EFFECTS OF THERMALLY-INDUCED FRACTURES ON EGS PERFORMANCE

by

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A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Doctor of Philosophy (Mining and Earth Systems Engineering).

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ABSTRACT

An Enhanced (or Engineered) Geothermal System (EGS) is defined as an engineered reservoir formed by hydro-fracturing hot dry rock to extract heat from low permeability geothermal resources to generate electricity. EGS technology is undergoing stages of advancement, and a substantial amount of research has been conducted to understand different aspects of this technology.

It is well known that in the EGS reservoir, circulation of the cold fluid through the stimulated region induces thermo-elastic stresses that triggers thermal fractures. Initially, when the induced temperature gradient is critically high, a thermally-shocked region comprising a network of small, disorganized, closely-spaced thermal cracks is formed adjacent to the primary hydraulic fractures. These small thermal cracks tend to coalesce, and better-defined planar thermal fractures propagate into the rock matrix. Thermally-induced fractures (in both forms of small thermal cracks within the thermally-shocked region, and well-defined planar thermal fractures) are believed to improve EGS reservoir performance by increasing the surface area for heat exchange, and by lowering the flow impedance. However, current investigations exclude thermally-induced fractures from reservoir simulation practices. Due to physically removing thermally-induced fractures from EGS reservoir simulation, research on the mechanisms of fluid flow, heat, and mass transport within thermally-shocked region of an EGS reservoir has drawn less attention. This exclusion also hinders understanding the contribution of the thermally-induced fractures in EGS performance.

The main goal of this research is to improve the understanding of the coupled transport mechanisms within the EGS reservoir. In the first part of this research, which is a microscale study, the mechanisms of heat and mass transport within the thin, thermally-shocked region of an EGS reservoir are assessed. A segment of the thermally-shocked region is idealized as a porous medium, and ten models of identical geometrical features but different domain scales are developed. These models cover a wide range of fragmentation, from severely thermally-shocked to lightly thermally-shocked regions. Two methods are utilized to determine the fluid flow and transport processes, the direct pore-scale and the continuum Darcy-scale methods. The COMSOL Multiphysics software is utilized as a Finite Element (FE) framework for the
numerical implementation. It is found that for the severely thermally-shocked model, diffusion is a dominant mechanism of heat and mass transport. For a moderately thermally-shocked model, mass transfer is mainly accomplished by advection. However, heat is transferred via both fluid motion and conduction.

In the second part of this thesis, the effects of the thermally-induced fractures on EGS performance are assessed by integrating thermally-induced fractures into the field-scale reservoir simulation. An innovative hybrid approach comprised of the explicit discrete-fracture method and the Effective Continuum Method (ECM) is developed for simulating thermo-hydro processes within the EGS reservoir. The proposed hybrid approach allows to integrate thermally-induced fractures into the numerical simulation without additional computational burden. The results of the numerical model showed that the presence of thermally-induced fractures increases the production temperature of the EGS reservoir by 24% on average over 30 years of heat extraction from the reservoir. A sensitivity analysis study shows that the effect of the parameters of the planar thermal fractures on the thermal performance of the EGS was not as significant as that of the presence of these thermal fractures on the reservoir performance. Results of the parametric study show that minute differences in the permeability, length, number and width of thermal fractures are not so significant to the modeling results. But the inclusion of these thermal fractures do have a significant impact on modeling long term reservoir characteristics.
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ACKNOWLEDGMENTS

After an intensive period of time, today is the day. It has been a period of intense learning for me, not only in the scientific arena, but also on a personal level. I would like to reflect on the people who have supported and helped me so much throughout this period. First of all, I would like to express my regards to my adviser Dr. Masami Nakagawa, for all of his advice and expertise throughout my graduate studies. There were moments in which your advice was as necessary as the air I breathe; I thank you for telling me to not give up. Dr. Nakagawa was more than just a mentor; his perseverance, integrity and people-loving nature are just a few of his qualities that continue to inspire me.

I would like to express my gratitude to Dr. Priscilla Nelson, the head of the Mining Engineering department, for her contributions of time, ideas, and funding that make the Mining Engineering department productive and stimulating. My sincerely thanks also goes to the research committee chair, Dr. Xiaolong Yin, and the committee member, Dr. Rennie Kaunda, for their encouragement, insightful comments, and hard questions.

I would like to acknowledge Matthew Schriener, Edgar Mine manager, and Clinton Dattel, Edgar Mine Superintendent, who gave me an opportunity to gain a hands-on experience in a variety of underground mining activities (i.e., drilling, blasting, mucking, and mine safety). Lastly, I would like to thank my family and friends for all their love and encouragement, for my parents who raised me with love and supported me in all my pursuits, and most of all, for my loving, supportive, encouraging, and patient wife, Mona Noori, whose faithful support during the final stages of this Ph.D. is so appreciated. Thank you.
“It does not matter how long you live, but how well you do it.”

*Martin Luther King Jr.*
CHAPTER 1
INTRODUCTION

Climate change and global warming due to the excessive emission of greenhouse gases (GHG) have been reported as critical issues that mankind will face in the next 20 years (KPMG 2012, 2014; World Economic 2015). According to the IPCC\textsuperscript{1} Report (2014), burning of fossil fuels for generating electricity is the largest single source of global GHG emission. On the other hand, the International Energy Agency (IEA) reported that global electricity demand is increasing at the rate of 1.6\% per year (Sawin et al. 2016).

To meet the global electricity demand and to mitigate the environmental effects caused by current energy supply, the exploitation of renewable energies (RE) is inevitable (European Commission 2006, 2009). Rapid increase in global deployment of RE in recent years endorses the transition of the energy supply of the world to RE sources. Solar and wind are RE resources with a great potential of electricity generation. However, due to the intermittent nature of solar and wind energy, the electricity output of these RE technologies is variable and, to some degree, unpredictable (Skea et al. 2008; Edenhofer et al. 2011). Geothermal energy, the heat from the Earth’s crust, can be a suitable option for supplying constant base-load power, and a promising alternative for fossil fuel-based power plants.

The Etymology of the geothermal term is Greek; geo means Earth, and thermal means heat. Geothermal energy has been used in the form of hot springs for multiple purposes since Paleolithic times (Cataldi 1993). Howepage er, electricity was first generated from geothermal energy in

\textsuperscript{1} The Intergovernmental Panel on Climate Change
Larderello, Italy, in 1904 (Tiwari & Ghosal 2005). Armstead & Tester (1987) reckoned that the total heat available in the crust is around $2.631 \times 10^{19}$ J/km$^2$. As another example, according to the World Energy Council survey (2013), heat content of the crust is around $540 \times 10^7$ EJ. Although different assumptions and processes of estimation led to the different results, they all agreed that the amount of heat stored in the crust is tremendous (Edwards et al. 1982; Mock et al. 1997; Tester et al. 1994; Sass 1993). Harvesting just 1% of the Earth’s crust heat meets all the energy that the planet requires for 2800 years (Olasolo et al. 2016).

The status of a geothermal power capacity is about 13.3 Gigawatts as of January 2016, spread across the world (Matek 2016). Although a few countries shared the current capacity, reports published by the US Geothermal Energy Association (GEA) and by the International Geothermal Association (IGA) show that the number of countries generating geothermal power is increasing significantly (Holm et al. 2010). Most of the geothermal energy produced worldwide is limited to shallow depths and conventional hydrothermal reservoirs. The main drawback of the traditional geothermal reservoir is that these reservoirs are limited to certain geological conditions, and occurring predominantly in volcanic regions with abundant groundwater (Tester et al. 2007). Moreover, these reservoirs, similar to oil and gas reservoirs, can only be exploited until most of the contained fluid has been extracted (Olasolo et al. 2016).

The Enhanced or Engineered Geothermal System (EGS) can move geothermal power generation to the level beyond the conventional reservoir. This technology has the potential to utilize the Earth’s crust energy worldwide, and become a major supplier of primary energy for baseload electricity generation. Several studies have been carried out to develop efficient means to harvest thermal energy in large-scale from hot, low permeability crystalline rock by focusing on the principles of the EGS concept.
In the first part of this chapter, we briefly describe EGS technology and the foundation of this idea. In the second part we introduce the theoretical background of EGS reservoir simulation, with emphasis placed on coupled thermo-hydro processes. A short discussion about thermal fracturing phenomena within EGS reservoir, and its effect on the reservoir performance is given in the third part of this chapter. Finally the objective of this research, scope and organization of the thesis are given in the last part of this chapter.

1.1. Enhanced Geothermal System (EGS)

The idea of geothermal power generation at depths beyond conventional reservoirs laid out in the early 1970s, when Los Alamos National Lab developed a Hot Dry Rock (HDR) concept. The HDR concept was practiced at Fenton Hill site, New Mexico to demonstrate the feasibility of heat mining from hot, low permeability crystalline rock (Armstead & Tester 1987). The definition of EGS\(^2\) is diverging from the HDR concept, and referring to unconventional geothermal systems. In order to facilitate understanding of EGS, the major pioneer field-scale HDR projects must be addressed as follows:

1.1.1. American HDR Program

The first extensive field experiments to examine the feasibility of harvesting heat from impermeable, crystalline basement rocks was completed at Fenton Hill site located in the Jemez Mountains of northern New Mexico (Figure 1.1a). The Fenton Hill region is selected because the volcanic character of this region provides a higher than average geothermal gradient at reasonably shallow depth. The main objective of the project was to drill into hot crystalline rock at a suitable depth, using sufficient hydraulic pressure to create large vertical fractures, and drill a second well

\(^2\) Drill a well into the deep crystalline formation, create multiple heat exchange surfaces by hydraulically fracturing the rock, and ultimately drill the second well to intercept the generated fractures. By circulating water down one well, through the stimulated fractures, and up the other well, heat can be carried off from the hot rock to the surface.
to access that fractures at some distance above the first wellbore. The configuration of vertical planar fractures and wellbores can provide a path for circulation of fluid to harvest heat from a matrix of hot rock. The Fenton Hill project was conducted in two phases:

- **Phase I**

  A doublet system of two wells, GT-2B and EE-1, were drilled into the depth of approximately 3 km in biotite granodiorite rock at temperature about 185°C (Figure 1.1b). The objectives of phase I were to: (1) evaluate the hydraulic fracturing of the hot deep crystalline rock; (2) characterize the *in situ* stresses of the field; (3) detect seismic events associated with hydraulic fracturing in a low permeability crystalline formation; and finally (4) build a closed loop system to extract heat form the hot rock and generate electricity. Two reservoir systems were engineered for the heat extraction test at phase I. The first reservoir was comprised of (1) a large vertical hydraulically induced fracture formed behind the Casting in EE-1 at the depth about 2.75 km, (2) EE-1 wellbore as an injection well, and (3) GT-2 wellbore as a production well. The second reservoir was comprised of a deeper fracture with a radius of 300 m (three times that of first fracture), and EE-1 and GT-2 wellbores as an injection and production wells respectively (Figure 1.1c). During a 286-day circulation test of second reservoir, pressurized water was circulated through the fractures, bringing heat to the surface at 150°C. Delivered hot water from the reservoir ran an R-113 binary cycle power plant, and the first electric power of about 60 kW was generated successfully.
**Phase II**

A doublet system of two deeper wells, EE-2 and EE-3, about 50 m apart at the surface, were drilled directionally into the depth of approximately 4 km in meta-volcanic rock at a temperature about 300°C (Figure 1.1b). The objective of phase II was to construct a large deep reservoir with multiple fractures in order to produce water with the temperature and rate high enough to support a commercial-sized power plant. Multiple hydraulic fracturing tests were conducted in the open section of EE-2 with the aim that the fractures would tend to propagate vertically from EE-2 toward EE-3. Although attempt to connect EE-2 and EE-3 was unsuccessful, several other aspects of the HDR system, such as the packer test, cemented line test, sand plug test and micro-seismic tests were examined successfully during phase II of the Fenton Hill project.

1.1.2. British Hot Dry Rock Program

Pioneering efforts of the Fenton Hill project encouraged other countries to replicate the HDR concept. Learning from the American project, Camborne School of Mines in the UK conducted a series of experiments at Rosemanowes site in 1984 (Batchelor 1987; Camborne School of Mines 1988). The UK project aimed to construct a prototype HDR system where the rock temperature is sufficient to produce measurable thermal drawdown, yet shallow enough to avoid most of the operational problems associated with the Fenton Hill project. The Camborne School of Mines project consisted of two phases.

**Phase I**

The emphasis of the first phase was to understand the development of a full-scale reservoir at the shallow depth in which the complication of working at excessively high temperature can be eliminated. Four holes to the depth of 300 m in the Carnmenellis granite were
drilled in the period 1977 to 1980. Before hydraulic fracturing, the bottom of the holes were pre-treated by explosive stimulation to provide better access for the water to enter into the reservoir. Ultimately, hydraulic fracturing activated the pre-existing joint network, and a horizontal reservoir was created successfully.

✓ Phase II

The second phase was conducted by drilling two holes (RH11 and RH12) to the depth of 2 km entirely through the granite in the temperature range of 100°C. The objective of this phase was to create a heat exchange surface area of $2 \times 10^6$ m² within a volume of $2 \times 10^8$ m³, in which the flow of 100 kg/s can sweep the fractures and harvest the heat from the rock matrix. Due to the unsatisfactory results, the third well, RH15, was drilled below the original wells. Hydraulic fracturing of the RH15 well created a more permeable reservoir with lower impedance between the doublet system of the RH15 and RH12 wells (Figure 1.2).

In summary, according to the collected data from the Fenton Hill field, the project experts concluded that by applying hydraulic pressure on a homogenous, isotropic rock formation in an anisotropic stress field, nearly vertical fractures with planar structures can be induced. In contrast, in the British project, they concluded that by applying hydraulic pressure, pre-existing natural fractures became active and ultimately determined the orientation and propagation of the stimulation. In addition to the Fenton Hill and Rosemanowes projects, several HDR projects have been developed, e.g., Soultz in northeastern France, Hijiori in Japan, and Tirniauz in the Caucasus Mountains of Russia (Bresee, J.C. 2005; Baria et al. 1992; Tsutomu et al. 1992).
These prototype full-scale projects have moved the EGS technology forward to the point where energy extraction from the HDR has become ever closer to being technologically and economically feasible.

Figure 1.1: Fenton Hill HDR project: (a) location of the project in the Jemez Mountains of northern New Mexico (b) scheme of phase I (GT-2B/EE-1) and phase II (EE-3/EE-2) doublet systems in relation to the lithology, (c) conceptual model of Phase I (from Armstead & Tester 1987)
1.2. EGS Modeling

Despite recent advancement in the technical aspect of the EGS (e.g., drilling technique and borehole measurements), this technology is still in the research and development stage. Owing to the multiphysics nature of the EGS reservoir, geological complexity, and the dynamic behavior of the reservoir, developing a comprehensive EGS model that can capture the thermo-hydro behavior...
of the reservoir requires a profound understanding of the flow and transport processes within the reservoir. During the last two decades, several reservoir simulation models have been developed and numerical modeling has become standard practice in the planning, development and prediction of performance in the geothermal fields.

In order to develop an accurate model for simulating flow and transport processes within an EGS reservoir, the following six steps should be taken: (1) specifying objectives of the model, (2) developing a conceptual model, (3) formulating a mathematical model, (4) developing a numerical model, (5) calibration and validation of the numerical model, and finally (6) sensitivity analysis of the effective factors.

Once the objectives of the modeling are determined, identifying involved physical processes that are relevant to the explicit description of the system, and developing an accurate conceptual model, are the most critical issues in the development of an EGS model. The EGS conceptual model, which is the idealization of a real-world system, includes set of assumptions on:

- Geometrical properties of the system (e.g., dimensionality, aspect ratio)
- Geological properties of the system (e.g., homogeneity, heterogeneity, and geological layers)
- Hydrological properties of the system (e.g., flow regime, sink and source of fluid and mass)
- Geothermic properties of the system (e.g., heat transport mechanism, sink and source of heat)
- Material properties (e.g., density, viscosity, thermal properties of fluid and rock matrix)
- Boundary conditions of the system (e.g., fluxes at the boundaries)
• Paring subdomains of the system (e.g., hybrid-dimensional modeling)

• Coupling physical processes (e.g., direct coupling, one-way coupling)

• Evolution of the system (e.g., spatial time-dependent modeling, stationary modeling, growth behavior of active reservoir)

Developing a conceptual model that is not a faithful representation of the real-world system leads to an inaccurate mathematical formulation, and subsequently to incorrect and/or meaningless numerical results.

The ability to develop a commercial-sized EGS reservoir with sufficient thermal capacity to generate electricity over a satisfactory period of time requires a comprehensive understanding of the involved heat and mass transport processes. Heat transfer within EGS reservoir depends on a combination of several parameters (e.g., geometric parameter, reservoir structure, thermal properties of the reservoir, flow regime, injection/production scheme) (Kruger et al. 1991). At the stage of feasibility study, and prior to the production phase, the field data for many of these parameters are sparse. Therefore, predicting reservoir performance (e.g., thermal drawdown, production rate, lifetime of heat extraction) of a specific EGS reservoir relies mostly on the conceptual model of the system.

Manifold conceptual models with different sets of assumptions have been developed to estimate both heat extraction from the EGS (e.g., Gringarten et al. 1975; Hunsbedt et al. 1977; Pruess 1983) and economic feasibility of the hypothetical fracture-simulated reservoir (e.g., Boguslavsky 1981; Murphy et al. 1985; Dyadkin & Gendler 1985) during the last 20 years.
Willis-Richards & Wallroth (1995) conducted a comprehensive review on developed approaches of HDR reservoir modeling. They classified the HDR conceptual model into three main categories based on the geometric representation of the model. These categories are: (1) *the abstract geometry models*, in which the conceptual model is simplified and condensed into a single geometrical shape, (2) *the reduced geometry models*, in which the conceptual model is simplified into either an equivalent single fracture or tailored multiple fractures embedded in the hot rock, and (3) *the realist geometry models*, in which the geometrical properties of the fractures are interpreted from field data (Figure 1.3). A short review of a few conceptual models ranging from the most simplified model to the most rigorous model are given in the following section.

Armstead & Tester (1987), by excluding the EGS from the uncertainties associated with geological complexity and rock fracturing theory, and by considering the geometrical properties of the system static, assessed the scale of commercial-sized EGS reservoir analytically. The geometrical model of the EGS based on this concept is divided into two subdomains of (1) a rock matrix, which represents an abundant heat source, and (2) a set of parallel, equally spaced hydraulic fractures, which represents the flow paths that carrying heat to the surface.

Tenzer (2001) provided a first order approximation for idealized commercial-sized EGS reservoir. He showed that developing an EGS reservoir that can produce a thermal capacity of 10 to 100 MW with a sustained rate of 50 to 100 liters per second for at least 20 years requires 3 to 10 km$^2$ of heat exchange surface with low fluid flow impedance in the range of 0.1 mega-Pascal-seconds per liter.

Bödvarsson & Tsang (1982) developed an EGS model consisting a doublet system of injection/production wells and a set of equally spaced horizontal fractures. A set of assumptions
are used to make a simplified model of a real-world system, and the effect of the heat conduction on the advancement of the cold front along the fracture was evaluated. Finally, they built two numerical examples using a hypothetical doublet and the Cerro Prieto geological model to examine thermal breakthrough time and thermal front advancement in the rock matrix.

Bažant & Ohtsubo (1978) envisaged the simplest scheme of heat extraction from an HDR geothermal reservoir, i.e., an idealized single large fracture embedded in an impermeable rock matrix (Figure 1.4a). They established mathematical formulations based on the adopted conceptual model. Finally, they utilized a finite element code to calculate flow field, heat transfer, and fracture width growth at various times after the start of circulation. Bažant and his colleague results found favorable for some aspects of the geothermal heat extraction. However, a rapid drop in outlet temperature confirmed that their proposed scheme of a single large fracture would be inapplicable for the creation and operation of a stimulated EGS reservoir.

Heuer et al. (1991) also developed a mathematical model to investigate the evolution of the temperature in an HDR system. Similar to the Bažant & Ohtsubo (1978) model, they simplified the scheme of the reservoir to a single cylindrical fracture with arbitrary point injection and extraction (Figure 1.4b). They assumed that the heat flow in the rock matrix is 1D orthogonal to the fracture plane, and that the flow is a 2D dipole-flow form the injection point. Although much simplified, the derived analytical solution for the proposed mathematical formulations allowed them to validate their numerical examples.
Figure 1.3: Examples of abstract (a), reduced (b, c, d, and e), and realistic geometry models for HDR reservoirs (f). (from Elsworth 1990; Willis-Richards & Wallroth 1995)
Between the late 1970s and early 1980s, a group of Russian scientists at Leningrad Mining Institute (LMI) developed a conceptual model with the aim of estimating the heat extraction from geothermal systems based on available data (Smirnova 1978; Artemieva 1979b, 1979a; Gendler & Pavlov 1980; Mukhin & Smirnova 1981; Dyadkin & Gendler 1985; Artemieva & Stroganova 1986). Concurrently with the efforts made by Russian scientists, experts of the Stanford Geothermal Program (SGP) developed a 1D heat sweep model based on pre-production data to evaluate reservoir characteristics and to estimate the thermal performance of the geothermal reservoir (Hunsbedt et al. 1977, 1978, 1979; Kuo et al. 1977; Kruger 1982; Hunsbedt et al. 1983; Lam & Kruger 1988).

Shortly afterwards, Kruger et al. (1991) made a comparison between the LMI heat extraction model proposed by Russian experts and the 1D heat sweep model proposed by the SGP’s scientists. Kruger and his colleagues’ objective was to estimate the uncertainty associated
with the modeling of thermal extraction in a hypothetical circulation system. With this aim they set up a test case of the Russkie Komarovtsy geothermal prospect to compare the LMI model with the SGP 1D model (Figure 1.5). They indicated that there are some key aspects that are unknown during the planning and initial production phases (e.g., results of the massive hydro-fracturing, the actual flow paths taken by the injected fluid, and the induced changes in the reservoir when heat extraction is underway). With these unknowns, the ability to estimate possible ranges of productivity becomes very important. They finally concluded that developing different models with a wide range of assumptions provides a reasonable range of potential results, which ultimately leads to mitigating the risk of investment in geothermal industry remarkably.

![Figure 1.5: Scheme of Russkie Komarovtsy reservoir comprised of three-parallel hydraulically induced fractures (from Dyadkin & Kruger 1989)](image)

Satisfactory results of the initial conceptual models, in conjunction with advances in numerical simulation, encourage researchers to develop more elastic conceptual model by relaxing the other assumptions of the primary simplified models. For example, in contrast with early
developed models (e.g., Abe et al. 1976; Bödvarsson & Tsang 1982) in which the heat flow within the rock matrix is assumed to be one-dimensional perpendicular to the fracture plane, Kolditz (1995) developed the finite element solution to model heat conduction in the rock as a three-dimensional matrix-heat-diffusion. Kolditz investigated the dimensional effect of the heat conduction within the rock matrix. He also showed that by adopting 3D heat conduction, which reflects the real-case spatial heat propagation in a rock formation, the thermal drawdown of the production fluid was up to 11% less than the model with 1D matrix-heat-diffusion after 20 years of production (Figure 1.6a). Application of this modified model has been tested at the Rosemanowes HDR site as well (Kolditz & Clauser 1998).

Ghassemi et al. (2003) also developed the integral equation formulation with Green’s function to simulate heat extraction by the circulation of fluid through an idealized single large fracture. The proposed formulation allowed them to simulate the flow and transport processes by adopting 3D heat flow through the rock matrix without the need of discretizing the reservoir. Ghassemi and his colleague showed that the assumption of 1D heat conduction within the rock matrix could lead to the underestimation of both the reservoir thermal performance and life time significantly (Figure 1.6b), which is the same as results obtained by Kolditz (1995).

Figure 1.6: Thermal drawdown at production fluid, comparison of models with 3D and 1D matrix-heat-diffusion: (a) from Kolditz 1995(b) from Ghassemi et al. 2003)
Adapting realistic 3D heat conduction within a rock matrix is an example of relaxing one of multiple assumptions of the simplified EGS model to get to a more robust conceptual model. There are several other studies as well, in which relaxing further assumptions are examined. For example, the well-known ‘cubic law’ (Witherspoon et al. 1980), which is the simplest model of flow through a rock fracture, is derived under the assumption that the fracture in subsurface formations is comprised of a narrow region bounded by two smooth, parallel plates (Huit 1956; Snow 1965). This assumption is widely used by many researchers to characterize the fractures flow within subsurface systems, including in an EGS reservoir. However, several studies showed that in the real-world case, in which the fracture surfaces are rough, topography of the surfaces of a natural fracture has a strong influence on the flow and transport properties of fracture (Louis 1969; Bear 1972; Kranzz et al. 1979; Tsang & Witherspoon 1981; Golf-Racht 1982). Specifically in EGS field, Neuville et al. (2010), by excluding the cubic law assumption and by assuming the fracture aperture to be self-affine, i.e., rough, investigated the influence of fracture roughness on thermal exchange when a cold fluid is injected into a homogeneous hot rock. Neuville’s proposed model also applied to the deep geothermal reservoir of Soultz-sous-Forets in France. They showed that the roughness of the fracture is responsible for channeling inside the fracture.

Up to this point, in most of the mentioned EGS conceptual models, the geometry of the model is assumed to remain unchanged, whereas the EGS system evolves over time during fluid circulation within the reservoir. The real-case EGS reservoir is multiphysics in nature comprised of hydrological (H), mechanical (M), thermal (T), and chemical (C) processes. The interaction between involved physical processes alters the properties of the EGS reservoir while the heat extraction from a reservoir is underway. In the early days, although the theoretical foundation for coupling the physical processes was available, computing resources were scarce. Therefore, the
conceptual model of mutliphysics phenomena, i.e., EGS reservoir modeling, poorly captured the realistic HDR/EGS system. Over the years, enhancement in the theories of coupling interactive physical processes and advances in numerical solver as well as computational capacity allows to simulate complex systems efficiently. Numerical Thermo-Hydro-Mechanical (THM) models have since been developed and applied to several EGS sites (Kohl et al. 1995; Hicks et al. 1996; McDermott et al. 2006; Watanabe et al. 2010).

As mentioned earlier in this chapter, the concept of EGS involves drilling two or more wells into the reservoir to intersect multiple hydraulic fractures. By injecting cold fluid down one well, through the stimulated fractures, and up to the other well, heat can be carried off from the hot rock to the surface. Once the heat recovery process started, the rock matrix is subjected to continuous thermal stresses, and in turn, structural changes (Arshad et al. 2016). The seismicity monitoring of the Wairakei geothermal field (Sherburn 1984) and Geysers geothermal reservoir (Stark 1990; Mossop 2001) during a cold-water injection also pointed out the significant contribution of seismicity to the thermally-induced stresses in geothermal fields.

From simple laboratory-size cases (e.g., Chen & Marovelli 1966; Finnie et al. 1979) to more elaborate cases (e.g., Barr 1980; Perkins & Gonzalez 1985) and recent numerical studies (Ghassemi et al, 2005; Chun 2013a) several works have been conducted to analyze thermal stresses development, in turn, thermal fracture propagation in a geothermal reservoir. Table 1.1 highlights just a few of several research efforts that have been conducted to understand the mechanisms of thermal stresses and its consequences on an EGS reservoir.

Although the mentioned studies tried to prepare comprehensive models of an EGS system with the aim of better understanding the EGS system, they can rarely quantify the contribution of
thermal fractures in reservoir performance. Only a small number of studies have been conducted to investigate the effect of thermal fractures on reservoir performance (Harlow & Pracht 1972; Huang et al. 2013).

1.3. Objective of the Research

The focus of this study is to develop a better understanding of the fluid flow and transport processes within an EGS system, and then to determine the role of thermal fractures in an EGS reservoir. Thermal fractures are believed to improve reservoir performance (Armstead & Tester 1987; Murphy 1978; Tarasovs & Ghassemi 2011). In this study, the transport mechanisms within the thermally-shocked region of an EGS reservoir are well defined. Furthermore, a hybrid numerical approach, capable of integrating thermal fractures into reservoir simulation, is developed to simulate thermo-hydro processes within the EGS reservoir.

1.4. Scope and Organization of Thesis

The thesis is divided into 4 chapters. Chapter 2 is modified from an article previously presented at the GRC’s 40th Annual Meeting in October 2016. The comprehensive version of this paper is also submitted to peer-reviewed journal. Chapter 3 is the extended version of the article presented and published at the 42th Stanford Geothermal Workshop on February 2017. This article is in the processes of being submitted to peer-reviewed journal. An introduction and conclusions are provided in chapter 1 and 4, respectively. The main contents of each chapter are summarized as following:

**CHAPTER 2**, entitled “On heat and mass transfer within thermally-shocked region of Enhanced Geothermal System (EGS)” develops a conceptual model based on the direct pore-scale simulation approach to explain the transport mechanisms within a thermally-shocked region of an
EGS reservoir. In order to investigate the complex interplay between the scales of thermally-shocked region and transport mechanisms within this region, we create computational domains that are geometrically identical, but different in scale. In the second part of this chapter, the continuum approach is also adopted to develop a conceptual model with the aim of replicating transport behavior of the thermally-shocked region modeled previously by utilizing the direct approach. My contribution to this article was as the principle researcher and first author.

CHAPTER 3, entitled, “A hybrid approach for an efficient numerical modeling of the thermo-hydro processes within the EGS reservoir” presents a modified concept of EGS capable of integrating thermal fractures together with the main hydraulic fractures into the reservoir simulation. A hybrid flow model comprised of the explicit discrete-fracture model and Effective Continuum Method (ECM) is developed to formulate flow and heat transport processes within the reservoir. Finally, the effect of thermally-induced fractures on EGS performance is investigated. My contribution to this article was as the principle researcher and first author.

CHAPTER 4, entitled, “conclusions and recommendations” is the final chapter of this thesis. This chapter presents the summary of findings of the research and provides recommendations for the future research.
Table 1.1: Research efforts conducted to understand the mechanisms of thermal stresses and its consequences on EGS reservoir

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<th>Reference</th>
<th>Description</th>
<th>Application</th>
<th>Comments</th>
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<tbody>
<tr>
<td>Chen &amp; Marovelli (1966)</td>
<td><em>Theoretical analysis &amp; experimental study</em> / analyze thermal stresses in a rock disk subjected to an external thermal shock</td>
<td></td>
<td>Cooling shock analysis showed that applying higher temperature difference leads to a higher density of the thermal crack in the specimen (Figure 1.7a). The close agreement between the average stress theory and experimental results is observed.</td>
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<tr>
<td>Finnie et al. (1979)</td>
<td><em>Experimental study</em> / Thermal crack propagation is examined experimentally by injecting liquid nitrogen into the cube of limestone, and calculated theoretically by considering semi-infinite slab cooled on its face by liquid nitrogen</td>
<td>Rock breaking technique</td>
<td>Crack patterns observed, results showed thermal crack propagation rates are slow and thermal crack direction is unpredictable.</td>
</tr>
<tr>
<td>Nemat-Nasser et al. (1978); Nemat-Nasser &amp; Oranratnachai (1979)</td>
<td><em>Theoretical study</em> / with the aim of understanding the mechanism and stability of thermally induced fractures growth in brittle elastic solids.</td>
<td>Thermal fracturing in nuclear reactor, HDR reservoir, dried up lake</td>
<td>Assuming that the induced thermal fractures are initially parallel with equal space. The growing behavior of the fractures over time is formularized.</td>
</tr>
<tr>
<td>Bažant &amp; Ohtsubo (1977)</td>
<td><em>Theoretical study</em> / attempted to lay down the foundations of stability analysis of a system of cracks by highlighting that in the real situation the crack system are not perfect and equidistance and even small disarray in crack spacing would probably not exhibit bifurcation of equilibrium path</td>
<td>Understanding the pattern of thermal fracture system which propagates normal to the wall of the main hydraulic fracture (Figure 1.8a)</td>
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<th>Reference</th>
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<td><strong>Murphy (1978)</strong></td>
<td><em>Theoretical study</em> showed that during the heat extraction process form HDR reservoir, a network of closely spaced thermal fractures, which resembles a ‘waffle’ grid of grooves, is formed adjacent to the primary fracture. As time elapses, these small thermal cracks tend to coalesce and better-defined planar thermal fractures propagate into the rock matrix.</td>
<td>Effects of thermal fractures on HDR/EGS performance</td>
<td>Thermal fractures eventually form new conduits to the reservoir precisely where the water flow had been most constricted.</td>
</tr>
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<td><strong>Johnson et al. (1978)</strong></td>
<td><em>Experimental &amp; theoretical study</em> the characteristic of thermally induced micro crack subjected to slow uniform temperature change is studied.</td>
<td></td>
<td>The effect of inter-granular thermal stresses on thermal cracking of rock in a geothermal reservoir is investigated. The author indicated that inter-granular thermal stresses developed independently of a temperature gradient due to the different thermal expansion coefficient of neighbor minerals. The mismatching of thermal expansions of neighboring mineral grains can give rise to micro-cracks, in turn, may significantly affect the development of micro-cracks induced by temperature-gradient thermal stresses.</td>
</tr>
<tr>
<td><strong>Barr (1980)</strong></td>
<td><em>Analytical study</em> investigated the possibility of branching in thermal cracks propagating away from the surface of the main fracture by relaxing the assumption that excludes the thermal cracks from branching.</td>
<td>EGS/HDR thermal fracturing</td>
<td>Under some situation, branching from parent thermal crack is probable and this could result in thermal fracturing, resembles a clastic zone moving into the rock with the temperature front.</td>
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<tr>
<td>Reference</td>
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<td>Application</td>
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<td>Geyer &amp; Nemat-Nasser (1982)</td>
<td><em>Experimental study</em>/<em>An attempt to validate proposed theory by Nemat-Nasser et al. (1978)</em> is conducted by sinking two hot glass plate (with and without initial cracks on edge) into the dry ice (Figure 1.7b).</td>
<td>Thermal fracturing mechanism within HDR reservoir.</td>
<td>The experiment results confirmed the Nemat-Nasser et al. (1978) proposed theory.</td>
</tr>
<tr>
<td>Stephens &amp; Voight (1982)</td>
<td><em>Theoretical study</em>/<em>Pressure required to initiate hydraulic fractures in a vertical borehole problem has been calculated by modifying the classic theory of hydraulic fracturing including thermal stresses effect</em></td>
<td>Modifying hydraulic fracturing theory</td>
<td>Showed the influence of temperature on determination of the maximum far-field compression stress and ultimately on hydraulic fracturing.</td>
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<td>Perkins &amp; Gonzalez (1985)</td>
<td><em>Numerical study</em>/<em>developed an empirical equations for estimating induced thermal stresses around two-winged hydraulic fracture owing to injection of cold fluid into the fracture (Figure 1.8b)</em>.</td>
<td>Fracturing of geothermal wells</td>
<td>Results of the example problem showed that cold-water injection can reduce in-situ stresses around injection wells, in which ultimately causing thermal cracking at pressure considerably lower than pressure needs to hydraulic fracturing the rock in the absence of thermo-elastic effect.</td>
</tr>
<tr>
<td>Bahr et al. (1986)</td>
<td><em>Theoretical &amp; experimental study</em>/<em>quenching preheated sintered slabs made from a glass-quartz powder mix cooled on surface with coolant fluid.</em></td>
<td>Thermal-shock phenomenon in ceramics</td>
<td>Transient thermal load and the concept of energy release rate are considered to explain the crack propagation. Thermal crack patterns are observed by pouring fluorescent liquid on specimens (Figure 1.7c).</td>
</tr>
<tr>
<td>Clifton et al. (1991)</td>
<td><em>Analytical study</em>/<em>prepared a computational model for simulating hydraulic fracturing when cold water is injected into reservoir.</em></td>
<td>Modified hydraulic fracturing simulator</td>
<td>Changing in in-situ stresses due to thermoplastic and poro-elastic effect is calculated.</td>
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<td>Reference</td>
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<td>Dusseault (1993)</td>
<td><em>Theoretical study</em> / stress changes in the reservoir during thermal operation is addressed</td>
<td>Thermo-elastically contraction inclusion in HDR heat extraction.</td>
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<td>Kurashige et al. (1997)</td>
<td><em>Analytical study</em> / developed an analytical approach to estimate size of induced fractured zone around the injection borehole bottom in DHR system.</td>
<td>EGS/HDR reservoir</td>
<td>The fractured region size is calculated for three extreme thermal and mechanical conditions and for the depth of 2 km or more, the fractured zone is about ten times the borehole radius.</td>
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<td>Tarasovs &amp; Ghassemi (2011)</td>
<td><em>Numerical study</em> / the boundary element method is developed to investigate physical parameter of EGS system (e.g., in-situ stresses, flow rate) on the length and spacing of the thermally induced fractures (Figure 1.9a).</td>
<td>EGS/HDR reservoir</td>
<td>Interaction and trajectories of multiple fractures in a poro-thermoelastic rock also investigated in this research.</td>
</tr>
<tr>
<td>Chun (2013)</td>
<td><em>Numerical study</em> / developed a 2D displacement discontinuity method to investigate the impact of transient cooling on propagation of poro-thermally induced fractures.</td>
<td>EGS/HDR reservoir</td>
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<td>Huang et al. (2013)</td>
<td><em>Numerical study</em> / developed a quasi-static discrete element method (DEM) modeling fracture propagation induced by thermal stress. The array of thermal crack investigated under small and large thermal strain load (Figure 1.9c).</td>
<td>EGS/HDR reservoir</td>
<td>For the large thermal strain load the morphology of crack pattern would be more complicated and no accordance with hierarchically ordered parallel cracks array exists anymore.</td>
</tr>
<tr>
<td>Tran (2013)</td>
<td><em>Theoretical &amp; numerical study</em> / explained the conditions under which the thermal cracks will occur. Using finite element methods, thermal crack length and width growth under different conditions also have been examined in this study (Figure 1.9b).</td>
<td>EGS/HDR reservoir</td>
<td></td>
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Figure 1.7: Thermally induced fractures patterns: (a) granite disks subjected to a cooling shock, from Chen & Marovelli (1966) (b) hot glass plates (with/without initial crack on the edge) sunk into the dry ice, from Geyer & Nemat-Nasser (1982) (c) stack of preheated samples cooled on surface, from Bahr et al. (1986)
Figure 1.8: (a) General and special crack systems in geothermal reservoir investigated by Bažant & Ohtsubo (1977), (b) thermal stresses development around two-winged hydraulic fracture due to injection of cold fluid from Perkins & Gonzalez (1985b)
Figure 1.9: (a) Scheme of secondary thermal cracks in geothermal reservoir (top), and distribution of the total stress in the reservoir rock matrix (bottom) from Tarasovs & Ghassemi (2011) (b) Finite element methods developed for studying thermal crack in EGS reservoir. Nodal elements before and after crack propagate (top) and the scheme of multiple thermal fractures (bottom) from Tran (2013). (c) Fracture patterns at different thermal load in geothermal energy system. thermal load $\alpha\Delta T = 0.4\%$ (top) and $\alpha\Delta T = 1\%$ (bottom) from Huang et al. (2013).
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CHAPTER 2

ON HEAT AND MASS TRANSFER WITHIN THERMALLY-SHOCKED REGION OF
ENHANCED GEOTHERMAL SYSTEM

Modified from a paper submitted to the Geofluid journal

Kamran Jahan Bakhsh, Masami Nakagawa

2.1. Abstract

An Enhanced Geothermal System (EGS) is an artificially created geothermal reservoir formed by hydro-fracturing hot dry rock. Hydro-fracturing causes a great temperature difference between the fluid and the hot rock, and thermal shock occurs when the cold water is injected into a hot rock of EGS. In a thermally-shocked region near the injection borehole, a network of small, disorganized, closely-spaced micro cracks are formed. As the cold water injection continues, the hot rock cools down, and these micro cracks tend to coalesce to become a better-defined network of thermal fractures. Thermal fractures in an EGS reservoir are believed to improve reservoir performance by increasing the surface area for heat exchange and lowering the flow impedance; however, it is difficult to predict how they grow and thereby become the most effective permeable reservoir.

In this chapter an insight into the transport mechanisms within the thin thermally-shocked region of an EGS reservoir is provided. For simplicity, this region is assumed to be porous and permeable. In order to understand how heat and mass are transferred through this thin porous region filled with idealized fractures (micro cracks initially and thermal fractures at a later development), COMSOL Multiphysics is used to set up a porous region of the identical

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geometrical features, but at different domain scales. The small domain scale (represented by a 1 mm computational cell) can be envisioned as the initial state of the thermally-shocked region with micro cracks. The larger domain scales (represented by a 100 mm computational cell) is used to represent the same thermally shocked region, but now filled with coalesced and better defined thermal fractures. The same geometry was used to caution that flow patterns alone cannot be used to estimate how heat and mass are transferred at different scales. Pore-scale coupled equations were used to identify their applicability and limitations in different domain scales. This research shows the importance of the degree of fragmentation and coalescence in determining how heat and mass are transferred at different scales and how to select appropriate analytical tools.

**Keywords:** EGS, Enhanced Geothermal Reservoir, thermally-shocked region, mass breakthrough time, thermal breakthrough time, EGS performance, pore-scale simulation

### 2.2. Introduction

Global demand for electricity generation from alternative energy sources is increasing. More countries are evaluating the potential of geothermal as their alternative energy source for electricity generation (Huenges 2011). An Enhanced Geothermal System (EGS) has the potential to take geothermal energy production to a new level of utility-scale energy production. For the last several decades, starting with the Fenton Hill project, several EGS projects have been developed with the hope of understanding the complex nature of man-made geothermal reservoirs. This type of man-made geothermal reservoir requires a cold-water injection to a hot but dry granitic rock at several kilometers deep to create an artificial reservoir, and recover the injected water as hot steam through production wells. Hot dry granitic rocks are easier to find at that depth. One of the main engineering problems has been the inability to connect the injection with production wells that are several hundred meters apart. This is partially due to the lack of our
understanding of how the state of stresses from the weight of the overlaying strata and locked in
stresses of the tectonic origin combine to interact with the induced thermal changes. The authors
assume that the initial development of thermal fractures caused by the cold-water injection controls
the patterns of fracture propagation, as this pattern development will initially define the connecting
paths between injection and production wells. Thus, it is important to investigate how heat and
mass are transferred in the thermally-shocked region and how they will influence the development
of reservoir permeability.

Thermal fractures are believed to improve reservoir performance (Armstead & Tester
1987; Murphy 1978; Tarasovs & Ghassemi 2011). In an EGS reservoir, as the cooling process
continues, thermal fractures are widened and penetrate deeper into the hot rock. This stimulation
action increases the reservoir’s ability to transport heat and mass by lowering the flow impedance,
and also by increasing the heat exchange areas. A reservoir model that incorporates thermal
fractures together with the main hydraulic fractures is required to understand the effects of cold
water injection; however, it will certainly add another layer of complexity in reservoir modeling
and simulation.

Several authors have studied how thermal stresses are developed in brittle materials due to
cold water injection. Chen & Marovelli (1966) conducted an experiment to analyze thermal
stresses in a rock disk subjected to an external thermal shock. Perkins & Gonzalez (1985), as well
as Kocabas (2006), proposed analytical models to investigate the state of stresses induced by cold
fluid injection. Ghassemi et al. (2005) developed an integral equation to calculate thermally-
induced stresses associated with the cooling of a planar fracture in a hot rock. These studies
demonstrate that induced tensile stresses in the cooled region of the EGS reservoir stimulate
thermal fractures. They also find that there is a direct correlation between the difference in the applied temperature and the crack density.

A series of studies have also been conducted to understand the mechanical and thermal behavior of thermally-induced fractures and their interactions in brittle elastic materials (Geyer & Nemat-Nasser 1982; Bahr et al. 1986; Bahr et al. 2010; Huang et al. 2013). Nemat-Nasser et al. (1978) investigated stability of growing thermal fractures. Barr (1980) investigated the branching of thermal fractures by examining the potential of crack propagation away from the surface of the primary fracture in a Hot Dry Rock (HDR) system. Bažant & Ohtsubo (1978), as well as Murphy (1978) and Barr (1980), show that during the heat extraction process, a network of closely spaced thermal fractures, which resembles a ‘waffle’ grid of grooves (Armstead & Tester 1987), is formed adjacent to the primary fractures. One of the common observations of these studies is that the growth patterns of thermal fractures are complex, particularly under the large thermal strain close to the surfaces of primary fractures.

Although these studies present a comprehensive view of the impact of thermal fracturing, thermal fractures have not clearly been integrated into an EGS reservoir modeling. In fact, a common practice of reservoir modeling neglects the positive effects of thermal fractures by excluding them from the core structure of simulation, and this exclusion hinders progress towards a better understanding of the contribution of thermal fractures in reservoir performance.

Only a small number of studies have been conducted to investigate the effect of thermal fractures on reservoir performance. Harlow & Pracht (1972) were probably the first to integrate thermal fractures into a reservoir model as an additional porosity. Stephens & Voight (1982) showed that the presence of thermal stresses lowers the pressure requirement to initiate hydraulic
fractures in the reservoir. Tran (2013) also indicates that the presence of thermal fractures in a reservoir could change both the shape and aperture of the primary hydraulic fractures, and as a consequence, reservoir performance is affected. Huang et al. (2013) developed a quasi-static discrete element model to simulate fracture propagation induced by thermal stresses. Huang’s model shows that the propagation of thermal fractures has a significant influence on heat conduction. These studies highlight the importance of thermal fractures in an EGS reservoir model; however, the heat and mass transport mechanisms within the thermally-shocked region of an EGS reservoir have not yet been clearly investigated.

Motivated by these observations, this paper investigates the transport mechanisms within a thermally-shocked region to provide a better understanding of the overall heat and mass transport in an EGS reservoir. In response to the cold-water injection, a thin thermally-shocked region is formed adjacent to the hydraulically-induced fracture. The thermally-shocked region initially acts as a transition zone between the hydraulically-induced fracture and thermal fractures. The structure of the thermally-shocked region and its transport property can affect overall reservoir performance in two ways: first, by controlling the growth behavior of the thermal fractures, and second, by altering heat transfer from the rock mass to the working fluid. In this study, a porous medium consisting of solid skeleton and fluid pathways is considered as a conceptual model of the thermally-shocked region. The pore-scale approach is adopted and mathematical formulation and numerical examples are developed to investigate the transport mechanisms within the region of interest.

2.3. Conceptual model

Figure 2.1 shows a conceptual model of an EGS reservoir comprising a series of parallel hydraulically-induced fractures connected to define a doublet system of an injection and a
production well embedded in hot dry crystalline rock. This system is commonly used to characterize an idealized EGS reservoir (Armstead & Tester 1987; Fox et al. 2013; Li & Lior 2015), although this configuration does not fully portray a realistic EGS reservoir.

This paper focuses on the transport behavior in a thin, thermally-shocked region adjacent to a hydraulically-induced, lenticular fracture. A representation of the thermally-shocked region adopted from earlier studies (Murphy 1978; Bahr et al. 1986) is shown in Figure 2.1. The thermally-shocked region with micro cracks is idealized as a granular porous medium. Following this assumption, a MATLAB® was used to generate a random 2D porous region composed of randomly placed, non-overlapping circles.

The degree of fragmentation due to thermal shock depends on several factors, such as the severity of the temperature gradient, the depth of the reservoir, the temperature mismatch between the rock and the water at the fracture surfaces, the thermal expansion coefficient, Young’s modulus of the rock, and the rate of water circulation (Armstead & Tester 1987). In this work, two models of different domain scales of 1 and 100 mm were developed to represent a severely-shocked region and a moderately-thermally-shocked region, respectively. The former represents the initial stage of the thermally-shocked region, and the latter represents the initial region at a later time, or the initial region that can be developed when the thermal shock was not severe enough so that fragmentation was coarse. Porous media with length scales lower than 1 mm and larger than 500 mm are beyond the scope of this paper. The former length range may cause nanoscale pore spaces, and the latter may cause an unwanted turbulent flow regime.
2.4. Contributing physics

In order to describe the transport mechanisms within the thermally-shocked porous region of an EGS reservoir, a set of equations that describe the fluid flow, heat, and mass transport are required. Furthermore, these equations must be coupled to capture the multi-physics nature of the described transport phenomena. In this work, a sequential coupling approach is taken. Initially, fluid flow and mass transport are considered to be the only contributing transport processes without heat transfer. Thus, the connected pore network alone is responsible for fluid and mass transport and they are coupled in an isothermal manner. Later, the solid rock matrix is added in conjunction with the pore network, and the equation of heat transfer is added to the mass transport model to
build the sequential coupling for heat and mass transport. This sequentially but fully coupled system is capable of analyzing the non-isothermal transport behavior of a thermally-shocked region.

The physics of fluid flow, heat, and mass transport in porous media exhibit complex phenomena that stem from different length scales. Transport phenomena in the severely thermally-shocked region with many small fractures can be best described by coupling the Navier-Stokes and advection-diffusion equations together with conjugate heat transport. In order to investigate the complex interplay between different scales in defining transport phenomena, we create computational domains that are geometrically identical but different in scale. In either scale, the small identical Reynolds number assures that the flow is laminar.

2.5. Pore-Scale modeling

In this section, we will describe our sequential coupling method to analyze heat and mass transport at pore-scale.

2.5.1. Mass transport (isothermal coupling)

Following the sequential coupling approach, the physics of fluid flow and mass transport are first coupled. There is no thermal interaction between the fluid in the pore and the solid rock matrix. The flow is assumed to be isothermal single-phase laminar flow, and the Navier-Stokes equation governs the fluid flow. Figure 2.2 shows the computational domain, and the relative concentration of mass and temperature arrivals can be monitored at discrete locations (A, B, C and D) of this simulation domain.
\[ \rho_f \frac{\partial \mathbf{u}}{\partial t} + \rho_f \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \nabla \cdot \left[ \mu (\nabla \mathbf{u} + (\nabla \mathbf{u})^T) - \frac{2}{3} \mu (\nabla \cdot \mathbf{u}) \mathbf{I} \right] + \mathbf{F} \]  

(2-1)

where, \( \rho_f \) denotes the density of the fluid (kg/m\(^3\)), \( \mathbf{u} \) the fluid velocity (m/s), \( p \) the pressure (Pa), \( \mathbf{F} \) a body force term (N/m\(^3\)), and \( \mathbf{I} \) is the identity matrix. The low-pressure gradient of \( \nabla p = 0.1 \) Pascal is applied on the boundaries to keep the flow regime laminar. The initial and boundary conditions can be expressed as:

\[
\mathbf{u}(x, y, 0) = 0 \quad x, y \in \text{pore space} \\
p(x_i, y, t) = p_i \\
p(x_o, y, t) = p_o
\]

(2-2) \hspace{1cm} (2-3) \hspace{1cm} (2-4)

A no-slip boundary condition is applied at the interior walls, as well as on the upper and the lower walls. The transient advection-diffusion equation governs transport of non-reactive species of mass in a laminar flow regime.

\[
\frac{\partial C}{\partial t} + \nabla \cdot (-D \nabla C) + \mathbf{u} \cdot \nabla C = R
\]

(2-5)
where, C denotes mass concentration (mol/m$^3$), D the diffusion coefficient (m$^2$/s), u the velocity (m/s), and R the source or sink term (mol/m$^3$/s).

The complexity in the topology of the pore network in conjunction with the coupling of the contributing physical process makes the simulation computationally expensive. To maintain numerical accuracy with a manageable simulation time, a Gaussian profile is given to express the initial condition of the physics of mass transport.

$$C(x, y, 0) = C_0 \quad x, y \in \text{pore space}$$  \hspace{2cm} (2-6)

$$C_0 = C_{\text{max}} \times \exp(1000 \times \left(-\left(\frac{x}{0.5}\right)^2\right)$$  \hspace{2cm} (2-7)

A constant concentration of $C_{\text{max}}$ is applied to the inlet boundary, and the species are transported out of the model domain by fluid motion.

$$C(x_i, y, t) = C_{\text{max}}$$  \hspace{2cm} (2-8)

$$\mathbf{n} \cdot (-D \nabla C) = 0 \quad \text{at outlet, } x_o$$  \hspace{2cm} (2-9)

All other boundaries, including rock matrix surfaces and the upper and lower boundaries, are assumed to be insulating boundaries where no mass flows in or out.

$$-D_i \nabla C_i + u C_i = N_i$$  \hspace{2cm} (2-10)

$$\mathbf{n} \cdot N_i = 0$$  \hspace{2cm} (2-11)

For a complex flow field geometry such as the one considered here, the Stokes equations do not have simple analytical solutions; however, the transport of species in one-dimension has been analytically solved (Ogata & Banks 1961; Bear 1972; Bear 1979; Freeze & Cherry 1979; Van Genuchten & Alves 1982) and it can be expressed as:

$$\frac{C}{C_0} = 0.5 \left[ \text{erfc} \left(\frac{d-vt}{\sqrt{D\tau}}\right) + \exp \left(\frac{v d}{D}\right) \text{erfc} \left(\frac{d+vt}{\sqrt{D\tau}}\right) \right]$$  \hspace{2cm} (2-12)
where, \( \frac{c}{c_0} \) is the Relative Concentration (RC) defining the ratio of the species concentration to its initial value at a distance d from the inlet (m), \( erf c \) is the complementary error function, \( v \) is the flow speed (m/s), \( D \) is the diffusion coefficient (m\(^2\)/s), and \( t \) is the time (s).

Using Eq. (2-12), the Mass Breakthrough Time (MBT) is calculated against velocity for a given RC value. This RC specific MBT is calculated at the outlet D, i.e., the time to travel 1 mm in distance. Two major trends can be observed in Figure 2.3. First, when the velocity becomes small enough, i.e., less than 10E-6 m/s, then MBT for each RC value becomes constant. This is an indication that mass is transported by diffusion, and the MBT depends only on the concentration gradient. On the other hand, when the velocity becomes large enough, MBT values for each RC value merge to a single value that can be calculated as the time it takes for the fluid velocity to travel 1 mm in distance. This is the indication that the mass is now transported along the movement of fluid. More specifically, for example, for RC of 0.1, the MBT due to pure diffusion can be found by reading off the value for the point where the plotted red line intersects with the smallest velocity value. On the other hand, the MBT due to pure advection can be found as the point where the red line intersects with the largest velocity value. Any MBT between these two extremes are due to the combined effect of diffusion and advection. The precise contribution of each effect is unknown. It is clear from Figure 2.3, though, that for slower velocities, the MBT is influenced more by the diffusional mass transfer. Here, only the case with the length scale of 1 mm is considered for validation. It is noted that the coefficient of diffusion is assumed to be equal to that of self-diffusion (or tracer-diffusion) of water, 1E-9 m2/s.

In Figure 2.4, based on our theoretical analysis, we showed which transport mechanisms are at work for a given velocity and relative concentration. Now, the model is validated by measuring the RC values as the flow passes through the outlet D. Figure 2.4 shows that for a given
RC value, the MBT is the shortest when both diffusion and advection participate in transfer mechanisms, and the longest when pure advection controls the dispersion. It is also noted that for the advection dominated flow, the mass passes the outlet D with a large concentration gradient.

![Mass Breakthrough Time (MBT) graph](image)

**Figure 2.3**: Mass Breakthrough Time (MBT) as a function of velocity for pure diffusion, diffusion with advection, and pure advection (Analytical solution for the case with scale length of 1 mm, modified from Manassero & Shackelford 1994)

![Relative Concentration (RC) graph](image)

**Figure 2.4**: Relative Concentration (RC) over time at the outlet for pure diffusion, diffusion with advection, and pure advection (Numerical solution for the case with length scale of 1 mm)
2.5.2. Heat and mass coupled transport (non-isothermal)

A fully coupled non-isothermal, transient model is needed to capture the transport phenomena within the thermally-shocked porous region of the EGS. Unlike the isothermal coupling model, where only the fluid phase in the pore network was responsible for mass transport, for the non-isothermal coupled case both the pore fluid network and solid rock matrix participate in heat and mass transfer. The conjugate heat transport concept (Lee et al. 2001) is used to couple the physics of heat transfer in both domains.

It is assumed that heat is transferred within the solid matrix only due to conduction. Therefore, Fourier’s law can define the temperature field in this domain.

\[ \rho_r C_{Pr} \frac{\partial T}{\partial t} = \nabla \cdot (k_r \nabla T) + Q \tag{2-13} \]

where, \( \rho_r C_{Pr} \) is the effective volumetric heat capacity of the solid phase at constant pressure (J/m\(^3\)o°C), and \( k_r \) is the thermal conductivity of the solid (J/m\(s\)o°C). In the pore fluid network, the energy equation is modified to reflect the influence due to the viscous effect and the temperature-dependent pressure work. Accordingly, the following equations are used to govern the energy transport in the system:

\[ \rho_f C_{Pf} \frac{\partial T}{\partial t} + \rho_f C_{Pf} \ u \cdot \nabla T + \nabla \cdot q = Q \tag{2-14} \]

\[ q = -k_f \nabla T \tag{2-15} \]

where, \( \rho_f C_{Pf} \) indicates the effective volumetric heat capacity of the fluid at constant pressure (J/m\(^3\)o°C), \( k_f \) the thermal conductivity of fluid (J/m\(s\)o°C), and \( u \) the fluid velocity. Initial and boundary conditions are applied as follows:
\[ T_s(x, y, 0) = T_f(x, y, 0) = T_0 \quad x, y \in \text{both domains} \quad (2-16) \]

\[ T_0 = (T_{\text{max}} - T_{\text{in}}) \times \left[ 1 - \exp(1000 \times \left(-\left(\frac{x}{0.5}\right)^2\right)) \right] + T_{\text{in}} \quad (2-17) \]

A constant temperature of \( T_{\text{in}} \) is prescribed at the inlet. It is also assumed that there is no heat flux across the upper and lower boundaries as shown in the following equations:

\[ T_f(x_\text{i}, y, t) = T_{\text{in}} \quad x, y \in \text{pore network} \quad (2-18) \]

\[ -\mathbf{n} \cdot \mathbf{q} = 0 \quad (2-19) \]

In accommodating these coupled equations in the numerical model, COMSOL Multiphysics\(^\circledR\) was used to numerically study coupled heat and mass transport phenomena in a complex fractured rock. The COMSOL Multiphysics is well suited for simulating mechanical-thermal-hydrological coupled problems. For the pore-scale modeling approach, the computational domain of interest is discretized explicitly for both pore-network and solid rock domains. Time is also discretized by utilizing the Backward Differentiation Formula (BDF) time stepping method. The BDF is a family of implicit, linear multistep methods used to numerically integrate ordinary differential equations, and its transient solver is both stable and versatile and provides extra robustness required for transport applications. Parameters used in the pore-scale simulation are listed in Table 2.1. For more details on the numerical model, see the Appendix.
Table 2.1: Parameters used in the pore-scale simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value/Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Solid Phase</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>$k_r$</td>
<td>2.9 W/(m K)</td>
</tr>
<tr>
<td>Heat capacity</td>
<td>$C_{P_r}$</td>
<td>850 J/(kg K)</td>
</tr>
<tr>
<td>Density</td>
<td>$\rho_r$</td>
<td>2600 kg/m³</td>
</tr>
<tr>
<td>Porosity</td>
<td>$\varepsilon$</td>
<td>0.431</td>
</tr>
<tr>
<td><strong>Fluid (water)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>$k_f$</td>
<td>0.6 W/(m K)</td>
</tr>
<tr>
<td>Heat capacity</td>
<td>$C_{P_f}$</td>
<td>Function of</td>
</tr>
<tr>
<td>Density</td>
<td>$\rho_f$</td>
<td>Temperature (see</td>
</tr>
<tr>
<td>Dynamic viscosity</td>
<td>$\mu$</td>
<td>the appendix)</td>
</tr>
<tr>
<td>Inflow Temperature</td>
<td>$T_{in}$</td>
<td>15 °C</td>
</tr>
<tr>
<td>Initial Temperature</td>
<td>$T_0$</td>
<td>85 °C</td>
</tr>
</tbody>
</table>

2.6. Darcy-scale modeling

In the pore-scale modeling section, we created a model with a detailed geometry. The pore-scale modeling approach can give detailed information about fluid flow and transport processes within the domain. However, this microscale modeling approach is not practical for solving field-scale problem. In this section, fluid flow and transport processes through the porous structure are treated using simplified homogeneous model with effective transport properties. Figure 2.5 shows the computational domain for the Darcy-scale model. The relative concentration of mass and temperature arrivals can be monitored at discrete locations (A, B, C and D) of this simulation domain. The main goal of this section is to investigate if the Darcy-scale modeling approach, with its built-in assumptions and simplifications, can duplicate same results as the detailed structure model produced. The Darcy-scale assumption ignores the fact that a domain is comprised of both
a pore-network and solid phases. Instead, the physics is governed by quantities averaged over control volumes.

![Figure 2.5: Computational domains adopted for the Darcy-scale modeling. Reference lines A, B, C, and D divide the computational domain into four equal subdomains.](image)

### 2.6.1. Mass transport (isothermal coupling)

Darcy’s law together with the continuity equation are coupled with the mass transport equations in this section. The permeability of the porous medium must be known to determine Darcy’s velocity field. As the detailed structure of the pore-network is known, permeability can be calculated by employing the direct pore-scale modeling approach.

\[
\frac{\partial}{\partial t} (\rho \varepsilon_P) + \nabla \cdot (\rho \mathbf{u}) = Q_m
\]

\[
\mathbf{u} = -(k/\mu) \nabla (p + \rho g \nabla D)
\]

where, \( k \) denotes the permeability of the porous medium (m\(^2\)), \( \mu \) the dynamic viscosity of the fluid (kg/m \( \cdot \) s), \( p \) the pressure (Pa), \( \mathbf{u} \) the Darcy velocity (m/s), \( \varepsilon_P \) the porosity (dimensionless), \( \rho \) the
density of the fluid (kg/m$^3$), $Q_m$ the mass source term (kg/m$^3$/s), $g$ the acceleration of gravity (m/s$^2$), and $D$ the elevation (m). The gravity effect is assumed to be neglected. The same pressure gradient of $\nabla p = 0.1$ Pascal is applied to drive the flow within the domain. The initial and boundary conditions can be expressed as:

$$p(x, y, 0) = 0 \quad x, y \in porous\ domain \quad (2-22)$$

$$p(x_i, y, t) = p_i \quad (2-23)$$

$$p(x_o, y, t) = p_o \quad (2-24)$$

No-flow boundary condition is applied on both upper and lower sides. This boundary condition states that there is no flow across the impervious wall.

$$\mathbf{n} \cdot \rho \frac{k}{\mu} \nabla p = 0 \quad at\ upper\ and\ lower\ walls \quad (2-25)$$

Mass transport in porous media is governed by the following equations:

$$\nabla \cdot \mathbf{J}_i + \mathbf{u} \cdot \nabla C_i = R_i + S_i \quad (2-26)$$

$$\mathbf{N}_i = \mathbf{J}_i + \mathbf{u} C_i = -D_{e,i} \nabla C_i + \mathbf{u} C_i \quad (2-27)$$

$$D_{e,i} = \frac{\varepsilon_p}{\tau_{F,i}} D_{F,i} \quad (2-28)$$

where, $D_{e,i}$ denotes the effective diffusion coefficient (m$^2$/s), $D_{F,i}$ the fluid diffusion coefficient, and $\tau_{F,i}$ the tortuosity (dimensionless). As it shown in the Eq. (2-27), the Darcy-scale approach treats the mass transport by simplifying the model into a continuous model with effective transport properties. In the Darcy-scale approach, the effective diffusion coefficient becomes different from the real diffusion coefficient. There are effective diffusivity models that relating the tortuosity to
the domain porosity. The Millington & Quirk (1959) and the Bruggeman (1935) models are two well-known models that correlate the tortuosity to the porosity by defining \( \tau_{F,i} = \varepsilon_p^{-1/3} \) and \( \tau_{F,i} = \varepsilon_p^{-1/2} \), respectively. These models are applied to investigate whether the Darcy-scale model can replicate the pore-scale modeling results.

2.6.2. Heat and mass coupled transport (non-isothermal)

The energy balance equations are coupled with the physics of fluid flow and mass transport to create a more realistic scenario. The following equations are used to govern heat transfer in the porous medium:

\[
(\rho C_p)_{\text{eff}} \frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T + \nabla \cdot q = \nabla \cdot (k \nabla T) \tag{2-29}
\]

\[
q = -k_{\text{eff}} \nabla T \tag{2-30}
\]

\[
(\rho C_p)_{\text{eff}} = (1 - \varepsilon_p) \rho_r C_{p_r} + \varepsilon_p \rho_w C_{p_w} \tag{2-31}
\]

\[
k_{\text{eff}} = (1 - \varepsilon_p) k_r + \varepsilon_p k_w \tag{2-32}
\]

where, \((\rho C_p)_{\text{eff}}\) denotes the effective volumetric heat capacity at constant pressure \((J/m^3\,^\circ C)\), \(k_{\text{eff}}\), the effective thermal conductivity of the rock matrix \((J/ms\,^\circ C)\), and \(\rho_w C_{p_w}\), the volumetric heat capacity of the water. The second and the third terms on the left-hand side of the Eq. (2-29) represent heat transfer via convection and conduction, respectively. The initial and boundary conditions are presumed same as whatever applied for the pore-scale approach. Parameters used in the Darcy-scale simulation are listed in Table 2.2.
Table 2.2: Parameters used in the Darcy-scale simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value/Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Thermal conductivity</td>
<td>$k_{\text{eff}}$</td>
<td>1.908 W/(m K)</td>
</tr>
<tr>
<td>Effective Volumetric Heat capacity</td>
<td>$(\rho C_v)_{\text{eff}}$</td>
<td>Function of Temperature (see the appendix)</td>
</tr>
<tr>
<td>Dynamic viscosity</td>
<td>$\mu$</td>
<td></td>
</tr>
<tr>
<td>Porosity</td>
<td>$\varepsilon$</td>
<td>0.431</td>
</tr>
<tr>
<td>Permeability$^4$</td>
<td>$k$</td>
<td>2.73E-12 and 2.84E-8 m$^2$</td>
</tr>
<tr>
<td>Inflow Temperature</td>
<td>$T_{in}$</td>
<td>15 °C</td>
</tr>
<tr>
<td>Initial Temperature</td>
<td>$T_0$</td>
<td>85 °C</td>
</tr>
</tbody>
</table>

2.7. Results and discussion

2.7.1. Pore-scale simulation results

Fully coupled models were simulated at the domain length scales of 1 and 100 mm. A small pressure difference of 0.1 Pa between the inlet and outlet quickly led to a steady-state condition. Due to the Venturi effect, fluid velocity locally increases as the fluid passes through constrictions and evolves to an uneven flow field. The fluid velocity in the preferential paths is higher and rapidly drops to almost zero as the fluid diverts from the preferred paths to locally stagnant regions. The flow patterns of the preferred flow paths for both length scales are identical. Although the flow patterns are identical to both domain length scales because the local velocity gradients define flow paths, the values are different by two orders of magnitude proportional to the scale of the domain, as can be seen in Figure 2.6. In the following discussion of the results, the mass that is dispersed is interpreted as a tracer.

$^4$ Permeability is calculated by employing the pore-scale approach. The values are 2.73E-12 and 2.84E-8 for models with the length scale of 1 and 100 mm, respectively.
Figure 2.7 shows the transport of a tracer (as an example of mass transport) within the pore network for both domain length scales. The RC value of 0.5 measured at the center line B is used as a criterion to define this specific MBT for both length scales. For the model with the domain length scale of 1 mm, it takes about 300 seconds for the tracer to reach RC of 0.5 at B, whereas for the model with the length scale of 100 mm, it takes about 500 seconds. It is important to note that there is a significant difference in the way the tracer is spatially dispersed. For the 1 mm domain length scale, the tracer transport is distributed uniformly across the domain with a flat propagating concentration front, while for the 100 mm scale model, unevenly propagating tracer front with preferential paths can clearly be observed. This difference evidently shows that at the smaller domain scale, the tracer is dispersed by diffusion due to the concentration gradient, and, at the larger scale, mass is dispersed by advection. It is reminded that similar flow patterns do not assume similar mass transport. As shown in Table 2.3, the Reynolds numbers for flows at 1 and 100 mm scales are 1.36E-3 and 1.40 m/s, respectively. In both scales, the flow is extremely slow and laminar.

Figure 2.8 shows how temperature is transported at both domain scales. While the fluid with lower temperature sweeps the rock domain with a higher initial temperature, thermal energy is transported through conduction in the rock matrix, and through both conduction and convection in the pore network. The Relative Temperature (RT) is defined as the ratio of the current temperature to its initial value, and the RT value of 0.5 at B is used to define the Temperature Breakthrough Time. Results in Figure 2.8 indicate that for the model with the length scale of 1 mm, the average temperature at B achieves the criterion in less than 1 second\(^5\) of the cold fluid injection. However, for the model with domain length scales of 100 mm, it takes 471 seconds for

\(^5\) The exact value is 260 milliseconds
the RT to reach the value of 0.5 at B. It is noted that for the smaller geometry, heat is transported uniformly across the model with a straight temperature propagation front, while, for the larger geometry, an uneven heat front can clearly be observed. This difference can also be explained based on Eq. (2-14). In the case with the length scale of 100 mm, the energy transported by the fluid motion is dominant, whereas in the case with 1 mm scale length, the dominant heat transport mechanism is conduction.

Figure 2.6: Velocity field in thermally-shocked regions. 1 mm and 100 mm domain length scale models are shown on the left and right, respectively. There is a two order of magnitude difference in the velocity.
Figure 2.7: Relative Concentration (RC) of the tracer within each scale domain. For the model with the length scale of 1 mm (a), it takes 306 seconds for the tracer to reach the relative concentration of 0.5 at the center line B, whereas for the model with the length scales of 100 mm (b), it takes 500 seconds.

Figure 2.8: Relative Temperature (RT) within the computational domain. For the model with the length scale of 1 mm (a) it takes 0.26 seconds for the heat to reach the relative temperature of 0.5 at the center of the domain, whereas for the model with the length scale of 100 mm (b) it takes 471 seconds.
Table 2.3 summarizes which mechanisms are dominant for heat and mass transport at each domain scale. It is noted that the small Reynolds numbers indicate that the flow remains laminar at all scales, and furthermore for the domain length scale up to a few millimeters, the given pore structure produces a Stokes flow with creeping motion. The Reynolds number defines the relative influence between the inertial and viscous resistance on flow behavior. The Péclet number \((Pe)\) was also calculated to define the ratio of the rate of advection of a physical quantity by the flow to the rate of diffusion of the same quantity driven by an appropriate gradient. In the context of mass transfer, the Péclet number is calculated as the product of the Reynolds number and the Schmidt number. In the context of heat transfer, the Péclet number is equivalent to the product of the Reynolds number and the Prandtl number. As can be seen in Figure 2.10, mass transfer is dominated by diffusion for the length scale of 1 mm but as the length scale increases, mass transfer due to advection quickly becomes more dominant. On the other hand, heat transfer remains diffusion dominated up to the scale of 10 mm, whereas advection and diffusion are equally important for the length scales between 10 and 30 mm, and beyond the length scale of 50 mm, heat transfer will be dominated by advection (Figure 2.10). In summary, for the flow considered here at different domain length scales, advection has a greater influence on how mass is transported for length scales for a few millimeters or greater. However, the way heat is transported goes through three different combinations of mechanisms, and they are: diffusion up to around 10 mm, advection-diffusion between 10 and 30 mm, and advection greater than 50 mm of domain length scales.
Figure 2.9: Relative Temperature (RT) within for the model with the length scale of 1, 5, 10, 50, 100, and 500 mm

Figure 2.10: Relative Concentration (RC) of the mass (tracer) for the model with the length scale of 1, 5, 10, 50, 100, and 500 mm
Table 2.3: the average velocity, Reynolds Number, and Peclet Number of different length scales

<table>
<thead>
<tr>
<th>Length Scale ( l ) (mm)</th>
<th>Average Velocity ( \bar{u} ) (m/s)</th>
<th>Reynolds Number ( Re )</th>
<th>Péclet number ( (Pe) )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Form mass</td>
</tr>
<tr>
<td>1</td>
<td>7.53E-07</td>
<td>1.36E-03</td>
<td>0.75275</td>
</tr>
<tr>
<td>2</td>
<td>1.51E-06</td>
<td>5.44E-03</td>
<td>3.0108</td>
</tr>
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<td>3</td>
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<tr>
<td>5</td>
<td>3.76E-06</td>
<td>3.40E-02</td>
<td>18.82</td>
</tr>
<tr>
<td>10</td>
<td>7.53E-06</td>
<td>1.36E-01</td>
<td>75.324</td>
</tr>
<tr>
<td>20</td>
<td>1.50E-05</td>
<td>5.43E-01</td>
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<td>30</td>
<td>2.33E-05</td>
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<td>700.44</td>
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<tr>
<td>50</td>
<td>3.84E-05</td>
<td>3.47E+00</td>
<td>1922.25</td>
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<tr>
<td>100</td>
<td>7.72E-05</td>
<td>1.40E+01</td>
<td>7720.9</td>
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<tr>
<td>500</td>
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2.7.1.1. Thermal versus Mass Breakthrough Time

Quantitative criteria to assess EGS reservoir performance are divided into two groups, and they are the criteria that could be used to judge the hydraulic performance and those that evaluate the thermal performance of the EGS reservoir. Mass Breakthrough Time (MBT) and Thermal Breakthrough Time (TBT) are usually used to identify the distribution of fluid residence times within the reservoir and temperature decline in the recovery as a function of time. Specific cases of MBT and TBT have always been used in the previous sections of this paper.

As mentioned, the scheme of the thermally-shocked region and its transport properties can affect overall reservoir performance. Comparing MBT and TBT for both cases at different length scales can give a better understanding of the transport mechanism within this region and its effect on overall EGS performance.
Figure 2.11 shows the mass and heat breakthrough times at the outlet for the length scales of 1 and 100 mm. Results show that for the case with the length scale of 1 mm (Figure 2.11a), heat transport is much faster than mass transport. For example, it takes 193 seconds for the mass to reach RC of 0.1 at the outlet; however, for the heat, it takes less than one second to reach a RT of 0.9 at the outlet. For both cases, the time for the 10% of the original amount of mass (racer) or temperature to reach at the outlet was measured. Three orders of magnitude difference in breakthrough times of heat and mass indicate the critical role of diffusion at the model with the length scale of 1 mm. For the case with the length scale of 100 mm, the mass transports faster than the heat; however, both heat and mass transport mostly at the same rate (Figure 2.11b). For example, it takes 529 seconds for mass to reach the RC of 0.1 at the outlet of the model. The time for the RT of 0.9 at the outlet is about 844 seconds. Unlike the smaller case, the role of advection is pronounced in the model with the length scale of 100 mm and breakthrough times of heat and mass are in the same order of magnitude.

Figure 2.11: Relative Concentration (RC) of the mass and Relative Temperature (RT) of the fluid at the outlet as a function of time: model with the length scale of 1 mm (a), model with the length scale of 100 mm (b)
2.7.2. Darcy-scale simulation results

This section presents the results of the Darcy-scale simulation. The fluid flow and transport processes of models with the length scales of 1 and 100 mm are analyzed and results are compared with the pore-scale results. The same four reference lines across the models are considered for comparison (see Figure 2.5), and the average values of the mass concentration and temperature at these lines are calculated. Table 2.4 presents the given acronyms for the isothermal coupling simulation.

The cases labeled as ISC1D and the ISC100D represent isothermal cases solved by utilizing the direct pore-scale simulation for the length scales of 1 and 100 mm, respectively. Other cases denote models solved by utilizing the Darcy-scale simulation. In Eq. (2-28), the porosity is assigned a value of $\varepsilon_p = 0.43$ (This value is calculated from the pore-scale model). Applying the porosity, the ratio of the effective diffusion coefficient to the molecular diffusion coefficient for the Millington-Qurik and the Bruggeman models would be 32 and 28%, respectively. The $D_e/D_F$ ratio for the Tortuosity model is also assumed to be 24%.

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Figure 2.12 shows the RC value at the reference lines versus time for the model with the length scale of 1 mm. In all cases, after an initial rapid increase followed by a moderate monotonic increase in the Relative Concentration, the RC values become 1 indicating the saturation of the
field. As shown in Figure 9, at any given time, the RC values at reference lines A, B, C, and D are in ascending order. The blunt propagating front of the mass indicates that the mass within the model with the length scale of 1 mm transports mainly by diffusion. Figure 2.7a can provide a visual confirmation of this interpretation. The spacing between the RC curves illustrates how the mass is distributed within the domain. The closer the RC curves, the more homogeneously the mass is distributed within the domain. It is evident from Figure 2.12a that, in the ISC1N case, the domain is saturated with the transported mass much faster than the ISC1D case does. This result indicates that adoption of the molecular diffusion coefficient for the Darcy-scale model, such as the case of ISC1N, fails to replicate the results of the pore-scale simulation.

The results obtained from the ISC1MQ and the ISC1B cases showed a partial agreement with the ISC1D case (Figure 2.12b and Figure 2.12c) while the ISC1T case captures almost the same transport behavior governed by the pore-scale simulation (Figure 2.12d). To better illustrate the discrepancies between the direct pore-scale and the Darcy-scale results, the Mass Breakthrough Time (MBT) at the outlet for the RC of 0.1 is calculated. As seen in Figure 2.13, although the MBT is 208 seconds for the direct pore-scale model, this value is considerably lower for all continuum cases except the ISC1T case. The MBT for ISC1D and ISC1T cases is very close, and this may present an opportunity for the tortuosity model to similarly represent the transport behavior of the ISC1D case.
Figure 2.12: Relative Concentration (RC) at the reference lines of A, B, C, and D over time for the isothermal model with the length scale of 1 mm. The RC curves at the reference lines for the pore-scale models (solid curves) are compared with the Darcy-scale models (dashed curves); direct versus the continuum model with no correction (a), direct versus the Millington-Qurik (b), direct versus the Bruggeman (c), and direct versus the Tortuosity model (d).
The RC value at the reference lines versus time for the isothermal model with the length scale of 100 mm is shown in Figure 2.14. A crossover of the RC curves of the ISC100D case at reference lines A and B illustrates that the fluid motion dictates the mass transport, and the mass is distributed unevenly within the domain. Furthermore, unlike cases with the length scale of 1 mm, none of the Darcy-scale models can duplicate the RC curves of the ISC100D case. One can explain this difference based on Eq. (2-26). As discussed earlier, for the model with the length scale of 100 mm, the role of diffusion in mass transport is insignificant. Therefore, the attempt to modify the diffusion coefficient to replicate the behavior of the ISC100D case is ineffective. As seen in Figure 2.14 the RC curves for all Darcy-scale models are identical, and they go from the value of zero to the value of one, almost instantaneously. This behavior is equivalent to the case of pure advection, where all of the mass reaches the particular distance at the same time.

Figure 2.13: The Mass Breakthrough Time (MBT) at the outlet for the non-isothermal model with the length scale of 1 mm. The MBT at the RC of 0.1 for the pore-scale model is compared with the Darcy-scale simulations.
Table 2.5 presents the given acronyms for the non-isothermal coupling simulation. The cases labeled NISC1D and NISC100D represent non-isothermal cases solved by utilizing direct pore-scale simulation for the length scales of 1 and 100 mm, respectively. Other cases denote models solved by utilizing the Darcy-scale simulation. Figure 2.15 and Figure 2.16 show that for the non-isothermal cases, unlike isothermal simulations, none of the Darcy-scale models can replicate the RC graphs of the pore-scale simulation. Interpreting the discrepancy between the results of the pore-scale and the Darcy-scale simulation of fully coupled non-isothermal cases needs more investigation. One can interpret that since the properties of the carrying fluid are assumed to be temperature dependent, adding the energy balance equation to the sets of equations could lead to variation in the results.

Figure 2.14: Relative Concentration (RC) at the defined probe lines of A, B, C, and D over time for the isothermal model with the length scale of 100 mm. The RC curves at the reference lines for the direct pore-scale case (solid curves) are compared with the Darcy-scale cases (dashed curves).
Table 2.5: The case acronyms for the non-isothermal coupling simulation

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Figure 2.15: Relative Concentration (RC) at the defined probe lines of A, B, C, and D over time for the non-isothermal model with the length scale of 1 mm. The RC curves at the probe lines for the pore-scale approach case (solid curves) are compared with the Darcy-scale models (dashed curves); direct versus the continuum model with no correction (a), direct versus the Millington-Qurik (b), direct versus the Bruggeman (c), and direct versus the Tortuosity model (d).
The non-dimensional temperature, defined as $\hat{T} = \frac{(T - T_{\text{initial}})}{(T_{\text{inlet}} - T_{\text{initial}})}$ at A, B, C and D reference lines is calculated for both length scales of 1 and 100 mm. As seen in Figure 2.17, in all instances, after an initial sharp decline in temperature, the rate of decreasing drops and finally the temperature graphs for all reference lines merge to the temperature of the injecting fluid. As shown in Figure 2.17a, for the case with the length scale of 1 mm, although the Darcy-scale approach could replicate the same heat transport behavior, the temperature decline is faster for the Darcy-scale modeling. Results show that for the pore-scale case, the average temperature of the domain drops to the injection temperature after 5 seconds of cold fluid injection. However, for the Darcy-scale models, it takes less than 3 seconds for $\hat{T}$ to reach zero within the entire domain. For the case with the length scale of 100 mm (Figure 2.17b) the result obtained from the Darcy-scale model shows a notable agreement with the direct pore-scale case.
Conclusion and recommendation

The mechanisms of the heat and mass transport within a thermally-shocked region of an EGS reservoir were studied. In this numerical study, the thermally-shocked region adjacent to the primary hydraulic fractures was assumed to be a porous medium. A pore-scale simulation approach was considered to study its applicability and limitations in capturing coupled transport physics of heat and mass. For the pore-scale modeling, mass and heat transfer at two domain length scales of 1 and 100 mm were considered to represent a thermally-shocked region with two different degrees of fragmentation or fracture coalescence. Using the COMSOL platform, contributing physical laws were sequentially coupled to capture multiphysics features of the problems. The results showed that for the severely-thermally-shocked region represented by the domain length scale of 1 mm, diffusion is responsible for both heat and mass transfer. The TBT was found to be three orders of magnitude faster than the MBT. The ratio of thermal diffusivity to molecular diffusivity was also found to be $10^3$ for this model. One can interpret this to mean that this ratio can determine the relationship between heat and mass transfer in a diffusion-dominated small system where the flow speed is insignificant. The pore-scale simulation results also indicated that

Figure 2.17: The non-dimensional temperature, at A, B, C and D reference lines for both length scales of 1 mm (a) and 100 mm (b).
for a moderately-thermally-shocked region represented by the domain length scale of 100 mm, mass transfer is mainly accomplished by advection, but heat is transferred via both fluid motion and conduction. Thermal and mass breakthrough times were found to be in the same orders of magnitude.

Although a much-simplified model and its results have been presented in this study, the results of pore-scale analyses confirmed that the transport behavior of the thermally-shocked region of an EGS would strongly depend on the degree of fragmentation of this region. In actual field cases, one can identify the following appropriate regions of EGS reservoir where the presented pore-scale analysis may be beneficial:

- **Near the injection point of water:** This is where an intense cooling on the surface of the primary hydraulic fracture produces a thin thermally-shocked region with a high degree of fragmentation.
- **Near the production point of hot water:** This is where the cooling effect becomes less intense, and the adjacent thermally-shocked region is less fragmented.
- **Early stage of EGS fluid circulation:** This is when the thermal front advances very rapidly along the primary hydraulic fracture and isotherms in the rock matrix are parallel to the main hydraulic fracture.
- **Later stage of EGS fluid circulation:** This is when the cold front penetrates more into the rock matrix and isotherms in the rock matrix become perpendicular to the main hydraulic fracture.

Differences in the transport behavior in the thermally-shocked region due to the variation in its fragmentation degree may cause temporally and spatially sensitive behavior in the reservoir as speculated above. The exact fragmented geometry of the inside of an EGS reservoir will never be
known, but it seems there may be plenty of temporal and spatial fluctuations based on how heat and mass are transported in the EGS circulation system.

The ability of the Darcy-scale simulation approach to model transport behavior of the thermally-shocked region has also been assessed. The results of the Darcy-scale simulation for severely- and moderately-thermally-shocked regions are summarized as follows:

- **Severely-thermally-shocked region**

The isothermal coupling of the Darcy-scale simulation captured almost the same mass transport governed by the direct pore-scale simulation method. However, for the full non-isothermal coupling, the Darcy-scale failed to replicate what the direct pore-scale simulation provided. For the heat transport, although the Darcy-scale simulation captured a similar spatial distribution of the temperature, the Darcy-scale led to earlier depletion of the energy content of the domain.

- **moderately-thermally-shocked region**

Unlike cases with the length scale of 1 mm, neither the isothermal nor the non-isothermal form of the Darcy-scale captured the same mass transport governed by the pore-scale simulation method. However, the Darcy-scale simulation captures the exact same heat transport governed by the pore-scale approach.

The comparison between the pore-scale and the Darcy-scale simulation showed that the ability of the Darcy-scale representation to replicate the pore-scale results depends on both the contributing physical processes and the length scale of the models. Figure 2.18 illustrates the status of the agreement between the mass transport governed by the direct pore-scale and the continuum Darcy-scale simulation approaches. For example, for the advection-dominated system—cases with
the length scale of 100 mm—making an agreement between the pore-scale and the Darcy-scale method by just modifying the coefficient of diffusion is not feasible.

![Diagram showing the status of the agreement between the mass transports governed by the pore-scale and the Darcy-scale simulation approaches.](image)

**Figure 2.18:** Status of the agreement between the mass transports governed by the pore-scale and the Darcy-scale simulation approaches. Isothermal coupling for the model with the length scale of 1 mm (a) and 100 mm (b). Non-isothermal coupling for the model with the length scale of 1 mm (c) and 100 mm (d).

### 2.9. Appendix A: Numerical model description

The computational domain in COMSOL Multiphysics was created in 2D space. In the pore-scale approach, the geometry is discretized explicitly for both pore network and solid phases. The pore network was assumed to be fully saturated with water and the granite with predefined properties was designated as the solid domain. The properties of the assigned fluid, such as heat capacity, density, and thermal conductivity were assumed to be temperature dependent (Figure 2.19) while the properties of the solid phases were considered constant. The values of the basic
properties of the solid phases are \( \rho_r = 2600 \text{ kg/m}^3 \), \( C_{pr} = 850 \text{ J/(kg °C)} \), and \( k_r = 2.9 \text{ W/(m °C)} \). An unstructured triangular mesh was created for both solid and pore-network domains. The mesh is adequately sized and is refined at the region adjacent to the inlet where both the species and temperature gradients are higher. The element size of the pore network and solids is calibrated according to the contributing physics, and the average element quality of the mesh for both 1 and 100 mm models is computed higher than 0.94. The porosity of the generated domain is calculated through dividing the integration of the pore-network region by the length and width of the structure:

\[
\varepsilon_p = \frac{1}{L_1 L_2} \int_0^{L_1} \int_0^{L_2} 1 \, dx \, dy.
\]

where, \( L_1 \) and \( L_2 \) denote dimensions of the computational domain in x and y directions. The porosity results in a value of 0.431.

As mentioned, to avoid high numerical dispersion, a gradual profile was given to express the initial condition for both the physics of heat and mass transport (Figure 2.20). The initial mass concentration everywhere in the domain is zero except in the vicinity of the inlet where the concentration is equal to the inlet concentration. The initial temperature was also assumed to be 85° C everywhere, except adjacent to the inlet where the temperature is assigned to be the same as the inlet temperature.

In the Darcy-scale approach, a structured quadrilateral mesh was selected to discretize the domain. Unlike the pore-scale modeling, each point of the continuum domain contains both fluid and grains in the average sense. Hence, the effective properties of the computational domain must be computed by accounting for both matrix and fluid properties. The volume average method was selected to compute the effective conductivity of the Darcy-scale models Eq. (2-32). The
permeability of both models is calculated by employing the pore-scale approach and results in values of 2.73E-12 and 2.84E-8 for models with the length scale of 1 and 100 mm, respectively. These values were employed for the Darcy-scale modeling.

Figure 2.19: Properties of the fluid as a function of temperature. (a) Dynamic viscosity (blue curve) and thermal conductivity (red curve). (b) Heat capacity at constant pressure (blue curve) and density (red curve).

Figure 2.20: the initial condition for both physics of mass and heat transport
2.10. References


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CHAPTER 3

A HYBRID APPROACH FOR AN EFFICIENT NUMERICAL MODELING OF THE THERMO-HYDRO PROCESSES WITHIN THE EGS RESERVOIR

Modified from a paper published and presented at 42nd Stanford Geothermal Workshop

Kamran Jahan Bakhsh, Masami Nakagawa

3.1. Abstract

An innovative computational approach to capturing the essential aspects of an Enhanced Geothermal System (EGS) is formulated. The modified finite element method is utilized to model transient heat and fluid flow within an EGS reservoir. Three main features are modified to determine their impact on the reservoir performance: the fracture model, the porous model, and the coupling of the physical models. For the first feature, the fractures are modeled as a two-dimensional subdomain embedded in a vast three-dimensional rock mass. The fracture model eliminates the need to create slender fractures with a high aspect ratio by allowing reduction of the spatial discretization of the fractures from three- to two-dimensional finite elements. In this model, pseudo three-dimensional equations are adopted to drive the physics of heat and fluid flow in the fractures. In the second feature, a porous subdomain with effective transport properties is modeled to integrate a thermally-shocked region in the reservoir simulation. In the third feature, three-dimensional heat flow in the rock mass is coupled to the two-dimensional heat and fluid flow in the fractures. Numerical examples are shown to illustrate the computational capability of the proposed hybrid model to simulate heat and fluid flow in an EGS. Results show that the proposed hybrid model is capable of both effectively integrating thermal fractures into reservoir simulation,

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as well as efficiently tackling the computational burden exerted by high aspect ratio geometries. A parametric sensitivity analysis is also performed in which the effect of thermal fractures and thermally-shocked region on reservoir performance is evaluated.

3.2. Introduction

The rapid increase in energy demand to meet social and economic development, in conjunction with the call for climate change mitigation requires the transition of the world’s energy supply to Renewable Energy (RE) sources. Wind, solar and geothermal are all clean renewable energy sources that have a great potential for electricity generation with a low-carbon footprint. Despite the fact that the wind and solar are the fastest-growing renewable energy sources (Sawin et al. 2016; Shankleman 2016), their electricity output is variable and, to some degree, unpredictable (Skea et al. 2008; Edenhofer et al. 2011). Geothermal energy, the heat from the Earth’s crust, is a suitable option for supplying constant base-load power and a promising alternative for fossil fuel-based power plants. According to the World Energy Council survey (2013), the total heat content of the crust of the Earth is around $540 \times 10^7$ EJ. Just 1% of that heat could supply the world’s current energy demand for 2800 years (Olasolo et al. 2016). However, current geothermal power capacity is about 13.3 GW worldwide (Matek 2016).

The current electricity generation from geothermal resources is limited to shallow-depth conventional hydrothermal reservoirs. These resources are relegated to a small portion of the total accessible geothermal energy, predominantly in volcanic regions with abundant groundwater (Tester et al. 2007). Moreover, similar to oil and gas reservoirs, they can only be exploited until the contained fluid has been extracted (Olasolo et al. 2016).
A major fraction of the accessible geothermal energy is located at considerable depth where the abundant heat is stored within low-permeability Hot Dry Rock (HDR). The idea of extracting heat from HDR reservoirs is relatively new, proposed for the first time during the first oil crisis in the early 1970s. A group of US scientists at Los Alamos National Laboratory conducted a field-scale experiment with the aim of developing a technique for harvesting heat from the HDR to generate electricity. The concept of an Enhanced/Engineered Geothermal System (EGS) has since then been developed, and several projects have moved the EGS technology forward to the point where energy extraction from the HDR is ever closer to being technologically feasible. The EGS technology has attracted broad attention worldwide, and according to the reports published by the GEA\(^7\) and IGA\(^8\), the number of countries generating geothermal power is increasing significantly (Holm et al. 2010), e.g., the US DOE recognized the first grid-connected commercial EGS success in Desert Peak Nevada in 2013.

The initial concept of EGS to create a man-made reservoir with a sustained rate of heat extraction and long life was straightforward: drill a well into the HDR, create multiple heat exchange surfaces by hydraulically fracturing the rock, and ultimately drill the production well to intercept the generated fractures. By circulating water down one well, through the stimulated fractures, and up the other well, heat can be carried off from the hot rock to the surface. The initial concept of EGS and all later redefined concepts instigated a base for understanding of the flow and transport processes in such a system and for mathematically modeling thermo-hydro processes within the EGS reservoir.

\(^7\) US Geothermal Energy Association \\
\(^8\) International Geothermal Association
Since the 1960s, several studies have been conducted to understand the mechanisms of subsurface flow and transport processes in the fractured rock system and accordingly different flow models have been developed to handle fracture-matrix interaction. The Effective Continuum methods (ECM), Multiple Interacting Continua (MINC), explicit discrete-fracture approach, and Discrete Fracture Network (DFN) are commonly used in hydrogeology, petroleum and geothermal for simulating flow and transport processes (Bear et al. 1993).

The ECM flow model is the simplest conceptual model to approximate the flow and transport processes within the fractured media. This flow model describes fractured rock by merging the fracture network and the matrix into a single continuum with a set of effective properties. Several types of ECM methods have been developed and widely used due to their simplicity in terms of data requirements and computational efficiency (e.g., Pruess et al. 1988; Nitao 1989; Berkowitz et al. 1988; Kool & Wu 1991; Wu et al. 1996). Wu (1999) introduced a rigorous, generalized ECM approximation to evaluate the applicability of this method under certain conditions by implementing the proposed formulation into the TOUGH2 code.

The MINC approach covers a variety of flow models (e.g., classic double-porosity and dual-permeability models). The double-porosity model was introduced half a century ago first by Barenblatt et al., (1960) and Warren & Root (1963). In this model, by assuming the formation to be homogenous, the fractured rock is divided into two subdomains of isolated porous blocks of low-permeability (matrix blocks), and a network of interconnected high-permeability medium (fracture network). In this model, it is assumed that global flow and transport processes only occur within the fracture network, and the flow regime is in quasi-steady state. The double-porosity model can handle fracture-matrix interaction by assigning the matrix blocks as sinks or sources to
the fracture network (Warren & Root 1963), and it is adequate for modeling slightly fractured systems where the fracture network is the main conduit for the flow.

The double-porosity was later extended by incorporating inter-block matrix-matrix interaction and the dual-permeability model was proposed first by Blaskovich et al., (1983) and Hill & Thomas (1985). In contrast with double-porosity, in the dual-permeability model the matrix blocks are no longer insulated and flow occurs within both the matrix and the fracture network. The dual-permeability model, as a generalized form of the double-porosity approximation, is capable of simulating a wide range of problems from slightly- to highly-fractured systems.

Besides the double-porosity and dual-permeability models, which are the most commonly used mathematical models for the practical simulation of fractured systems, several other modified forms of the MINC methods have been developed and proposed for better approximation of the flow and transport processes (Kazemi 1969; Pruess & Narasimhan 1985; Wu & Pruess 1988; Kazemi et al. 1992; Pruess 1991). For example Wu et.al, (2004) developed a triple-continuum model consisting of a rock matrix, large-fracture and small-fracture continuua. In contrast with dual-continuum models (e.g. double-porosity, dual-permeability), the Wu’s triple-continuum model adds an additional continuum to the system in order to incorporate small-scale fractures in the modeling procedure. In sum, as the MINC methods are computationally inexpensive and do not require a detailed knowledge of fractures and matrix geometric properties, they are the most widely used flow models to describe flow and mass transport within the fractured reservoirs.

In an attempt to develop a more realistic flow model, the explicit discrete-fracture approach has been developed and utilized for dealing with fracture-matrix interactions (e.g., Snow 1965; Stothoff & Or 2000). In this model, the fractures are incorporated as explicit discrete elements,
and fluxes between the rock matrix and fractures are allowed. Although the explicit discrete-fracture approach requires detailed information on all fractures embedded in the matrix (e.g., location, geometric properties, hydraulic properties), this model can provide meaningful results when modeling fault zones or domains with few planar fractures (Bundschuh & Suárez Arriaga 2010).

The DFM approach as an alternative approach to the continuum method was first introduced in the late 1970s. In this approach, each fracture is treated as a continuous medium surrounded by an impervious rock matrix. In contrast to the explicit discrete-fracture method, the fluid flow in DFM is restricted to the fractures. Several DFM methods have since been developed (Snow 1965; Sudicky & McLaren 1998; Baca et al. 1984; Juanes et al. 2002; Sarda et al. 2002; Karimi-Fard et al. 2004). The DFM methods allow for more realistic modeling of the fractured rock than the continuum methods; however, they require detailed knowledge of fracture and matrix geometric properties. Despite the recent advances in characterization methodology and numerical simulation, the use of DFMs for field scale problems is computationally challenging. There are innovative approaches to reduce the need for highly resolved data by simplifying the fracture network; e.g., fractures can be approximated by line (1D medium) or by plane (2D medium) in two- and three-dimensional models respectively (Bundschuh & Suárez Arriaga 2010).

All the above-mentioned approaches can be adopted for modeling thermo-hydro processes within the EGS reservoir; however, the question remains which method is the best fit for the EGS? The objectives of the modeling, availability of the field data, and the scale of the system (i.e., spatially and temporally) are essential factors to select the appropriate flow model. Since the mathematical model of the flow and transport processes is based on the conceptual model, in
complex systems such as an EGS, developing a conceptual model that can properly incorporate the geometrical details of the system is an essential factor and must be considered.

In the initial concept of EGS model, it is assumed that the flow and heat exchange occur only within the hydraulic fractures. Moreover, incorporated geometric properties of the system are assumed static. By adopting the initial concept of the EGS and by assuming that all information on hydraulic fractures is available (e.g., location, geometric properties, hydraulic properties), the explicit discrete-fracture approach can be applied to assess the long-term thermo-hydro processes of the idealized commercial-sized EGS.

It is well known that the EGS is a dynamic system and that the geometrical properties of the system are altering as heat extraction takes place. Indeed, circulating cold fluid through the stimulated region induces a temperature gradient within the rock matrix, resulting in thermo-elastic stresses that propagate thermal fractures. Extensive studies from simple laboratory-scale to field-scale modeling have been conducted to analyze thermal fracture development within rock subjected to the thermal stresses (e.g., Chen & Marovelli 1966; Finnie et al. 1979; Barr 1980; Perkins & Gonzalez 1985; Ghassemi et al. 2005; Mossop 2001; Chun 2013).

In an EGS reservoir, initially, when the induced temperature gradient is of high severity, a thermally-shocked region comprising of a network of small, disorganized closely-spaced thermal cracks are formed adjacent to the hydraulic fractures. As time elapses, these small thermal cracks tend to coalesce and better-defined planar thermal fractures propagate into the rock matrix. Although thermally-induced fractures (in the form of both small thermal cracks within thermally-shocked region and better-defined planar thermal fractures) may not contribute much to the global flow and transport processes, they may provide additional conduits for interflow between hydraulic
fractures and the rock matrix, which eventually affects fracture-matrix interactions and ultimately the reservoir performance.

Since the initial concept of an EGS does not physically incorporate thermally-induced fractures, the corresponding flow and transport model is unable to capture the effects of thermally-induced fractures. By adopting the modified concept of the EGS, a flow and transport model can be described by utilizing a multi-subdomain flow model; one subdomain comprising the hydraulic fractures, one subdomain with a network of numerous smaller thermal cracks (thermally-shocked region), and one subdomain comprising the planar thermal fractures. For the first and last of the aforementioned subdomains, the explicit discrete-fracture model can be utilized. However, for the middle, the continuum medium approach can be used by treating the numerous smaller thermal cracks as a porous medium.

The main objectives of this study are (1) to formulate flow and heat transport process within EGS based on both the initial and the modified concept of EGS; (2) to propose an efficient computational model capable of integrating thermally-induced fractures into simulation; and (3) to demonstrate the effect of thermally-induced fractures in EGS performance. In particular, parametric examples are developed to investigate the effects of different parameters of the thermally-induced fractures including number, width, length and permeability on flow and heat transfer in the EGS reservoir.

3.3. The initial concept of the EGS

The physical model of the EGS based on the initial concept is divided into two subdomains: the rock matrix, representing an abundant heat source, and a set of parallel equally spaced hydraulic fractures, representing the flow paths for carrying heat to the surface (see Figure 3.1).
The geometries of the fractures are assumed to be identical, thin-cylindrical fractures of radius $R$ and uniform aperture $d_{hf}$. It is also assumed that each fracture receives the same mass flow rate.

Figure 3.1: Schematic of the initial concept of the EGS

### 3.3.1. Mathematical formulation

To model the thermo-hydro processes within the EGS reservoir mathematically, a set of governing equations consisting of fluid flow and heat transfer equations must be coupled. Besides the assumptions mentioned above, the following are additional assumptions:

i. The rock matrix is assumed to be non-deformable, homogeneous, isotropic, and devoid of preexisting/natural fractures. Since the target area of the EGS technology is a deep intact crystalline basement rock, the properties of intact granite (e.g., low porosity and low permeability) are used to define the rock matrix.

ii. Initially, the temperature is $T_\infty$ everywhere in the system. However, at $t = 0$, cold fluid with the constant temperature of $T_{in}$ is injected into the reservoir.
iii. The fluid, i.e., water, which plays the role of an energy carrier, is assumed to be a single-phase flow within the reservoir.

iv. Non-linearity in the properties of the materials is not allowed, i.e., the density, heat capacity, and thermal conductivity of the fracture fluid and the rock matrix are assumed to be constant and the gravitational effects are neglected.

Due to the symmetry in the $x$ and $y$ directions, half of a single fracture surrounded by two blocks of the rock matrix of width $D$ is used for simulation (Figure 3.2).

![Figure 3.2: Schematic of model domain used in the numerical simulation](image)

3.3.1.1. Fluid flow in reservoir

In general, the conservation of mass and momentum of fluid are as follows:

$$\frac{\partial}{\partial t}(\rho_f) + \nabla \cdot (\rho_f \mathbf{u}) = 0$$

(3-1)
In a deep EGS reservoir, the aspect ratio of radius to aperture of a hydraulically-induced fracture is on the order of 1000 to 10000 (Armstead & Tester 1987). Accordingly, the fluid velocity across the fracture, in the \( x \) direction, can be assumed constant. Following this simplification and by assuming that the fluid is incompressible, the conservation of mass of the fracture fluid Eq. (3-1) can be rewritten as:

\[
\frac{\partial u_x}{\partial t} + \frac{\partial (u_x u_x)}{\partial x} + \frac{\partial (u_x u_y)}{\partial y} + \frac{\partial (u_x u_z)}{\partial z} = -\frac{\partial P}{\partial x} + \mu \left( \frac{\partial^2 u_x}{\partial x^2} + \frac{\partial^2 u_x}{\partial y^2} + \frac{\partial^2 u_x}{\partial z^2} \right) \tag{3-2}
\]

\[
\frac{\partial u_y}{\partial t} + \frac{\partial (u_y u_x)}{\partial x} + \frac{\partial (u_y u_y)}{\partial y} + \frac{\partial (u_y u_z)}{\partial z} = -\frac{\partial P}{\partial y} + \mu \left( \frac{\partial^2 u_y}{\partial x^2} + \frac{\partial^2 u_y}{\partial y^2} + \frac{\partial^2 u_y}{\partial z^2} \right) \tag{3-3}
\]

\[
\frac{\partial u_z}{\partial t} + \frac{\partial (u_z u_x)}{\partial x} + \frac{\partial (u_z u_y)}{\partial y} + \frac{\partial (u_z u_z)}{\partial z} = -\frac{\partial P}{\partial Z} + \mu \left( \frac{\partial^2 u_z}{\partial x^2} + \frac{\partial^2 u_z}{\partial y^2} + \frac{\partial^2 u_z}{\partial z^2} \right) \tag{3-4}
\]

The Reynolds number can be assessed to characterize flow regime within the fracture as shown below:

\[
Re = \frac{\bar{u} D_H}{\nu} \tag{3-6}
\]

where, \( \bar{u} \) is the mean velocity of the fluid (m/s), \( D_H \) is the hydraulic diameter of the fracture (m), and \( \nu \) is the kinematic viscosity (m\(^2\)/s). For our case,

\[
D_H = \frac{(d_{hf} \times r)}{2(d_{hf} + r)} \sim \frac{10^{-3} \times 10^{-3}}{10^{-3}} \sim 10^{-3}
\]

\[
\bar{u} \sim 10^{-2} \tag{3-8}
\]

\[
\nu = \frac{\mu}{\rho_f} \sim \frac{10^{-4}}{10^3} \sim 10^{-7} \tag{3-9}
\]
The calculated Reynolds number is sufficiently low to indicate that the flow in the fracture is in the laminar regime. Therefore it is reasonable to utilize two-dimensional Darcy’s law to govern the fluid momentum:

\[ -\frac{\partial p}{\partial y} = \frac{\mu}{\kappa_{hf}} u_y \]
\[ -\frac{\partial p}{\partial z} = \frac{\mu}{\kappa_{hf}} u_z \]

Initially the fluid velocity everywhere in the fracture subdomain is

\[ \mathbf{u}(x, y, z, 0) = 0 \]

For both the injection and recovery wells, flow rate of \( M_t \) (kg/s) is considered, and therefore, the mass flow rate of fluid in each fracture is

\[ m_{hf} = \frac{M_t}{N_{hf}} \]

where, \( N_{hf} \), is the number of fractures. Accordingly, at the boundary 5 (Figure 3.2),

\[ |\mathbf{u}| = 0.5 \frac{m_{hf}}{(2\pi r_l)} \]

The factor 0.5 on the left-hand side of Eq. (3-15) accounts for the fact that half of the fracture is simulated due to the symmetry in the \( y \) direction. It is also assumed that \( M_t \) (kg/s) is produced from the reservoir with no fluid loss in the reservoir.

3.3.1.2. Heat exchange in the reservoir

Heat transfer within the EGS reservoir is the combination of heat transfer in the rock matrix and in the hydraulic fracture. The fluid and rock matrix play the role of energy carrier and heat source respectively. Heat flow within the low-permeability rock matrix is merely via conduction.
Therefore, the macroscopic energy balance equation for the rock matrix can be described, using Fourier’s law as follows:

$$\frac{\partial}{\partial t} (\rho_r C_{p_r} T_r) - \nabla \cdot (k_r \nabla T_r) = 0$$

(3-16)

It is assumed that the only heat source of the rock matrix is the geothermal gradient of the Earth; therefore, the initial condition could be as follows:

$$T_r(x, y, z, 0) = T_\infty$$

(3-17)

where,

$$T_\infty = T_s + \mathcal{G} \cdot z$$

(3-18)

where, $\mathcal{G}$ is the geothermal gradient (°C/km). It is assumed that the fractures are thermally non-interacting, and heat stored within the rock matrix is the only energy source that fracture fluid can take away from the rock. Following this assumption, the symmetry boundary condition at surfaces 1, 2, 3, and no-flux boundary condition at surface 4 are applied (Figure 2).

$$-n \cdot \nabla T_r = 0$$

(3-19)

Heat can flux from the rock matrix into the fracture flow from two faces of the fracture as shown below:

$$q = -2 \times \left[ \frac{\partial T_r(0, y, z, t)}{\partial x} \right]$$

(3-20)

Eq. (3-20) provides the heat source for the energy balance equation of the fracture flow. Generally, within the fluid domain, there are four contributions to the energy balance equation including: the energy transport due to the conduction, the energy transport due to the convection, the viscous effect, and the pressure work. The contribution of the last two terms to the energy transport in viscous laminar flow is insignificant and can be neglected.
\[
\rho_f C_{pf} \frac{\partial T}{\partial t} + \rho_f C_{pf} \mathbf{u} \cdot \nabla T = \nabla \cdot (k_f \nabla T) + Q \tag{3-21}
\]

To handle the fracture-matrix interaction in terms of heat exchange, the energy balance equation of the rock matrix and the fracture subdomains must be coupled. Assuming the rock matrix is a heat source, heat flux from the interface of the rock matrix and the fracture can be inserted into the Eq. (3-21).

\[
Q \approx q = -2 \times \left[ \frac{\partial T_r(0, y, z, t)}{\partial x} \right] \tag{3-22}
\]

Ultimately, the transient heat equation of the fracture fluid can be rewritten as follows:

\[
\frac{\partial T}{\partial t} + \frac{\partial(T u_y)}{\partial y} + \frac{\partial(T u_z)}{\partial z} = \frac{k_f}{\rho_f C_{pf}} \left( \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{q}{\rho_f C_{pf} d_h} \tag{3-23}
\]

It is assumed that the energy resistance at the interface of the rock and the fracture is negligible, i.e., the fracture temperature is equal to the rock matrix temperature at the interface. Moreover, due to the relative thinness of the fracture, there is no thermal gradient across the fracture in the x direction (Figure 2).

\[
T(y, z, t) = T_r(0, y, z, t) \tag{3-24}
\]

Fluid with lower temperature than its surrounding rock is injected into the reservoir, therefore at boundary 5,

\[
T(t) = T_r(t) = T_{in} < \bar{T}_\infty \tag{3-25}
\]

**3.3.1.3. Non-dimensional form of governing equations**

In order to reduce the number of model parameters and computational time, the above equations are transferred into non-dimensional form. By rescaling the model variable into dimensionless form, the conservation equations are recast as follows:

The dimensional form of the heat conduction within the hot rock, is transformed into:
\[
\frac{\partial \hat{T}_r}{\partial \xi} = \frac{\partial^2 \hat{T}_r}{\partial \xi^2} + \left( \frac{d}{R} \right)^2 \left[ \frac{\partial^2 \hat{T}_r}{\partial \hat{y}^2} + \frac{\partial^2 \hat{T}_r}{\partial \hat{z}^2} \right]
\]  

(3-26)

The dimensional form of the energy conservation within the fracture subdomain, Eq. (3-23) is also transformed into:

\[
\frac{\partial \hat{T}_r}{\partial \hat{x}} = \xi \left[ \frac{\partial \hat{T}_\hat{u}_y}{\partial \hat{y}} + \frac{\partial \hat{T}_\hat{u}_z}{\partial \hat{z}} \right]
\]  

(3-27)

where,

\[
\xi = \frac{d \rho_f C_{pf} d_{hf} V_c}{2k_r R}
\]  

(3-28)

The dimensional form of the conservation of momentum within the fracture subdomain, Eq. (3-16) and (3-17) are also transformed into:

\[
-\frac{\partial \hat{p}}{\partial \hat{y}} = \hat{u}_y
\]  

(3-29)

\[
-\frac{\partial \hat{p}}{\partial \hat{z}} = \hat{u}_z
\]  

(3-30)

The initial and boundary conditions; Eq. (3-2), (3-4), (3-20), (3-24), and (3-25) can be rewritten respectively as:

\[
\hat{T}_r(\hat{x}, \hat{y}, \hat{z}, 0) = 1 - G \cdot \frac{(z - \bar{Z})}{(\bar{T}_\infty - T_m)}
\]  

(3-31)

\[-n \cdot \nabla \hat{T}_r = 0 \]  

(3-32)

\[|\hat{u}| = 1 \]  

(3-33)

\[\hat{T}(\hat{y}, \hat{z}, \hat{t}) = \hat{T}_r(0, \hat{y}, \hat{z}, \hat{t}) \]  

(3-34)

\[\hat{T}(\hat{t}) = \hat{T}_r(\hat{t}) = 0 \]  

(3-35)

For more details on the non-dimensional model, see Appendix 1.
3.3.2. Numerical implementation

As mentioned earlier, the initial concept of EGS consists of two subdomains: (1) a set of hydraulically-induced fractures with a high aspect ratio of $\left(10^5:10^5:1\right)$, and (2) a very wide rock matrix with aspect ratio of $(1:1:1)$. In such a system with a geometrical peculiarity, discretizing subdomains explicitly creates an enormous number of infinitesimally fine elements for the fractures, and thousands of coarse elements for the rock matrix, which ultimately amasses a tremendous computational burden. This problem becomes more difficult and computationally expensive in the case of coupled physical processes, i.e., thermo-hydro (TH) simulation of the reservoir.

There are several approaches available in the literature that can tackle this problem and reduce the computation time of the simulation (see, e.g., Pinder et al. 1993). In this study, the EGS reservoir is treated as a multi-dimensional system comprised of two subdomains of different spatial dimensions; (1) a three-dimensional rock matrix, and (2) two-dimensional hydraulic fractures. This approach eliminates the need to create fractures with a high aspect ratio by recasting fractures as 2D inert-element boundaries of the 3D rock matrix. With this approximation, the rock matrix, and the fractures are discretized by tetrahedral (3D) and by triangular (2D) elements, respectively. This simplification eventually spares a considerable number of fine elements and makes the numerical modeling feasible for EGS without sacrificing the accuracy of the simulation.

COMSOL Multiphysics is utilized as a framework for numerical implementation. The conservation equations are discretized spatially by employing the finite-element method. The second order Backward Differentiation Formula (BDF) is used for time discretization. Since the rock matrix is assumed to be granite, i.e., porous medium with porosity and permeability as low as of 0.1 and $10^{-18}$ m$^2$, continuous pressure gradients across the inter-element boundaries are
established. Moreover, by accounting for the fractures thickness and by defining a gradient operator restricted to the fractures’ tangential plane, the change in pressure along the 2D fractures can be calculated.

3.4. The modified concept of the EGS

The physical model of the EGS, based on the modified concept, is divided into four subdomains of (1) the rock matrix, representing the heat source; (2) the hydraulic fractures, representing the globally connected flow paths and heat exchange surfaces; (3) the planar thermal fractures, representing, locally connected flow paths and heat exchange surfaces; and (4) the thermally-shocked region, representing a buffer zone with high storage capacity, connecting the hydraulic fractures, the rock matrix, and the planar thermal fractures (Figure 3.3).

Since the proposed modified concept of EGS is considered an evolving system, the incorporated subdomains must be integrated into the simulation by following a specific sequence of the events of the EGS system. In the EGS reservoir, the sequence of events can be defined chronologically as follows: shortly after the cold fluid sweeps the hydraulic fractures, a thermally-shocked region comprised of a network of small, disorganized, closely-spaced thermal cracks forms in the rock adjacent to the hydraulic fractures. As time elapses, the density of thermal cracks within the thermally-shocked region increases which ultimately leads to higher storage capacity in this region. Afterwards, these small thermal cracks tend to coalesce into better-defined planar thermal fractures, which propagate into the rock matrix, perpendicular to the hydraulic fractures. These planar thermal fractures are hydraulically inactive initially for two reasons: (1) they are oriented away from the direction of the global flow, and (2) their aperture is relatively small. As time elapses, the cold front advances further into the rock matrix and planar thermal fractures grow in length and aperture and they become hydraulically active. Following the chronological order of
the events in an EGS system, the model components can be integrated into the simulation sequentially as shown in Figure 3.4.

Figure 3.3: The scheme of the modified concept of the EGS

Figure 3.4: The chronological order for integrating domain components of the EGS into the numerical simulation (developed based on the modified concept of the EGS)
3.4.1. Mathematical formulation

By adopting the modified concept of the EGS, a hybrid flow model comprised of the explicit discrete-fracture, and the Effective Continuum Models can be utilized to describe flow and heat transport within the reservoir. The assumptions for the rock matrix and for the hydraulic fractures are kept the same as that the initial concept of an EGS. However, there are a few more assumptions for the thermally-shocked region and the planar thermal fractures, as explained below:

➢ *Thermally-shocked region*

The geometry of the thermally-shocked regions is assumed to be identical, i.e., a thin-cylindrical slab of radius $R$ with a uniform width of $d_{sh}$ adjacent to the hydraulic fractures. This region is idealized as a porous medium, located on both sides of the hydraulic fracture. The spatially- and temporally-varying permeability is assigned to the thermally-shocked region. A Gaussian distribution is used to define the permeability distribution across the thermally-shocked region. As shown in Figure 3.5, it is assumed that at the interface of the hydraulic fracture and thermally-shocked region, where the intensity of the thermal shock is higher, the permeability is higher; i.e., approximately equal to the permeability of a hydraulic fracture. However, it decreases sharply with increased distance from the hydraulic fracture, and eventually it becomes equal to the permeability of the rock matrix. Since the density of thermal cracks within the thermally-shocked region also increases with time, it is assumed that the variance of the permeability distribution of the thermally-shocked region increases as time elapses. The same distribution profile is used for the porosity distribution of the thermally-shocked region.

➢ *Planar thermal fractures*
The geometry of the planar thermal fractures is assumed to be identical, i.e., a thin planar fractures of length $l_{th}$ and uniform aperture of $d_{th}$. It is also assumed that the planar thermal fractures are extended in the $x$ direction, into the rock matrix equally from both walls of the hydraulic fractures.

![Figure 3.5: An example of spatially- and temporally-variable Gaussian distribution that can be used to define permeability distributions across the thermally-shocked region](image)

3.4.1.1. Governing equations

The governing equations for all subdomains are provided in Table 3.1. Fluid flow and heat transfer within each subdomain are coupled reciprocally, and the interaction between subdomains with different spatial dimension is given by the linear transformation between the sub-models variable and the boundary conditions. Subscripts $r$, $hf$, $sh$, $tf$ refer to the rock matrix, hydraulic fracture, thermally-shocked region, and the planar thermal fracture respectively.
### Table 3.1: The governing equations for solving fluid flow and heat transfer within each subdomain numerically (developed based on the modified concept of the EGS)

<table>
<thead>
<tr>
<th>Subdomain</th>
<th>Fluid flow governing equations</th>
<th>Heat transfer governing equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock matrix</td>
<td>( \frac{\partial}{\partial t} (\varepsilon_r \rho_r) + \nabla \cdot (\rho_r u) = 0 )</td>
<td>( (\rho C_p)_r^{\text{eff}} \frac{\partial T}{\partial t} + \rho_f C_p f u \cdot \nabla T + \nabla \cdot q = 0 )</td>
</tr>
<tr>
<td></td>
<td>( u = -\frac{\kappa_r}{\mu} \nabla p )</td>
<td>( q = -k_r^{\text{eff}} \nabla T )</td>
</tr>
<tr>
<td>Hydraulic fractures</td>
<td>( d_{hf} \frac{\partial}{\partial t} (\varepsilon_{hf} \rho_f) + \nabla_t \cdot \left( d_{hf} \rho_f u \right) = 0 )</td>
<td>( d_{hf}(\rho C_p)<em>f^{\text{eff}} \frac{\partial T}{\partial t} + d</em>{hf} \rho_f C_p f u \cdot \nabla_t T + \nabla_t \cdot q_{hf} = n \cdot q )</td>
</tr>
<tr>
<td></td>
<td>( u = -\frac{k_{hf}}{\mu} \nabla_t p )</td>
<td>( q_{hf} = -d_{hf} k_{hf}^{\text{eff}} \nabla_t T )</td>
</tr>
<tr>
<td>Thermally-shocked region</td>
<td>( d_{sh} \frac{\partial}{\partial t} (\varepsilon_{sh} \rho_f) + \nabla_t \cdot \left( d_{sh} \rho_f u \right) = 0 )</td>
<td>( d_{sh}(\rho C_p)<em>sh^{\text{eff}} \frac{\partial T}{\partial t} + d</em>{sh} \rho_f C_p f u \cdot \nabla_t T + \nabla_t \cdot q_{sh} = n \cdot q )</td>
</tr>
<tr>
<td></td>
<td>( u = -\frac{k_{sh}}{\mu} \nabla_t p )</td>
<td>( q_{sh} = -d_{sh} k_{sh}^{\text{eff}} \nabla_t T )</td>
</tr>
<tr>
<td>Planar Thermal Fractures</td>
<td>( d_{tf} \frac{\partial}{\partial t} (\varepsilon_{hf} \rho_f) + \nabla_t \cdot \left( d_{tf} \rho_f u \right) = 0 )</td>
<td>( d_{tf}(\rho C_p)<em>f^{\text{eff}} \frac{\partial T}{\partial t} + d</em>{tf} \rho_f C_p f u \cdot \nabla_t T + \nabla_t \cdot q_{tf} = n \cdot q )</td>
</tr>
<tr>
<td></td>
<td>( u = -\frac{k_{tf}}{\mu} \nabla_t p )</td>
<td>( q_{tf} = -d_{tf} k_{tf}^{\text{eff}} \nabla_t T )</td>
</tr>
</tbody>
</table>

#### 3.4.2. Numerical implementation

As mentioned earlier, compared to the initial concept of the EGS, the modified concept of the EGS integrates two extra subdomains (i.e., a thermally-shocked region and planar thermal fractures) into the reservoir simulation. The challenges of pairing subdomains of different spatial dimensions are addressed by using explicit discrete-fracture method, which (1) circumvents the difficulties of matching boundary conditions between subdomains and (2) facilitates the numerical implementation of the thermo-hydro processes in an EGS.
The same explicit discrete-fracture approach can be adopted for the modified concept of the EGS to pair both the hydraulic fractures and the planar thermal fractures with the rock matrix. For the thermally-shocked region, despite the fact that a high aspect ratio of the region \((10^5: 10^5: 10)\) allows for the use of 2D inert-element boundaries of the rock matrix, the explicit discrete-fracture model cannot be utilized for integrating this region into the simulation. There are two reasons that make the explicit discrete-fracture model inapplicable for integrating the thermally-shocked region: First, the properties of the thermally-shocked region (i.e. porosity and permeability) evolves in time and space, i.e., across the domain in the \(x\) direction, therefore, the dimensional reduction offered by the explicit discrete-fracture approach, cannot capture the properties of this region. Second, defining the thermally-shocked region as an interior boundary leads to placing an interior boundary adjacent to another interior boundary, i.e., the hydraulic fracture. The side by side boundaries cannot be defined by an explicit discrete-fracture approach. The proposed hybrid approach is capable of integrating all four subdomains efficiently. In this approach, the concept of an Effective Continuum Method (ECM) is used to summarize the hydraulic fracture and thermally-shocked region into an equivalent subdomain with a set of “effective” parameters (Figure 3.6). The proposed algorithm to approximate the thermally-shocked/hydraulic fracture system is shown in Figure 3.7. By keeping dynamic similarity, i.e., same Reynolds number, between model A and B, the “effective parameters” (effective porosity and permeability) for the equivalent system can be calculated. Afterward the equivalent subdomain which contains enough information for both the hydraulic fracture and thermally-shocked region can be integrated into the simulation by representing the thermally-shocked/hydraulic fracture
system as a 2D interior boundary. Similar to the initial concept, COMSOL Multiphysics is unitized as a framework for numerical implementation.

Figure 3.6: The schematic of summarizing the hydraulically-induced fracture and thermally-shocked region into the equivalent subdomain with a set of “effective” parameters by utilizing the Effective Continuum Method (ECM)
3.5. Model setup; configuration and assumptions

A commercial-sized EGS must, extract a fluid of high temperature, i.e., of 150°C or above, with a sustained flow rate of at least 40-75 kg/s up to 30 years (Tester et al. 2006; Armstead & Tester 1987; Wan et al. 2005). In this work, based on the initial concept, an idealized EGS reservoir, comprising (1) a doublet system of injection/production wells, (2) and a set of 12 vertically oriented hydraulic fractures at the average depth of 5000 m is considered as a reference case (CS-A Case). A porosity and permeability of granite\(^9\) from the literature are assigned to the

---

\(^9\) Porosity = 0.1 and permeability = 10-18 m\(^2\)
rock matrix (e.g., Tester et al. 2006; De Simone et al. 2013; Finsterle et al. 2013). An average permeability of $10^{-13}$ m$^2$ (e.g., Zeng et al. 2013; Hu et al. 2013; Zeng et al. 2014; Finsterle et al. 2013; Li & Lior 2015) is selected for the permeability of the hydraulic fractures. The total flow rate at the production wellhead is fixed at 100 kg/s, assuming no fluid loss in the reservoir. The geometrical and site-specific properties of the reservoir are listed in Table 3.2 and all other fixed parameters are summarized in Table 3.3.

Table 3.2: The geometrical and site-specific properties of the reservoir

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value/Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average reservoir depth</td>
<td>$Z$</td>
<td>5 km</td>
</tr>
<tr>
<td>Thermal gradient</td>
<td>$G$</td>
<td>60 °C/km</td>
</tr>
<tr>
<td>Average reservoir temperature</td>
<td>$T_{\infty}$</td>
<td>315 °C/km</td>
</tr>
<tr>
<td>Hydraulic fracture radius</td>
<td>$R$</td>
<td>500 m</td>
</tr>
<tr>
<td>Half fracture separation distance</td>
<td>$D$</td>
<td>60 m</td>
</tr>
<tr>
<td>Number of Hydraulic fractures</td>
<td>$N_{hf}$</td>
<td>12</td>
</tr>
<tr>
<td>Hydraulic fracture aperture</td>
<td>$d_{hf}$</td>
<td>4 mm</td>
</tr>
<tr>
<td>Hydraulic fracture porosity</td>
<td>$\varepsilon_{hf}$</td>
<td>0.9</td>
</tr>
<tr>
<td>Hydraulic fracture permeability</td>
<td>$\kappa_{hf}$</td>
<td>1E-13</td>
</tr>
<tr>
<td>Total injection rate</td>
<td>$M_t$</td>
<td>100 kg/s</td>
</tr>
<tr>
<td>Reservoir life time</td>
<td>$t$</td>
<td>30 years</td>
</tr>
</tbody>
</table>

Two more cases are set up based on the modified concept of the EGS (i.e., CS-B and CS-C). The CS-B case represents the reservoir comprised of the hydraulic fracture, and four planar thermal fractures perpendicular to the hydraulic fracture. The properties of the hydraulic fractures are kept the same as that of the initial concept. The properties of the planar thermal fractures for the CS-B case are assumed to be those listed in Table 3.4. The planar thermal fractures are hydraulically inactive during the first five years of the heat extraction, so their contribution to the flow and heat transport process is negligible until the fifth year.
Table 3.3: Fixed input parameters used in the numerical simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value/Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot Rock</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>$k_r$</td>
<td>2.9 W/(m K)</td>
</tr>
<tr>
<td>Heat capacity</td>
<td>$C_{p_r}$</td>
<td>850 J/(kg K)</td>
</tr>
<tr>
<td>Density</td>
<td>$\rho_r$</td>
<td>2600 kg/m$^3$</td>
</tr>
<tr>
<td>Porosity</td>
<td>$\varepsilon_r$</td>
<td>0.1</td>
</tr>
<tr>
<td>Permeability</td>
<td>$\kappa_r$</td>
<td>1E-18 m$^2$</td>
</tr>
<tr>
<td>Fluid (water)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>$k_f$</td>
<td>0.6 W/(m K)</td>
</tr>
<tr>
<td>Heat capacity</td>
<td>$C_{p_f}$</td>
<td>4200 J/(kg K)</td>
</tr>
<tr>
<td>Density</td>
<td>$\rho_f$</td>
<td>977.8 kg/m$^3$</td>
</tr>
<tr>
<td>Dynamic viscosity</td>
<td>$\mu$</td>
<td>1E-3 Pa.s</td>
</tr>
<tr>
<td>Reservoir inflow Temperature</td>
<td>$T_{in}$</td>
<td>50 °C</td>
</tr>
</tbody>
</table>

In the CS-C case, in addition to a hydraulic fracture and four planar thermal fractures, two thermally-shocked regions of width 0.02 m on each side of the hydraulic fracture are included. The properties of the hydraulic fractures and planar thermal fractures are kept the same as the CS-A and CS-B cases. The porosity and permeability of the thermally-shocked region are obtained by solving Eq. (3-36). Figure 3.8 shows the assigned distribution of the porosity and permeability across the thermally-shocked region. It is assumed that the permeability function has a changing profile during the first five years and keeps a then constant profile, i.e., square-marked curve, as soon as planar thermal fractures become active after year five.
Table 3.4: The properties of all planar thermal fractures for the CS-B case

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value/Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of fractures</td>
<td>$N_{tf}$</td>
<td>4</td>
</tr>
<tr>
<td>Aperture</td>
<td>$d_{tf}$</td>
<td>1 mm</td>
</tr>
<tr>
<td>Penetration length</td>
<td>$l_{tf}$</td>
<td>60 m</td>
</tr>
<tr>
<td>Porosity</td>
<td>$\varepsilon_{tf}$</td>
<td>0.9</td>
</tr>
<tr>
<td>Permeability</td>
<td>$\kappa_{tf}$</td>
<td>1E-14 m²</td>
</tr>
</tbody>
</table>

Figure 3.8: The assigned distribution of the porosity and permeability across the thermally-shocked region. It is assumed that the profile evolves during the first five years of the heat extraction.
3.6. Initial vs modified concept of the EGS

Since the CS-A, CS-B, and CS-C cases represent scenarios derived from the initial and the modified concept of the EGS, a comparative study between these cases can reveal the capability of the developed hybrid-dimensional model to simulate fluid flow and heat transfer in an EGS reservoir. The effects of: (1) the planar thermal fractures and (2) the thermally-shocked region on the reservoir performance are examined by comparing the CS-A case with CS-B and CS-C cases respectively. Figure 3.9 shows the evolution of a dimensionless temperature profile in the rock matrix during 30 years of production for all three cases.

Figure 3.9: the evolution of dimensionless temperature profile of the rock matrix during 30 years of production for (a) CS-A, (b) CS-B, and (c) CS-C cases
For the CS-A case, in which the hydraulic fracture is the only flow path and heat exchange surface, the injection of cold fluid into the hot reservoir induces a horizontal temperature gradient, i.e., in the $x$ direction. The intensity of the induced temperature gradient is highest near the injection point, resulting in a localized convex shape for the cold front. Figure 3.9a shows the advancement of the cold front in the rock matrix at year 5, 15, and 30 for the CS-A case. As time elapses, the isotherms in the rock matrix advances into the rock matrix following the convex contour close to the injection point and become parallel to the fracture near the production point.

In the CS-B case (Figure 3.9b), the presence of the planar thermal fractures introduces additional flow paths and heat exchange surfaces to the model. During the first five years of the production when the planar thermal fractures are assumed hydraulically inactive, the advancement of the cold front into the rock matrix follows the same profile as the CS-A case. However, after year five as soon as the planar thermal fractures start contributing to the thermo-hydro processes, an additional horizontal temperature gradient, i.e., in the $y$ direction, is induced which untimely affects the advancement of the cold front into the rock matrix. The temperature profile of the CS-B case, at year 15 and 30, shows that although the cold front exhibits a general convex shape close to the injection point, it also extends along the planar thermal fractures.

For the CS-C case (Figure 3.9c), the presence of the thermally-shocked region on both sides of the hydraulic fracture introduces a porous subdomain with high storage capacity to the model. Fig.9c shows that for the CS-C case, during the first five years of the heat extraction when the thermally-shocked region is evolving, the advancement of the cold front is decelerated compared to the advancement of the cold front in both CS-A and CS-B cases. This is because the fluid can permeate into the thermally-shocked region, which would increase the exposure time of
the fluid to the hot rock. Similar to case CS-B case, as time elapses, the irregularity in the cold front caused by the planar thermal fracture can be clearly observed.

The dimensional outlet temperature over 30 years of heat extraction for CS-A, CS-B, and CS-C cases are shown in Figure 3.10. During the first five years of operation, in which the planar thermal fractures are hydraulically inactive, the temperature drawdown rate is faster than throughout the rest of the operation time for all three cases. For the CS-A case the dimensionless temperature at the production well drops to 0.5 after 30 years, however, for cases CS-B and CS-C the production temperature declines to 0.55 and 0.62, respectively. Although the overall trend for all cases is similar, for the CS-B case as soon as the planar thermal fractures become hydraulically-active, there is a sudden increase in the production temperature which reverses the temperature drawdown for couple years. This is because the contribution of the planar thermal fractures in the thermos-hydro process is started at year 5. In Figure 3.10, for case CS-C, the presence of the thermally-shocked region slows the temperature drawdown. The slight increase in production temperature at year 5, due to the presence of the planar thermal fracture can also be observed for the CS-C case; however, the effect of the thermally shocked region is dominant.

The presence of the planar thermal fractures increases the production temperature by 6% on average over 30 years of production; whereas, the combination of planar thermal fractures and a thermally-shocked region increases the production temperature by 24% on average over the operation time.
3.7. Sensitivity analysis of heat extraction to the planar thermal fracture parameters

The effects of the different parameters of the planar thermal fracture— including the number, the aperture, the length and the permeability— on the reservoir performance are examined in this section. The example scenarios with and without thermally-shocked regions are listed in Table 3.5.

Table 3.5: The case scenario examples with/without thermally-shocked regions

<table>
<thead>
<tr>
<th>CASE</th>
<th>Penetration length</th>
<th>Aperture</th>
<th>Permeability</th>
<th>Number</th>
<th>Thermally-shocked region</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS1</td>
<td>40,60,80 (m)</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>Not Considered</td>
</tr>
<tr>
<td>CS2</td>
<td>60 (m)</td>
<td>0.5,1,2</td>
<td>1</td>
<td>4</td>
<td>Not Considered</td>
</tr>
<tr>
<td>CS3</td>
<td>60 (m)</td>
<td>1</td>
<td>0.1, 1, 10</td>
<td>4</td>
<td>Not Considered</td>
</tr>
<tr>
<td>CS4</td>
<td>60 (m)</td>
<td>1</td>
<td>1</td>
<td>2,4,6</td>
<td>Considered</td>
</tr>
<tr>
<td>CS5</td>
<td>40,60,80 (m)</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>Considered</td>
</tr>
<tr>
<td>CS6</td>
<td>60 (m)</td>
<td>0.5,1,2</td>
<td>1</td>
<td>4</td>
<td>Considered</td>
</tr>
<tr>
<td>CS7</td>
<td>60 (m)</td>
<td>1</td>
<td>0.1, 1, 10</td>
<td>4</td>
<td>Considered</td>
</tr>
<tr>
<td>CS8</td>
<td>60 (m)</td>
<td>1</td>
<td>1</td>
<td>2,4,6</td>
<td>Considered</td>
</tr>
</tbody>
</table>

Figure 3.10: The dimensional outlet temperature over 30 years of heat extraction for CS-A, CS-B, and CS-C cases
3.7.1. Effect of penetration length

Figure 3.11 shows dimensionless production temperature $\hat{t}_{out}$ during the operation time for cases CS1 and CS5. As seen in Figure 3.11, there are two clusters of curves; the lower cluster (solid curves) represents the CS1 case where the thermally-shocked region is not included physically in the simulation, and the upper cluster (dashed curves) represents the CS5 case where the combined effect of the planar thermal fractures and the thermally-shocked region is included. As shown in Figure 3.11, for both cases, by increasing the penetration length the production temperature drawdown is decelerated because deeper penetration length provides larger heat exchange surface area and allows the fluid to access a larger volume of the hot rock. For the CS1 case (solid curves), by increasing the penetration length a sudden increase in the production temperature at year five becomes more pronounced and finally the curves converge at the end of operation time. On the other hand, for CS5 case (dashed curves), increasing the penetration length stops the temperature drawdown temporarily after year 5, and then drawdown continues steadily until the end of operation time. In other words, the presence of a thermally-shocked region distributes the effect of the penetration length throughout the operation time and the production temperature drops steadily during the operation years.

3.7.2. Effect of the aperture of the planar thermal fractures

Figure 3.12 shows the dependence of dimensionless production temperature $\hat{t}_{out}$ on the aperture $d_{th}$ of the planar thermal fractures during the operation time, using the parameters listed for cases CS2 and CS6 in the table. As seen in Fig. 11b, the production temperature is insensitive to the fracture aperture for both CS2 (solid curves) and CS6 (dashed curves) cases. Since the planar thermal fractures are oriented away from the global flow, the average velocity within planar thermal fractures is significantly smaller than the average velocity within the hydraulic fracture.
Therefore, the aperture of the planar thermal fracture has little influence on the velocity field of this subdomain and consequently, an insignificant effect on the fluid temperature carried out of the reservoir.

3.7.3. Effect of the permeability of the planar thermal fractures

Figure 3.13 shows the dependence of the dimensionless production temperature \( \hat{\theta}_{out} \) on the permeability of the planar thermal fractures \( \kappa_{hf} \) during the operation time, using the parameters listed for cases CS3 and CS7 in the table. As shown in the Fig. 11c increasing the permeability of the planar thermal fracture one order of magnitude from 1E-15 to 1E-14 m\(^2\) slows the production temperature drawdown slightly for both CS3 and CS7 cases. Although, the same behavior is expected when the permeability is increased further, the temperature curve for the cases with permeability of 1E-13 m\(^2\) drops to a lower value than cases with permeability of 1E-14 and 1E-15 m\(^2\).

This unexpected behavior is a result of our simulation assumption, in which the inlet/outlet flow rate for each hydraulic fracture is fixed at \((100/N_{hf})\) kg/s, and there is no pressure drop. Therefore, increasing the permeability of the fracture increases the velocity within the fracture and consequently reduces the exposures time of the fluid within the planar thermal fractures to the hot rock.

3.7.4. Effect of the number of planar thermal fracture

Figure 3.14 shows the dependence of the dimensionless production temperature \( \hat{\theta}_{out} \) on the number of planar thermal fractures \( N_{th} \) during the operation time, using the parameters listed for cases CS4 and CS8 in the table. As seen in Figure 3.14, for both cases, increasing the number of planar thermal fractures slows the production temperature drawdown because a larger number
of planar thermal fractures provides more heat exchange surface area and allows the fluid to access a larger volume of the hot rock. The results indicate that although the planar thermal fractures represent locally connected flow paths and heat exchange surfaces, a large number of them is desirable for mitigating the thermal drawdown of a reservoir.

![Diagram of Effect of the penetration length on the dimensional outlet temperature over 30 years of heat extraction for CS1 (solid curves) and CS5 (dashed curves)](image)

Figure 3.11: Effect of the penetration length on the dimensional outlet temperature over 30 years of heat extraction for CS1 (solid curves) and CS5 (dashed curves)

![Diagram of Effect of the aperture on the dimensional outlet temperature over 30 years of heat extraction for CS2 (solid curves), and CS6 (dashed curves) cases](image)

Figure 3.12: Effect of the aperture on the dimensional outlet temperature over 30 years of heat extraction for CS2 (solid curves), and CS6 (dashed curves) cases
Figure 3.13: Effect of the permeability on the dimensional outlet temperature over 30 years of heat extraction for CS3 (solid curves) and CS7 (dashed curves) cases.

Figure 3.14: Effect of the number of planar thermal fractures on the dimensional outlet temperature over 30 years of heat extraction for CS4 (solid curves) and CS8 (dashed curves) cases.
3.8. Conclusion

Thermally-induced fractures are believed to improve the EGS performance; however, the assumptions on which the initial concept of the EGS is based ignores the presence of thermal fractures. In this work, we introduced the modified concept of the EGS, in which the physical model of the EGS reservoir comprises four subdomains of the hot rock matrix, the hydraulic fractures, the thermally-shocked region and the planar thermal fractures. Accordingly, a hybrid flow model capable of integrating thermally induced features (i.e., a thermally-shocked region and planar thermal fractures) into the EGS reservoir simulation is developed. Since discretization of a model with such geometrical peculiarity is computationally expensive, a computationally efficient finite element model is developed to solve the transient heat and fluid flow within the reservoir. The proposed finite element model allows reducing the spatial discretization of the fractures from 3D to 2D, and thus reducing the CPU time remarkably. COMSOL Multiphysics is utilized as a framework, where the thermal interaction between subdomains can be included in the formulation. Three numerical examples are solved based on the initial and modified concepts of the EGS. The effects of the thermally-induced fractures on the thermal performance of an EGS are quantified. Finally, parametric scenarios are developed to investigate the sensitivity of the thermal performance of the EGS on the properties of the planar thermal fractures. Based on the study results, we find:

(1) Although, the initial concept of the EGS has been used widely to formulate the Thermo-Hydro processes of an EGS reservoir, the effect of thermally-induced fractures on reservoir performance cannot be studied by utilizing mathematical formulation originated from the initial concept of the EGS. Therefore, the mathematical formulation of the Thermo-Hydro processes must be revised in order to match the redefined conceptual model of the EGS.
(2) In the presence of a well-connected, large-scale hydraulic fracture, the locally-connected, small-scale thermally-induced fractures may not contribute much to the global flow and transport within the EGS reservoir. Therefore, they usually have not been considered in the simulation since they certainly add layers of complexity to the reservoir modeling and a computational burden in numerical simulation. In this work, we claim that thermally-induced fractures can affect the thermal performance of an EGS by providing additional connection area for interflow between the rock matrix and the well-connected, large-scale hydraulic fracture. The results of the numerical model show that integrating thermally-induced fractures into the simulation enhanced the thermal performance of the EGS reservoir; and the presence of these fractures increased the production temperature by up to 24% on average over 30 years of production.

(3) The results of the parametric examples showed that the penetration length $l_{tf}$, the aperture $d_{tf}$, and the permeability $\kappa_{tf}$ of the planar thermal fractures have a negligible effect on the thermal performance of the EGS, (i.e., for all cases the production temperature changes less than 1% on average over the operation time). Hence, increasing the number of thermal planar fractures $N_{tf}$ from 2 to 6 fractures increases the production temperature by 5% on average over the operation time.

(4) According to the results of the numerical examples, the effect of the parameters of the planar thermal fractures on the thermal performance of the EGS is not considerable as much as the effect of the presence of these fractures on the reservoir performance. This tells us that regardless of the many uncertainties associated with the properties of thermally-induced fractures, integrating them into a reservoir simulation can help to anticipate the beneficial effects of thermal fractures on the reservoir performance.
In conclusion, the results confirmed that adopting the initial concept of the EGS underestimates the performance of EGS technology. Hence, although it is simplified, the proposed hybrid flow model (developed based on a modified conceptual model) evaluates the EGS performance more realistically, which ultimately enhances the overall competitiveness of EGS technology as a form of green energy.

3.9. Nomenclature

\( \rho_r \) = density of rock matrix (kg/m\(^3\))

\( \rho_f \) = fluid density (kg/m\(^3\))

\( C_{pr} \) = rock matrix specific heat at constant pressure (J/kg K)

\( C_{pf} \) = fluid specific heat at constant pressure (J/kg K)

\( \alpha_r \) = thermal diffusivity of rock matrix (m\(^2\)/s)

\( \alpha_f \) = thermal diffusivity of fluid (m\(^2\)/s)

\( (\rho C_p)_{eff} \) = effective volumetric heat capacity at constant pressure (J/m\(^3\)°C)

\( \rho_f C_{pf} \) = volumetric heat capacity of fluid at constant pressure (J/m\(^3\)°C)

\( \rho_r C_{pr} \) = volumetric heat capacity of fluid at constant pressure (J/m\(^3\)°C)

\( \zeta \) = temperature gradient (°C/km)

\( T_r \) = rock matrix temperature (°C)

\( T_{\infty} \) = far field rock matrix temperature (°C)
\( T = \) fluid temperature within reservoir (°C)

\( T_{in} = \) fluid temperature at inlet (°C)

\( T_{out} = \) fluid temperature at outlet (°C)

\( T_{ref} = \) fluid reference temperature (°C)

\( k_r = \) thermal conductivity of rock (J m\( s^1\) °C\(^{-1}\))

\( k_f = \) thermal conductivity of fluid (J m\( s^1\) °C\(^{-1}\))

\( k_{r}^{\text{eff}} = \) effective thermal conductivity of the rock matrix (J m\( s^1\) °C\(^{-1}\))

\( k_{h_f}^{\text{eff}} = \) effective thermal conductivity of the hydraulic fracture (J m\( s^1\) °C\(^{-1}\))

\( k_{sh}^{\text{eff}} = \) effective thermal conductivity of the thermally − shocked region (J m\( s^1\) °C\(^{-1}\))

\( k_{th}^{\text{eff}} = \) effective thermal conductivity of the planar thermal fracture (J m\( s^1\) °C\(^{-1}\))

\( u_x = \) fluid velocity, \( x \) component (m/s)

\( u_y = \) fluid velocity, \( y \) component (m/s)

\( u_z = \) fluid velocity, \( z \) component (m/s)

\( q = \) heat flux from rock matrix to fluid

\( d_{hf} = \) aperture of the hydraulic fracture (m)

\( d_{th} = \) aperture of the planar thermal fracture (m)

\( d_{sh} = \) width of thermally − shocked region (m)
\( D = \) the half distance between hydraulic fractures (m)

\( R = \) hydraulic fractures radius (m)

\( r = \) well radius at inlet/outlet (m)

\( l = \) injection/production length for each hydraulic fracture (m)

\( x = \) length in \( x \) direction (m)

\( x_c = \) characteristic length in \( x \) direction (m)

\( y = \) length in \( y \) direction (m)

\( y_c = \) characteristic length in \( y \) direction (m)

\( z = \) length in \( z \) direction (m)

\( z_c = \) characteristic length in \( z \) direction (m)

\( \bar{Z} = \) average reservoir depth (m)

\( P = \) fluid pressure within reservoir (MPa)

\( P_c = \) characteristic pressure of fluid within fracture (MPa)

\( V_c = \) characteristic velocity (m/s)

\( \mu = \) dynamic viscosity of the fluid (kg/m.s)

\( \varepsilon_r = \) porosity of rock matrix

\( \varepsilon_{hf} = \) porosity of hydraulic fractures
\( \varepsilon_{tf} \) = porosity of thermal fractures

\( \varepsilon_{sh} \) = porosity of thermally − shocked region

\( \varepsilon_{eff} \) = effective porosity

\( \kappa_{hf} \) = permeability of hydraulic fractures (m²)

\( \kappa_{tf} \) = permeability of thermal fractures (m²)

\( \kappa_{sh} \) = permeability of thermally − shocked region (m²)

\( \kappa_{eff} \) = effective permeability (m²)

\( M_t \) = total mass flow rate within the reservoir (kg/s)

\( m_{hf} \) = mass flow rate in each hydraulic fracture (kg/s)

\( t \) = time (s)

\( t_c \) = characteristic time (s)

\( \hat{t} \) = dimensionless time

\( \hat{P} \) = dimensionless fluid pressure within reservoir

\( \hat{T} \) = dimensionless temperature of fluid

\( \hat{T}_r \) = dimensionless temperature of rock matrix

\( \hat{T}_{out} \) = dimensionless temperature of outlet

\( \hat{u}_x \) = dimensionless velocity of fluid, x component
\[ \hat{u}_y = \text{dimensionless velocity of fluid, } y \text{ component} \]
\[ \hat{u}_z = \text{dimensionless velocity of fluid, } z \text{ component} \]
\[ \hat{x} = \text{dimensionless length in } x \text{ direction} \]
\[ \hat{y} = \text{dimensionless length in } y \text{ direction} \]
\[ \hat{z} = \text{dimensionless length in } z \text{ direction} \]

**Operator**

\[ \nabla_t : \text{gradient operator restricted to the fracture's tangential plane} \]

**abs:** The absolute value

**exp:** Exponential function

**Subscripts/superscripts**

**f:** Fluid

**r:** Rock

**hf:** Hydraulic fracture

**sh:** Thermally – shocked region

**th:** Planar thermal fracture

**eff:** Effective

**\(\infty\):** Far field
c: Characteristic

3.10. Appendix B

3.10.1. Non-dimensional form of conservation equations

Initially, a set of dimensionless parameters have to be chosen to make the equations non-dimensional. The dimensionless parameters, denoted with a hat are defined according to the characteristic quantities denoted with the subscript c. The characteristic quantities are as follows:

1a) \( x_c = D \)  2a) \( y_c = R \)  3a) \( t_c = \frac{D^2}{\alpha_r} \)

4a) \( V_c = \frac{m_h f}{\rho_f \pi \nu l} \)  5a) \( p_c = \frac{\mu V_c R}{\kappa_{hf}} \)

And the dimensionless parameters are as following:

6a) \( \hat{x} = \frac{x}{d} \)  7a) \( \hat{y} = \frac{y}{R} \)  8a) \( \hat{z} = \frac{(z - \bar{z})}{R} \)

9a) \( \hat{t} = \frac{t \alpha_r}{D^2} \)  10a) \( \hat{p} = \frac{(P - P_{out})}{P_c} \)

11a) \( \hat{T} = \frac{(T - T_{in})}{(T_\infty - T_{in})} \)  12a) \( \hat{T}_r = \frac{(T_r - T_{in})}{(T_\infty - T_{in})} \)

13a)  14a)  15a)
\[ \hat{u}_x = \frac{u_x}{V_c} \quad \hat{u}_y = \frac{u_y}{V_c} \quad \hat{u}_z = \frac{u_z}{V_c} \]

### 3.10.2. Dimensionless form of conservation of energy

The dimensional form of the heat conduction equation of the hot rock can be derived from:

\[
\frac{\partial T_r}{\partial t} = \alpha_r \left( \frac{\partial^2 T_r}{\partial x^2} + \frac{\partial^2 T_r}{\partial y^2} + \frac{\partial^2 T_r}{\partial z^2} \right) \tag{16a}
\]

Substituting Eq.12a, the Left-hand side of Eq.16a can be rewrite:

\[
\frac{\partial T_r}{\partial t} = \frac{\partial \left[ T_r (T_{\infty} - T_{in}) + T_{in} \right]}{\partial \hat{t}} \times \frac{\partial \hat{t}}{\partial t} \tag{17a}
\]

The derivation of \( \hat{t} \) respect to time can be calculated from Eq.9a. Therefore the Eq.17a can be rewritten as follows:

\[
\therefore \frac{\partial T_r}{\partial t} = \left[ \frac{T_{\infty} - T_{in}}{D^2} \right] \alpha_r \frac{\partial T_r}{\partial \hat{t}} \tag{18a}
\]

To recast the right-hand side of the Eq.16a into non-dimensional form, at the beginning, the first derivation of the rock matrix temperature respect to \( x, y, \) and \( z \) must be non-dimensionalized. By substituting Eq.12a and derivation of Eq. (6a) the first derivation of \( T_r \) respect to \( x \) is

\[
\frac{\partial T_r}{\partial x} = \frac{\partial \left[ T_r (T_{\infty} - T_{in}) + T_{in} \right]}{\partial \hat{x}} \times \frac{\partial \hat{x}}{\partial x} \tag{19a}
\]

\[
= \left[ \frac{T_{\infty} - T_{in}}{D} \right] \frac{\partial T_r}{\partial \hat{x}} \tag{20a}
\]

The second derivative of the rock temperature respect to \( x \) is

\[
\frac{\partial^2 T_r}{\partial x^2} = \frac{\partial}{\partial x} \left( \frac{\partial T_r}{\partial x} \right) \tag{21a}
\]
\[
\frac{\partial^2 T_r}{\partial x^2} = \frac{\partial}{\partial x} \left[ \frac{(T_{\infty} - T_{in})}{D} \frac{\partial T_r}{\partial \hat{x}} \right]
\]
\[
= \frac{\partial}{\partial \hat{x}} \left[ \frac{(T_{\infty} - T_{in})}{D} \frac{\partial T_r}{\partial \hat{x}} \right] \times \frac{\partial \hat{x}}{\partial x}
\]

(22a)

\[
\frac{\partial^2 T_r}{\partial x^2} = \left\{ \frac{(T_{\infty} - T_{in})}{D^2} \right\} \frac{\partial^2 T_r}{\partial \hat{x}^2}
\]

(23a)

Following same procedure the second derivative of the rock temperature respect to \(y\) and \(z\) are

\[
\frac{\partial^2 T_r}{\partial y^2} = \left\{ \frac{(T_{\infty} - T_{in})}{R^2} \right\} \frac{\partial^2 T_r}{\partial \hat{y}^2}
\]

(24a)

\[
\frac{\partial^2 T_r}{\partial z^2} = \left\{ \frac{(T_{\infty} - T_{in})}{R^2} \right\} \frac{\partial^2 T_r}{\partial \hat{z}^2}
\]

(25a)

Substituting Eq.23a, 24a, 25a, and 18a into the Eq.16a, the heat conduction equation within the hot rock can be rewritten

\[
\left[ \frac{(T_{\infty} - T_{in})}{D^2} \right] \alpha_r \frac{\partial^2 \hat{T}_r}{\partial \hat{t}^2} = \alpha_r \left\{ \left\{ \frac{(T_{\infty} - T_{in})}{D^2} \right\} \frac{\partial^2 \hat{T}_r}{\partial \hat{x}^2} + \left\{ \frac{(T_{\infty} - T_{in})}{R^2} \right\} \frac{\partial^2 \hat{T}_r}{\partial \hat{y}^2} + \left\{ \frac{(T_{\infty} - T_{in})}{R^2} \right\} \frac{\partial^2 \hat{T}_r}{\partial \hat{z}^2} \right\}
\]

(26a)

The non-dimensional form of the heat conduction equation within the hot rock can be given by

\[
\frac{\partial \hat{T}_r}{\partial \hat{t}} = \frac{\partial^2 \hat{T}_r}{\partial \hat{x}^2} + \left( \frac{D}{R} \right)^2 \left[ \frac{\partial^2 \hat{T}_r}{\partial \hat{y}^2} + \frac{\partial^2 \hat{T}_r}{\partial \hat{z}^2} \right]
\]

(27a)

The dimensional form of the conservation of energy of fluid can be derived from:

\[
\frac{\partial T}{\partial t} + \frac{\partial (T u_x)}{\partial x} + \frac{\partial (T u_y)}{\partial y} + \frac{\partial (T u_z)}{\partial z} = \alpha_f \left[ \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right] + \frac{q}{\rho_f C_{pf} d_{hf}}
\]

(28a)
Hitherto dimensionless form of the first term on the left-hand side and the first, second and third terms on the right-hand side are calculated. Due to the high-aspect ratio of the fracture plane the fluid is assumed 2D and the x component of the conservation equations are assumed to be negligible.

\[
\frac{\partial T}{\partial t} + \frac{\partial ( Tu_y )}{\partial y} + \frac{\partial ( Tu_z )}{\partial z} = \alpha_f \left[ \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right] + \frac{q}{\rho_f c_{pf} d_{hf}} \tag{29a}
\]

Dimensionless form of the second term on the left-hand side of the Eq.29a is calculated as following

\[
\frac{\partial ( Tu_y )}{\partial y} = \frac{\partial \left[ \hat{\theta} ( \hat{T}_\infty - T_{in} ) + T_{in} \right] V_c \hat{u}_y}{\partial \hat{y}} \times \frac{\partial \hat{y}}{\partial y} \tag{30a}
\]

\[
\therefore \frac{\partial ( Tu_y )}{\partial y} = \left\{ \frac{V_c ( \hat{T}_\infty - T_{in} )}{R} \right\} \frac{\partial \hat{T} \hat{u}_y}{\partial \hat{y}} \tag{31a}
\]

Following same procedure dimensionless form of the third term on the left-hand side of the Eq.29a is

\[
\therefore \frac{\partial ( Tu_z )}{\partial z} = \left\{ \frac{V_c ( \hat{T}_\infty - T_{in} )}{R} \right\} \frac{\partial \hat{T} \hat{u}_z}{\partial \hat{z}} \tag{32a}
\]

The heat source of fluid \( q \) is the heat flux from the rock to the fluid from both fracture walls.

\[
q = -2k_r \frac{\partial T_r}{\partial x} \quad \text{at fracture walls} \tag{33a}
\]

Substituting Eq.20a, the dimensionless form of heat source is

\[
\therefore q = \left\{ \frac{-2k_r ( \hat{T}_\infty - T_{in} )}{D} \right\} \frac{\partial \hat{T}_r}{\partial \hat{x}} \tag{34a}
\]

Substituting Eq.23a, 24a, 25a, 31a, 32a, and 34a into the Eq.29a the heat conduction equation within the conservation of energy of fluid can be rewritten.
\[
\frac{1}{D^2} \left( T_\infty - T_{in} \right) \alpha_f \frac{\partial \hat{T}_r}{\partial \hat{t}} + \left[ \frac{V_c (T_\infty - T_{in})}{R} \right] \left( \frac{\partial \hat{T}_r}{\partial \hat{y}} + \frac{\partial \hat{T}_r}{\partial \hat{z}} \right) = \alpha_f \left[ \frac{(T_\infty - T_{in})}{R^2} \right] \left( \frac{\partial^2 \hat{T}}{\partial \hat{y}^2} + \frac{\partial^2 \hat{T}}{\partial \hat{z}^2} \right) + \left[ \frac{-2k_r (T_\infty - T_{in})}{D \rho_f C_p d_{hf}} \right] \frac{\partial \hat{T}_r}{\partial \hat{x}}
\]  \hspace{1cm} (35a)

Since the order of magnitude of the thermal diffusivity of fluid, the radius of the hydraulic fracture and the fracture separation distance are known.

\[ \alpha_f \sim 10^{-6}, D^2 \sim 10^2 \text{ and } R^2 \sim 10^4 \]

The first term on the left-hand side and the first and second terms on the right-hand side of the Eq.1212 tend to zero and could be neglected.

\[
\frac{1}{D^2} \left( T_\infty - T_{in} \right) \alpha_f \frac{\partial \hat{T}_r}{\partial \hat{t}} \sim 10^{-8} \times \left( T_\infty - T_{in} \right) \frac{\partial \hat{T}_r}{\partial \hat{t}} \hspace{1cm} (36a)
\]

\[
\alpha_f \left[ \frac{(T_\infty - T_{in})}{R^2} \right] \left( \frac{\partial^2 \hat{T}}{\partial \hat{y}^2} + \frac{\partial^2 \hat{T}}{\partial \hat{z}^2} \right) \sim 10^{-10} \times \left( T_\infty - T_{in} \right) \left[ \frac{\partial^2 \hat{T}}{\partial \hat{y}^2} + \frac{\partial^2 \hat{T}}{\partial \hat{z}^2} \right] \hspace{1cm} (37a)
\]

Therefore the Eq.35a shrinks to

\[
\frac{\partial \hat{T}_r}{\partial \hat{x}} = \xi \left[ \frac{\partial \hat{T}_r}{\partial \hat{y}} + \frac{\partial \hat{T}_r}{\partial \hat{z}} \right] \hspace{1cm} (38a)
\]

where, \( \xi \) is

\[
\xi = \frac{D \rho_f C_p d_{hf} V_c}{2k_r R} \hspace{1cm} (39a)
\]

### 3.10.3. Dimensionless form of conservation of momentum of fluid

The dimensional form of the momentum equation for the fluid is simplified to Darcy’s 2D equation.
Substituting Eq.5a, 10a, and 14a, dimensionless form of the Darcy’s law in $y$ direction is

$$
\frac{\partial P}{\partial y} = \frac{\mu}{\kappa_h f} u_y
$$

(40a)

$$
\begin{align}
\frac{\partial P}{\partial y} &= \frac{\partial (\hat{P}P_c + P_{out})}{\partial \hat{y}} \times \frac{\partial \hat{y}}{\partial y} \\
&= \left( \frac{P_c}{R} \right) \frac{\partial \hat{P}}{\partial \hat{y}} \\
&= \left( \frac{P_c}{R} \right) \frac{\mu V_c R}{\kappa_h f} \frac{\hat{u}_y}{P_c}
\end{align}
$$

(41a)

$$
\frac{\partial \hat{P}}{\partial \hat{y}} = \frac{\mu V_c R}{\kappa_h f} \frac{\hat{u}_y}{P_c}
$$

(42a)

$$
\therefore \frac{\partial \hat{P}}{\partial \hat{y}} = \hat{u}_y
$$

(43a)

Following same procedure of the Darcy’s law in $z$ direction can be written as

$$
\therefore \frac{\partial \hat{P}}{\partial \hat{z}} = \hat{u}_z
$$

(44a)

3.11. References


Sarda, S. et al., 2002. Hydraulic Characterization of Fractured Reservoirs: Simulation on


CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

4.1. Major Observations and Conclusions

This work contributes to understanding and quantifying the effects of thermally-induced fractures on the performance of an EGS reservoir. In chapter 2, the transport mechanisms within a thermally-shocked region were investigated to provide a better understanding of the overall heat and mass transport in an EGS reservoir. A segment of the thermally-shocked region was idealized as a porous medium, and the direct pore-scale simulation method was utilized to determine the fluid flow and transport processes within the thermally-shocked region. A group of ten models with identical geometrical properties but different length scales, were developed to simulate a wide range of the thermally-shocked region from the severely- to the lightly-thermally-shocked region. The effect of the degree of fragmentation of the thermally-shocked region on the mechanisms of heat and mass transport within this region was identified. The continuum Darcy-scale method was also used to investigate if it can replicate the results of the pore-scale modeling approach. In chapter 3, an innovative hybrid approach comprised of the explicit discrete-fracture method and the Effective Continuum Method (ECM) was developed to model thermo-hydro processes within the EGS reservoir. The proposed model allows integration of thermally-induced fractures into the numerical simulation for the field scale practices. By utilizing the proposed simulation approach, the effect of the thermally-induced fractures on the cold front advancement, thermal breakthrough, and production temperature of the EGS reservoir was determined. A suite of eight cases was also developed to investigate the effects of different parameters for the thermally-induced fractures, such as the number, width, length, and permeability on flow and heat transfer in the EGS reservoir.
The major findings and conclusions are as follows:

1) A conceptual model, based on the direct pore-scale method, can be developed that captures the details of the transport processes within the thermally-shocked region of an EGS reservoir. It was found that for the severely thermally-shocked region, diffusion is the responsible transport mechanism for both heat and mass transfer. In contrast, for a moderately thermally-shocked region, mass transfer is mainly accomplished by advection, and heat is transferred via both fluid motion and conduction.

2) The Thermal Breakthrough Time (TBT) and Mass Breakthrough Time (MBT) are defined to assess the distribution of fluid residence times, and the temperature decline within the thermally-shocked region, respectively. Three orders of magnitude difference in TBT and MBT reflects the critical role of diffusion at the model with the length scale of 1 mm. In contrast, for the models with the larger length scale, the role of advection is pronounced, and TBT and MBT are in the same order of magnitude.

3) The capability of the Darcy-scale simulation approach to model transport behavior of the thermally-shocked region is assessed. The comparison between the direct pore-scale and the Darcy-scale simulation showed that the competence of the Darcy-scale representation to replicate the pore-scale results depends on both the contributing physical processes, and the length scale of the thermally-shocked region. For example, for the advection-dominated system, cases with the length scale of 100 mm, attaining an agreement between the pore-scale and the Darcy-scale method was not feasible.

4) Since the exact fragment geometry inside the thermally-shocked region of an EGS reservoir will never be known, temporal and spatial fluctuations can be expected based on
how heat and mass are transported in the EGS circulation system, and this can consequently affect the overall EGS performance.

5) A novel hybrid approach, based on the modified conceptual model of EGS, has been developed to assess the effect of the thermally-induced fractures on an EGS performance. The mathematical formulation of this approach provides a robust tool to integrate locally-connected, small-scale, thermally-induced fractures with well-connected, large-scale hydraulic fractures to simulate a field scale EGS reservoir. The hybrid model also permits a reduction of the spatial discretization of the fractures from 3D to 2D, and thus reduction of the CPU time remarkably.

6) A comparative study, based on a group of three hypothetical EGS reservoir models, was conducted that reveals the competence of the proposed numerical approach in capturing the effect of the thermally induced fractures. Tracking the cold front advancement, and the production temperature over 30 years for the defined hypothetical reservoirs, was shown that the contribution of the thermally-induced fractures increases the production temperature, and delays the reservoir thermal breakthrough time considerably.

7) Although the proposed hybrid model adds layers of complexity to the reservoir simulation, the results of the numerical model show that the presence of the thermally-induced fractures in the reservoir increases the production temperature by up to 24% on average over 30 years of production.

8) The penetration length, aperture, and permeability of the planar thermal fractures have a negligible effect on the thermal performance of the EGS. Increasing the number of thermal planar fractures from two to six fractures increased the production temperature by 5% on average over the operation time.
9) The results of the parametric analysis show that the impact of changes in the geometrical parameters of the planar thermal fractures is not significant as much as the effect of the presence of these fractures on the reservoir performance.

10) Although simplified, the proposed hybrid flow model provides an effective means to evaluate the EGS performance realistically, which ultimately enhances the overall competitiveness of EGS technology among other forms of renewable sources of energy.

4.2. Recommendations for Future Research

Topics that should be further studied include:

1) In this work, the goal of simulation of the thermally-shocked region was to generate randomized flow paths at different scales to measure mass transport and thermal distribution. Various arrangements of clustered, and differently-sized circles approximate irregular shaped matrix elements. The resulting clusters of randomly sized particles create preferential flow paths that can be used to effectively measure the scale effect on mass transport and temperature distribution. To that end, the authors were less concerned with the particular shape of the particles, as long as the size and packing of particles were randomized and tortuous paths were created. It would be possible to extend this study by generating particles of various shapes that approximate matrix elements of the thermally-shocked region more realistically.

2) Investigate the mechanical effects of the thermal stresses on an EGS reservoir performance by inclusion of the mechanical behavior into the proposed thermo-hydro processes. Indeed, since a multidimensional Thermo-Hydro (TH) code is developed in this study, it would be interesting to extend the TH code to the THM by coupling the mechanical behavior of the reservoir. The alteration of performance of the EGS reservoir, due to the mechanical
changes, and associated change in the hydraulic performance can be investigated by implementing the THM coupled modeling approach.

3) Investigate the effects of the sorption, solution, and precipitation of the dilute species on an EGS reservoir performance by coupling the chemical processes with the proposed TH model. The Thermo-Hydro-Chemical (THC) model allows to better understanding of the analogy between mass and heat transport

4) This work revealed that the presence of the thermally-induced fracture in the reservoir enhances the performance of an EGS. Therefore, it will be interesting to investigate the possible approaches that can enlarge the number of the thermally-induced fractures in the reservoir. For example, modifying the Huff and Puff operation mode, which is used to reduce the impedance of the fluid within the reservoir, by controlling the temperature of the injection fluid may increase the role of thermally-induced fractures in the reservoir performance.

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10 According to this analogy one can characterize heat flow based on the dilute species transport and vice versa.

11 Discharging and shutting in the well and repeating this cycle several times until the well discharge has improved, and has become commercially viable to produce, is called Huff and Puff operation mode.