

3.2 The Námafjall geothermal field

The Námafjall geothermal field is located in northeast Iceland about 5 km northeast of Lake Myvatn as shown in Figure 9. It is located in the southern half of the Krafla fissure swarm and it is associated with the Krafla volcano. The Krafla geology is characterized by active rifting, forming a graben zone through its center, where volcanic craters, volcanic pyroclastics and lava flows, all of basaltic composition, dominate. The fissure swarm that intersects the Krafla central volcano (100 km long and 5 to 8 km wide) is part of the neo-volcanic zone of axial rifting in North Iceland [Malimo, 2012].

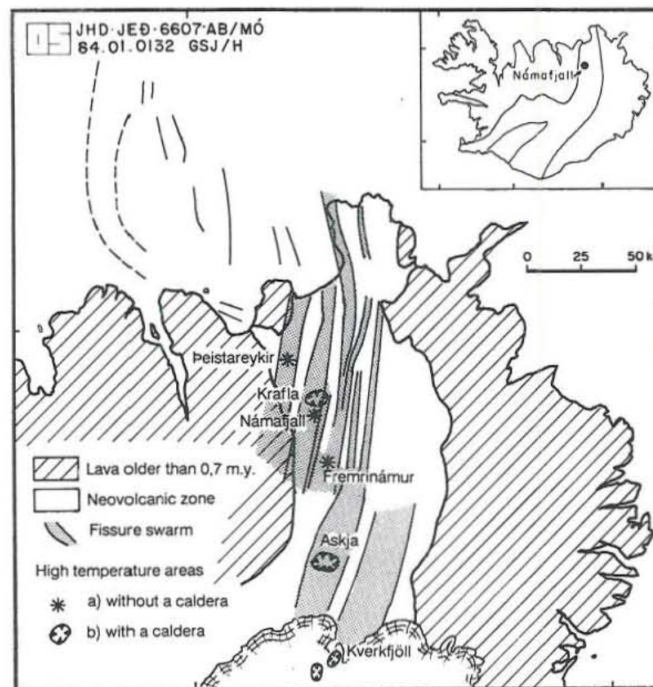


Figure 9 The high temperature areas in North Iceland and location of the Námafjall geothermal reservoir (from Isabirye, 1994)

Magma from the Krafla caldera traveled horizontally in the SSW direction along the fissures and fractures all the way down to Námafjall, and it serves as the heat source for the hydrothermal system. There are several fractures and faults in this area, such as the Krummaskard and Grjótagjá, and surface manifestations are often clearly aligned with the fractures. The geological characteristics of the Námafjall field indicate that the Námafjall ridge is part of the Námafjall-

Dalfjall-Leirhnjúkur ridge, and it has an overall length of about 15 km and width of about 1 km [Ragnars et al., 1970].

Deep drillings conducted in this area have provided important information on the sources and composition of geothermal fluids, thermal properties of the fluids and the geology and fracture system of this geothermal area. The data used in the simulations were obtained from the Rivera Ayala [2010], and boreholes and measurements by Landsvirkjun (see e.g. Gudmundsson et al. [2010]).

The Námafjall geothermal field is a large reservoir formed by the Krafla caldera. It is about 10 km long and 5-8 km wide. The GEOFRAC simulations (see Vecchiarelli et al. [2014]) are mainly focused on the fractured zone in this field, which is 2000m long, 1000m wide and at the depth from 1000m to 2000m. Given that the flow is mostly from the major faults and fractures, large expected fracture area $E[A]=800,000 \text{ m}^2$ and mean aperture values (log-normal distribution) are used in the simulation. The parameters are summarized in Table 3, for which the definitions can be found in Table 1.

Table 3 Summary of the Input Parameter for GEOFRAC Simulation of Námafjall geothermal field

$X \text{ (m)}$	$Y \text{ (m)}$	$Z \text{ (m)}$	$\mu \text{ (m}^{-1}\text{)}$	$E[A] \text{ (m}^2\text{)}$	m	k	$mPole$	rot
1000	2000	1000	0.02	800,000	4	20	$[\pi/2, 0]$	0
$\mu \text{ (m)}$	$\varepsilon \text{ (m)}$	$\Delta P \text{ (Pa)}$	$\mu_f \text{ (Pa}\cdot\text{s)}$	$k_t \text{ (W/m}\cdot\text{K)}$	$\rho \text{ (kg/m}^3\text{)}$	$C_{pf} \text{ (J/kg}\cdot\text{K)}$	$T_r \text{ (}^\circ\text{C)}$	$T_{in} \text{ (}^\circ\text{C)}$
0.004	0.04	1MPa	0.468×10^{-3}	0.6546	983	4185	250	60

Figure 10 is a schematic representation of the possible flow paths in one of the simulations. Compared to the case study of the Fenton Hill project, the reservoir is much larger. Since the objective of this case study is to simulate the large-scale fractures and faults, the flow rates in the fractures are higher than those in the Fenton Hill project.

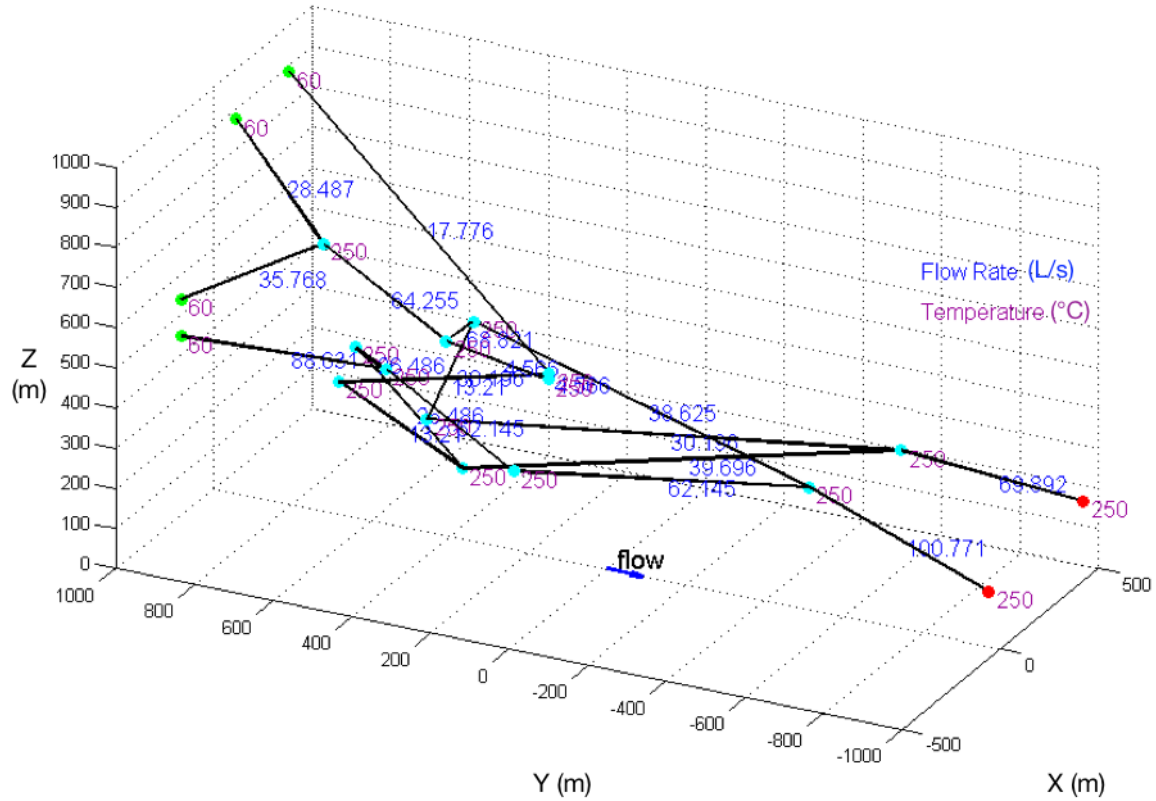


Figure 10 Schematic representation of the possible flow paths obtained in one simulation

Because of the stochastic processes used in GEOFRAC, the results are not deterministic. To draw reliable conclusions, a moderate number of simulations must be run as before. Again, 20 simulations are run. The average/mean value of the total flow rates is $0.21 \text{ m}^3/\text{s}$ with a standard deviation of $0.14 \text{ m}^3/\text{s}$. These values are in line with the measured production flow [Rivera Ayala, 2010] indicating that GEOFRAC can provide results that do not deviate much from the real data. The Reynolds number of all the branches is checked to make sure that the assumption of laminar flow in the flow model is satisfied.

Similar to the simulation results of the Fenton Hill project, the temperature of the water reaches that of the rock at the first node after the injection boundary. The average energy extraction rate estimated by GEOFRAC is 116,224 KW (see Vecchiarelli et al. [2014]); it is much higher than the capacity of the power plant, which is around 10 MW [Ragnars et al., 1970]. This is quite understandable given that the energy conversion efficiency of a geothermal plant is often around 20%. In addition, the heat transfer model is based on the above-mentioned assumption that the temperature of the rock is constant, but there is temperature drawdown in the rock. The heat

extraction rate cannot be maintained for a long time. Although the results GEOFRAC overestimate the power of the plant, they provide the upper bound of the power. Future work on the thermal model is needed to produce long-term temperature predictions.

4. Conclusion

This paper presented recent research developments on flow and heat transfer modeling with the GEOFRAC, a three-dimensional stochastic discrete fracture network model. Governing equations for flow and heat transfer in a single fracture are presented. Mass and energy conservation equations are used to solve the flow and heat transfer problem in the fracture network. Since GEOFRAC provides the geometric information for every fracture in the modeled volume, the flow rate and temperature for each fracture in the network can be calculated explicitly.

Two case studies have been used to demonstrate the applicability of the GEOFRAC package in modeling the flow and heat transfer in geothermal reservoirs. The case study with the Fenton Hill (HDR/EGS) project demonstrates how the parameters are chosen for GEOFRAC according to the measured data and geological description. Since most of the fluid flows in a few major fractures, relatively simple fracture networks are generated to simulate the flow and heat transfer in the geothermal reservoir. The flow rate and temperature produced by the simulations are in line with the measured data.

The case study with the Námafjall geothermal field, a hydrothermal case, focuses on the fractured zone of the geothermal reservoir. The parameters are chosen for GEOFRAC according to the measured data and geological description so that the major flow conducting faults and fractures can be modeled. The GEOFRAC simulations assume uniform rock temperature, so only the initial stage of the flow and heat transfer is modeled. Yet, the simulations provide reasonable results for flow rates and temperature in the reservoir.

With the discrete fracture network generated by GEOFRAC, the flow and heat transfer in each fracture can be explicitly calculated. The heterogeneity of flow and temperature in the fracture reservoir can be modeled easily with DFN. The current model assumes constant rock temperature, so only the initial stage of a geothermal reservoir can be modeled. However, this provide an upper bound for reference on the temperature and power extraction from the reservoir.

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