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Review Article

Enhanced Geothermal Systems – Promises and Challenges

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Abstract Geothermal energy plays a very important role in the energy basket of the world. However, understanding the geothermal hotspots and exploiting the same from deep reservoirs, by using advanced drilling technologies, is a key challenge. This study focuses on reservoirs at a depth greater than 3 km and temperatures more than 150°C. These resources are qualified as Enhanced Geothermal System (EGS). Artificially induced technologies are employed to enhance the reservoir permeability and fluid saturation. The present study concentrates on EGS resources, their types, technologies employed to extract energy and their applications in improving power generation. Studies on fracture stimulation using hydraulic fracturing and hydro shearing are also evaluated. The associated micro-seismic events and control measures for the same are discussed in this study. Various simulators for reservoir characterization and description are also analyzed and presented. Controlled fluid injection and super critical CO_2 as heat transmission fluid are described for the benefit of the readers. The advantages of using CO_2 over water and its role in reducing the carbon footprint are brought out in this paper for further studies.

Keywords:Enhanced Geothermal Systems (EGS); Reservoir permeability; Hydraulic fracturing; Hydro shearing; Super critical fluid; Simulators; Micro-seismic

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1. Introduction

Enhanced geothermal system (EGS) will play an important role in the future of renewable energy. EGS systems are buried at a depth more than 3 Km which bears temperature more than 150°C (Zheng *et al*., 2021). In EGS the reservoir or hot rock is artificially stimulated to improve the permeability and fluid saturation (Olasolo *et al.,* 2016).

Indirect and direct applications like electricity generation, food drying, honey processing, sericulture, horticulture, heating and cooling etc. are possible by extracting the hot water/steam (Sanyal and Steven, 2005). The techniques of geothermal energy utilization based on depths and its applications are shown in Figure 1 and 99 % of the thermal heat comes from the deep reservoirs (7-10 km) (DiPippo, 2012; Tester *et al.,* 2006).

Reservoirs in the subsurface are traversed by fractures, fissures and faults. The key to success is to expand the fracture network. Hydraulic fracturing (HF) is a widely used technology in hydrocarbon field where permeability is low. Fracturing is a key attribute to exploit heat from subsurface (Li and Lior, 2015; Li, 2020). The fractures are utilized to circulate cold fluid in the hot reservoirs. The process in turn helps to extract energy from the subsurface (Portier *et al.*, 2007; McClure & Horne, 2014; Archer, 2020). Large area in the subsurface is fractured in HF in order to exploit the EGS' energy (Sanyal and Steven, 2005).

EGS fields are observed close to natural geothermal fields. However, the use of external fluids for stimulation leads to micro-seismic activities (Majer *et al.,* 2007). The micro-seismic activities lead to earthquakes and reactivation of tectonic activities (Gan and Lei, 2020). The process can be minimized by controlled injection of fluids (Majer *et al.,* 2007). Reservoir simulation techniques can act as useful tools in dealing with issues related to EGS.

Reservoir simulation is a widely known procedure in fractured/porous rocks for pre-existing hydrothermal resources like hot water, steam or multi-phase reservoirs (Sanyal *et al.,* 2000). Studying the temporal and geographical evolution of geothermal reservoirs is crucial because extracting geothermal heat from an EGS is a challenging procedure. Several literatures suggest numerical methods for simulating fracture flow medium and heat generation (Zhou *et al*., 2021). These simulations are carried out in geothermal reservoirs employing coupled reactions like those of thermal-hydraulic reactions (TH), thermal-hydraulic-mechanical reactions (THM), and thermal-hydraulic-mechanical-chemical reactions (THMC) (Salimzadeh and Nick, 2019). Brown was a pioneer in the use of high-pressure (supercritical) CO_2 instead of water as a working fluid in EGS. CO_2 has several thermal, physical, and chemical properties making it an efficient heat transfer medium (Brown, 2000).

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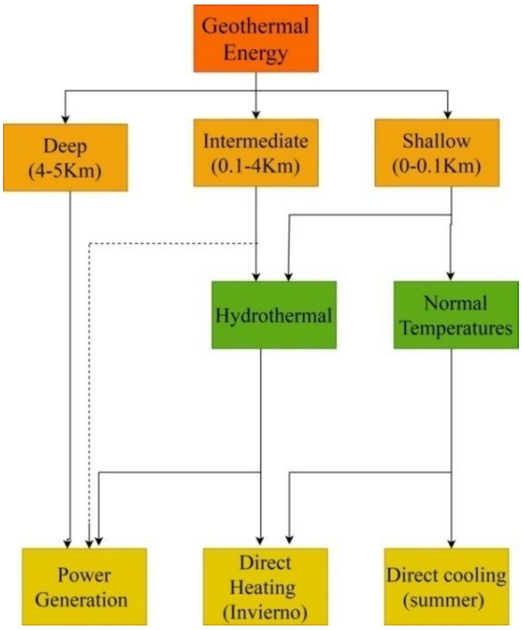

Fig. 1. Several techniques of geothermal energy utilization based on the depth and its applications (modified after Johnston et al., 2011; Olasolo *et al.*, 2016).

The present study provides a holistic view of the rapidly evolving technology of the application of hydraulic fracturing (HF) in EGS, since its origin to the current state of the art. The repercussions of HF-induced seismicity/micro seismicity, which leads to delays and prompted cancellation, are also discussed in the present study. The study tries to examine the benefits and drawbacks of CO_2 as an EGS working fluid. The similarities between the flow behaviors of CO_2 with H_2O are also weighed in the present work. Two types of simulators which are utilized by hydrocarbon industry; hydrothermal simulators such as TOUGH2, TETRAD, FEHM, STAR and HDR simulators such as GEOPHIRES v2.0, GEOTH3D, FRACTure, Geocrack2D, and FRACSIM-3D are discussed in this study. The merits and demerits of both are discussed in a descriptive manner in the following sections.

2. Literature Review

Geothermal resources are broadly classified into four categories primarily on their depth, permeability and nature of fluid (Bogie *et al.*, 2005). The classification of the resources is based on geological, geochemical, thermodynamic, and hydrological conditions. As depicted in Figure 2, the geothermal resources are: Hydrothermal resources, Geopressured resources, Hot dry rock (HDR) and Magma systems.

2.1 Hydrothermal Resource

Hydrothermal resource systems are naturally existing geothermal systems. The depth ranges from 0.1 to 4.5 kilometres. These systems are porous by nature. Based on the source of thermal energy, these systems are separated into volcanic and non-volcanic categories. A volcanic convective system receives thermal energy from a convective magma body, while a non-convective system receives thermal energy from meteoric water (Sanyal, 2010). There is no magma body in non-convective systems. The quantity of natural fluid utilised is efficient, and it may also be utilized to produce energy and provide direct heat.

2.2 Hot dry rock

In Hot dry rock (HDR) the native fluids, confined heat or steam is stored within the rock mass. The depth of the reservoir varies between 2 and 10 kilometres beneath the surface of the earth. Permeability and porosity of this rock is low in these reservoirs. EGS is an artificial system formed when hot rock exists but natural permeability or fluid saturation is insufficient. In HDR the fluid is pumped into the subsurface under precisely regulated conditions, causing previously closed cracks to re-open, resulting in permeability enhancement (Sanyal, 2010).

2.3 Geopressured resource

Geopressured resources are confined by a layer of an impermeable sedimentary cap rock. The depth of these resources varies between 3 and 6 kilometres. Under some circumstances, the weight of the layer of sediment, along with the absence of permeability, elevates the pressure inside the subsurface. The temperature of geopressured resources ranges from 90 to 200°C. These resources are available alongside the Pacific coast, in Appalachia, underneath the Gulf of Mexico, etc. The low to moderate permeability ranges in these systems indicates the presence of methane-rich brines (Sanyal, 2010).

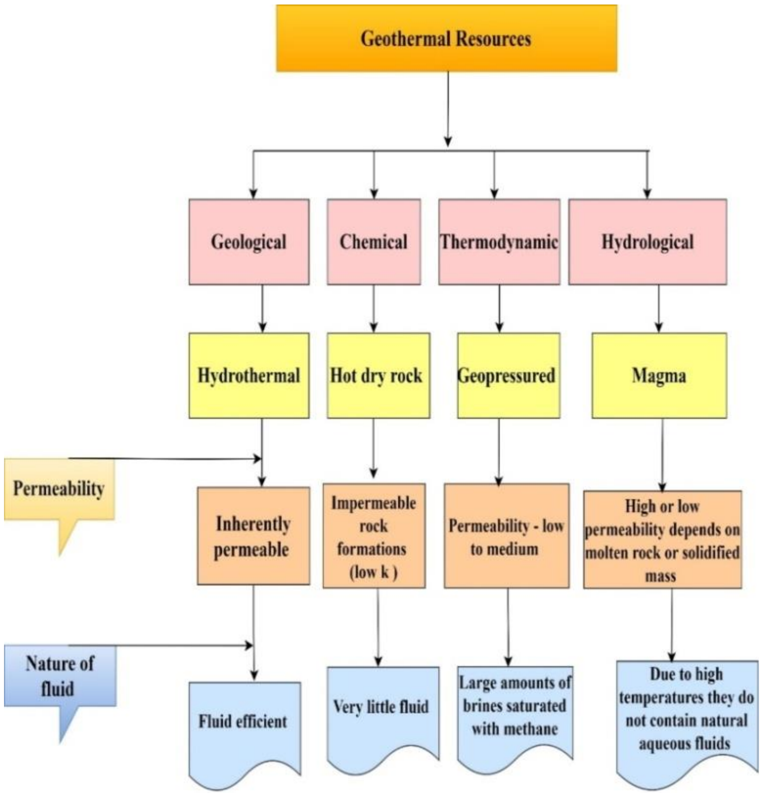

Fig. 2. Classification of geothermal resources (modified after Kitsou, 2000).

2.4 Magma systems

The magma is a constituent of molten hot rocks. The magmatic systems are high temperature sources of approximately 1000°C. Substantial quantities of electric power might be generated by extracting the heat of magma energy. The depth of magmatic chambers is usually 35 kilometres underneath the surface of the earth. Because of the high temperatures, traditional drilling methods are inefficient in these resources.

As depicted in Figure 3(a), the hydrothermal systems are high permeability resources and are able to convey heat from reservoir to the surface; whereas HDR are low permeability resources and heat is trapped at the subsurface only (Kitsou, 2000). Figure 3(b) depicts geothermal resources vs. volume of natural fluid. The hydrothermal system consists of ample amount of hot fluids whereas the HDR are fluid deficient (Kitsou, 2000).

Besides this, there are 2 geothermal systems which are sedimentary and co-produced. These systems use heat trapped in earth's surface for direct use and to generate power.

- *Sedimentary geothermal systems*

  To generate energy, sedimentary geothermal systems use high-flow-rate geothermal reservoirs with average temperatures.

- *Co-Produced geothermal systems*

  A co-produced geothermal system uses water produced as a by-product of oil or gas production. In a conventional oil and gas operations, the co-produced water is injected back into the earth. The co-produced water needs to be treated before using it for further applications. The energy of this water can be used by geothermal systems which would reduce the heavy costs associated with the treatment methods. The co-produced water can be directly utilised by Binary cycle power plants.

3. Traditional and Advanced EGS drilling

3.1 Drilling technologies in EGS systems

Drilling for geothermal energy is analogous to drilling for hydrocarbons since it uses the same cutting-edge technology, especially in low-enthalpy sedimentary conditions. In reservoir exploration, analysis, extraction, and reinjection, drilling is a critical tool. There are multiple parameters associated with geothermal drilling. Long-term geothermal exploration necessitates large-diameter wellbore at greater depths, and well integrity. As geothermal reservoirs are typically found in volcanic rather than sedimentary terrain, drilling a geothermal well is quite expensive. As a result, when drilling a geothermal well, the rocks are harder, abrasive, and fractured than those encountered in the oil and gas industry.

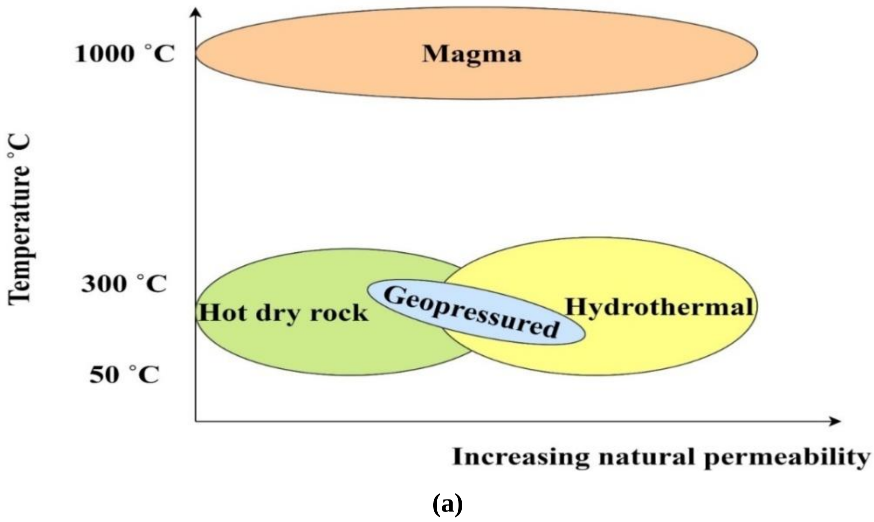

Fig. 3. (a) Geothermal resources vs. permeability; (b) Geothermal resources vs. amount of natural fluid (modified after Kitsou, 2000)

3.2 Challenges in geothermal drilling

The geothermal resources are associated with high temperatures. The elevated temperature accelerates wellbore tubular corrosion and shortens the life span of other components that interacts with the drilling fluid. In order to maintain the characteristics of the drilling fluid, it needs to be maintained at a set temperature. Lost circulation issues occur in all drilling operations. Drill bit is the most critical component in the drilling operation. Table 1 narrates various challenges and potentials associated with different bit types while geothermal drilling.

Challenges associated with drilling of geothermal wells are loss of circulation fluid, fracturing of strong and abrasive rocks and increased temperatures causing mechanical failures in the drilling equipments.

3.3 Advanced drilling technologies

The following are some of the new technologies used in EGS systems: (i) oil and gas well-drilling techniques that have evolved to fit EGS systems, and (ii) breakthrough innovations.

3.3.1 Oil and gas well-drilling techniques that have evolved to fit EGS systems

Cementing and casing deep EGS wells can be done in a variety of methods to save money. The basic casing designs which are commonly used in hydrocarbon business can also be applied in geothermal wells. Some of the well completion components which can be utilized in both geothermal and oil/gas systems are discussed in the subsequent subsections.

Table 1
Various types of bits used for geothermal drilling (modified after Dunn, 1987)

Bit type	Challenges emerged during geothermal drilling	Potential of Geothermal
Roller cone	Bearing and seals	Suitable bit type for hard rocks
Polycrystalline diamond compact (PDC)	Hard rock	Possible improvement with water jets
Water/ abrasive jet cutting	Pumping seals and high pressure	limited
Percussion	Maintaining Gage, good data	Good if gage problem can be solved
Flame jet	Water quench, System difficulties, Costs for deep wells	Hot dry rock reservoir (Granite)

3.3.1.1 Expandable tubular casing

For completion of deep wells, the expenses related to casing and cementing are high. An alternative method for minimising costs is to line the well with expandable casing. A lot of effort has been put into the development of specialised equipments to be used with expandable casings (Benzie *et al.*, 2000; Filippov *et al.*, 1999). Shell Development has patented a product which allows for on-site plastic deformation of tubular casing (Stewart *et al.*, 1996). The under-reamer is used to enlarge the bottom of the well and allows the casing to be cemented once it has been run and expanded. As a result, the interior surfaces of neighbouring casings are flushed.

3.3.1.2 Under-reamers

In the oil and gas sector, under-reamers have always been widely used during the drilling and completion technologies, to give cementing clearance for casing strings through the formation. Under-reaming is done with bi-centre bits and Polycrystalline diamond compact (PDC) type cutters in the petroleum industry. PDC bits are also useful for geothermal drilling. However for EGS operations, more reliable and consistent under-reamers are required.

3.3.1.3 Drilling-with-casing

Drilling with casing method allows longer casing intervals, hence reducing the number of casing strings and in turn reducing the completion costs (Kohl and Hopkirk, 1995). However better equipments like expandable tubular casings and under-reamers are required for dependable development of this technology.

3.3.2 Break through innovations

New drilling techniques might result in a higher penetration rate as well as longer bit life, subsequently lowering drilling costs. Some of the new drilling techniques are spallation, projectile, laser, and chemical drilling. Spallation drilling is a technology that involves high-temperature flames to rapidly heat the surface of the rocks, causing it to fragment or "spall." It may also be used to disintegrate non-spallable rocks (Potter and Tester, 1998). In Projectile drilling, steel balls are propelled at high speeds through pressured water to remove and disintegrate the rock's surface. Rock fragments are recovered when the drilling mud is removed from the projectiles (Geddes and Curlett, 2005). In Laser drilling the rock's surface is heated with laser pulses instead of traditional drilling bits. The last method, Chemical drilling can be used in conjunction with ordinary drilling techniques. It entails using powerful acids to dissolve the rock (Polizzotti *et al.*, 2003). These drilling techniques are still in the initial stages and are also not commercially accessible. More studies needs to be conducted for the development and inclusion of these techniques in the drilling domain. If developed and tested, either of these technologies may result in a considerable shift in drilling techniques, a large reduction in drilling costs, and the ability to drill deeper.

3.4 Hydraulic stimulation

Hydraulic stimulation is a crucial step in improving permeability of EGS (Häring et al., 2008). During the hydraulic treatment, two separate fracture stimulation processes may occur simultaneously: 1) Hydraulic fracturing, 2) Hydro shearing. The processes are discussed in the following sections:

3.4.1 Hydraulic fracturing

At reservoir levels, the properties such as fluid pressure, liquid loss rate, and thermal management are controlled by the presence of permeability. The thermal yield from HDR sources depend on the availability of an extensive fracture network in the reservoir (Park *et al.,* 2018).

Natural HDR sources have low permeability, which makes injecting geothermal fluids difficult, resulting in large quantities of loss of fluid and minimal heat recovery. In the case of natural HDR, extraction of geothermal energy is aided by the help of hydraulic fracturing (HF). HF is achieved by pressurizing geothermal water at elevated flow rates into reservoir fractures, enabling them to expand and join, and allowing significant flow of water. The process of injecting fluid into a pore elastic medium causes fracture propagation. In operation, HF is achieved by applying high pressure fluid to the rock until the peak principal effective Terzaghi's stress becomes tensile and surpasses the rock's tensile force (Cheng, 1979). HF assists in development of heat transfer channels in a geothermal reservoir (Cheng, 1979).

3.4.1.1 Thermo-elastic reaction on HF

When cold water is pumped in the hot geologic formation, a process known as thermally induced fracture occurs. The thermo–mechanical response of a porous medium during thermal strain, is described by the basic Eq. (1).

$$\sigma + \kappa p\, I = E : \left(\varepsilon - \varepsilon^{\theta}\right) \qquad \textbf{(1)}$$

Where E is the drained elastic tensor, ε^{θ} is thermal strain, ε is total strain, κp is assumed constant during cooling period and I is second order identity tensor. Fluid diffusion happens significantly faster than thermal conduction when the porous structure is sufficiently permeable. When modelling true EGS reserves, the parameter κp can be presumed to remain constant across the cooling time. It appears that the tension associated with thermal strain becomes tensile during cooling.

3.4.1.2 Fracture initiation

Figure 4 shows the concept of fracture initiation by depicting a vertical wellbore striking a uniform rock formation with isotropic elastic and transport characteristics (Dobson *et al.*, 2021).

Assuming that horizontal stresses are less compressive than vertical stresses, for distant field stresses i.e. $-\sigma_v > -\sigma_H > -\sigma_h$. With the injection of the cold fluid, the wellbore pressure pw rises, and the rock formation cools. As a result, the formation's ineffective Terzaghi's tangential stress σ'_ζ increases. Eq. (2) is the criterion for HF activation where Tc is the material's tensile strength. In EGS, the HF approach is depicted in Figure 5.

$$\sigma'_\zeta = Tc \qquad (2)$$

Improved geothermal fluid movement; particularly in HF to enhance reservoir permeability between production and injection wells, improves thermal recovery for HDR reservoirs. Increased permeability, on the other end, means that geothermal systems have a lesser duration of economic viability.

The total pressure must first be modulated in real - time basis as the fracture length expands to minimize fracturing arrests. Furthermore, proppants should be introduced to the drilling fluids in the appropriate proportions to prevent unnecessary decline in efficient and productive stimulation amounts, such as HF closures.

3.4.2 Hydro shearing

Department of Energy, USA is exploring a self-propping shear stimulation, also known as hydro shearing, for EGS, in which pre-existing fracture networks are studied without causing any new fractures which can boost the sub-surface permeability (Bijay and Ghazanfari, 2021). Hydro shearing is affected by various factors such as fracture properties; stress state; mechanical, hydrologic, thermal properties; chemical phenomenon and such other operational etc. (Ghassemi *et al.*, 2007; Safari and Ghassemi, 2015). The primary benefit of this method is that it results in a permanent increase in permeability and a reduction in the required injection pressure.

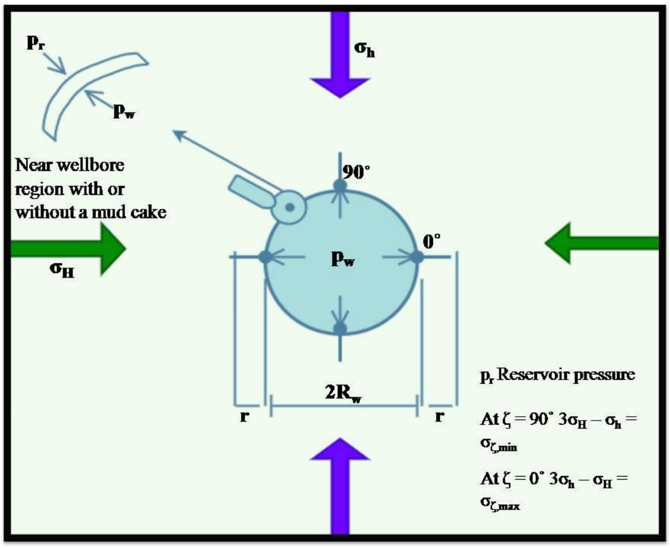

Fig. 4. Illustration of vertical fractures in a vertical wellbore where a mud cake may or may not be used to line the wellbore wall. (Modified after AbuAisha *et al.*, 2016)

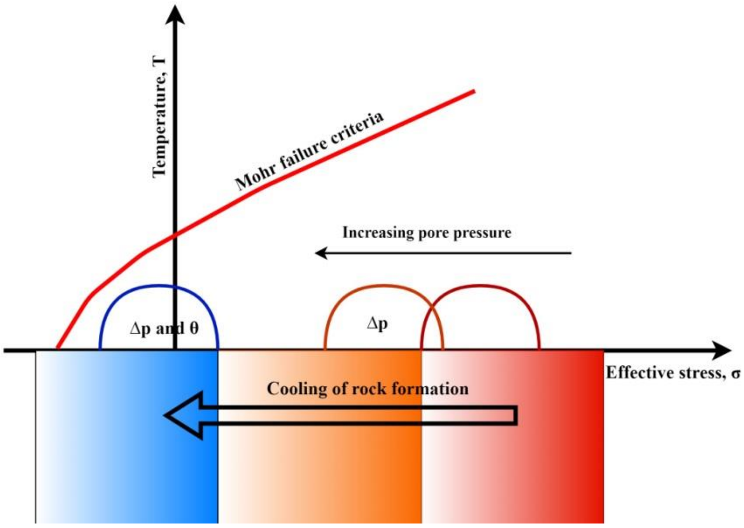

Fig. 5. Depiction of the effect of reducing temperature and increasing pore pressure on HF by Mohr circles and failure curve (modified after AbuAisha *et al*., 2016)

3.4.3 Impact of induced seismicity

Seismic effects are seen in numerous geothermal fields due to hydro fracturing, fluid injection, or acidization (Cornet *et al*., 1992). On a micro scale, these consequences have resulted in setbacks and the potential of abandonment of at least 2 EGS projects around the globe. Several Micro Earthquakes (MEQs) of up to 4-5 magnitudes are induced in the most prominent geothermal areas, most of which are not felt by people (De Simone, 2017). By definition and design, HF is a kind of induced seismicity. Engineering permeability in tight rock formations using this method has been an important approach. HF causes tensile failure which in turn results in "driven fracture (Rathnaweera *et al.,* 2020). HF operations also results in shear failure (Cornet *et al.,* 1992).

Numerous theories and model have been postulated for the occurrence of induced seismicity in geothermal systems, such as:

- *Temperature decrease*

When hot rocks and cold fluids interact, thermo elastic strain is generated which causes the contraction of fractured surfaces. The tiny fracture incision decreases static friction and generates slip somewhere along the break, which is reaching failure in a local stress field that is close to stress level. Seismicity and cracks are generated due to thermal contractions, when hot rock and cold fluid interacts.

- *Pore-pressure increase*

By fluid injection we can increase the pore pressure regionally due to which there will be high seismicity near the wells along the low permeability zones. Additional fractures are caused in the rocks due to high pressure fluid injection.

- *Volume change due to fluid withdrawal/injection*

When fluid is pumped in/out into the subsurface resources, contraction is observed in the reservoir rock. These volume changes pose a serious threat on local stress situations that are already on the verge of failure. Consequently, seismic slip is observed around or within the reservoir.

- *Chemical alteration of fracture surfaces*

MEQs may be induced by change in geochemistry due to the variation in the coefficient of friction while injecting external fluids. The characteristics of local or regional topography can aid in determining how active certain subsurface processes are in any given situations. Major characteristics are discussed below:

.

- Fractures and fault lengths: Enormous faults have a high risk of disastrous seismic events since the prevalent frequency of the event is related to the length of the shear fault. Generally, EGS operations must exercise caution while conducting any operation that includes physical/hydraulic contact with active earthquake faults.
- Ductility, shear modulus and compaction coefficient and other such rock mechanical properties.
- Hydraulic fractures, such like aquacludes, and the presence of aquifer, as well as rock permeability and porosity, and a static pressure profile.

- Prior natural seismicity: In certain cases, induced seismicity has occurred in zones where there has been little or no natural seismicity in the past. In certain circumstances, exploitation of subsurface resources in locations with high background seismicity has resulted in negligible or minimal generated seismicity. However, any estimate of the potential for induced seismicity should include a study of recent earthquake activity. (Majer *et al.,* 2007).

3.5 Supercritical CO_2 ($SCCO_2$) as a heat transmission fluid

The continued use of fossil energy has led to significant environmental challenges. It's imperative to adopt low-carbon energy initiatives which are critical in assuring sustainable global development (Xu *et al.*, 2014). An ideal method for employing Supercritical CO_2 ($SCCO_2$) as the heat transfer fluid in a closed loop HDR network instead of water to operate EGS at high pressure was proposed by Brown (2000). CO_2 has unique thermo - physical and chemical characteristics which makes it a promising a heat transfer medium (Brown, 2000).

It offers three major benefits which are as follows (Yao *et al.,* 2018):

- The temperature difference caused due to wellbore density among the cold $SCCO_2$ in the injection well (about 0.96 g/cc) and the hot $SCCO_2$ in the production wells (about 0.39 g/cc) would contribute a considerable buoyant drive (i.e., thermal siphoning). This would substantially minimize the circulating pumping energy demands over those of an identical water-based HDR structure.
- Because $SCCO_2$ is able to fully breakdown and transport mineral elements from the thermal reservoir to the surface, optimization of surface pipes, exchangers, as well as other infrastructure would be limited.
- HDR reservoirs might be built without the problems associated with silica dissolution in water-based mechanisms for temperatures over 374°C thereby enhancing overall thermodynamic performance.

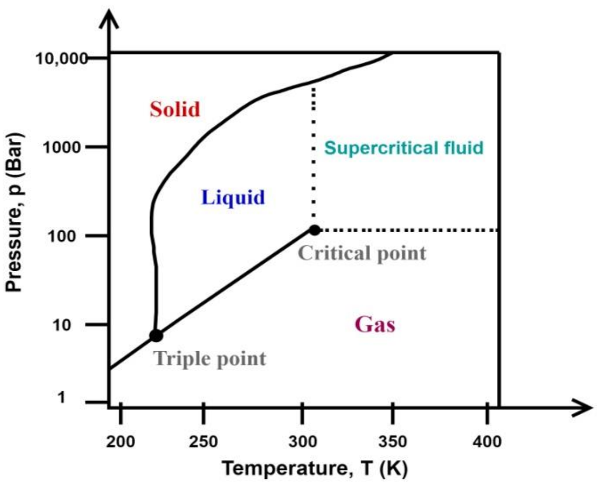

Fig. 6. CO_2 Phase diagram (modified after Sadrehaghighi, I., Multiphase Flow).

Figure 6 displays the related phase of CO_2 at different temperature and pressure. As supercritical $SCCO_2$ extends and contracts more than liquid, substantial buoyancy force is created between both the injecting and producing boreholes. Numerical methods were used to achieve a similar outcome (Pan *et al.*, 2017; Wang et al., 2018). CO_2-EGS has a higher total heat exchange rate and levels of production than H_2O -EGS. The CO_2-EGS percentage removal was significantly higher whenever the bottom strata had a higher permeability. The thermal recovery efficiency of the CO_2-EGS is improved and CO_2 loss is reduced by lowering the mean reservoirs permeability and beginning temperature (Song *et al.*, 2020). The thermal recovery efficiency of the CO_2 -EGS is improved and CO_2 loss is reduced by lowering the reservoirs permeability and initial temperature. Hence, CO_2 based EGS are far more vulnerable to reservoir pressure than H_2O based EGS systems (Wu *et al.*, 2021). Water mobility is dominated by viscosity effects, which decreases considerably as temperature drops. The heat extraction process via CO_2-EGS method is depicted in Figure 7.

3.6 Numerical simulation techniques in enhanced geothermal systems

Numerical simulation methods are well known techniques in all the major industrial operations which simulate the desired conditions before actually implementing them. These methods are cost effective, efficient and most importantly safe especially when dealing with deep subsurface conditions and HDR reservoirs (Cui and Wong, 2021). There are many types of simulators available which have different capabilities; however a single simulator model might not be useful throughout the life of an EGS system. During the early stages of an EGS project, due to the scarcity of the available data the simulators which can model the subsurface fracture network would be more beneficial. However, as the project progresses and subsurface data availability is not a constraint, we may advance onto discrete fracture type models which may help in optimization of the major operations such as injection/production operations (Chen and Jiang, 2016).

The existing HDR simulators are not very efficient in dealing with critical variables such as water/rock interaction or handling multi phase fluid, however these are efficient in dealing with dynamic conditions within a fracture network. Reservoir simulation is routine activity in conventional systems dealing with steam, hot water or multi phase fluids. However EGS systems are complex to model because of the complexity of the subsurface fracture networks. Information can be gained regarding the modelling of EGS reservoirs by studying artificially fractured systems in HDR projects.

It is imperative to correlate EGS reservoir systems in order to establish a framework for identifying its common characteristics with the hydrothermal reservoir systems. The basic understanding of porosity and permeability with the natural fracture network can be correlated with the hydraulically fractured artificial fractures. However, the EGS systems mainly aim at improvement of permeability of the reservoir for optimum heat extraction via injection fluids. Hence the heat from the HDR can be extracted by the movement of the injected fluids via artificially created fracture network.

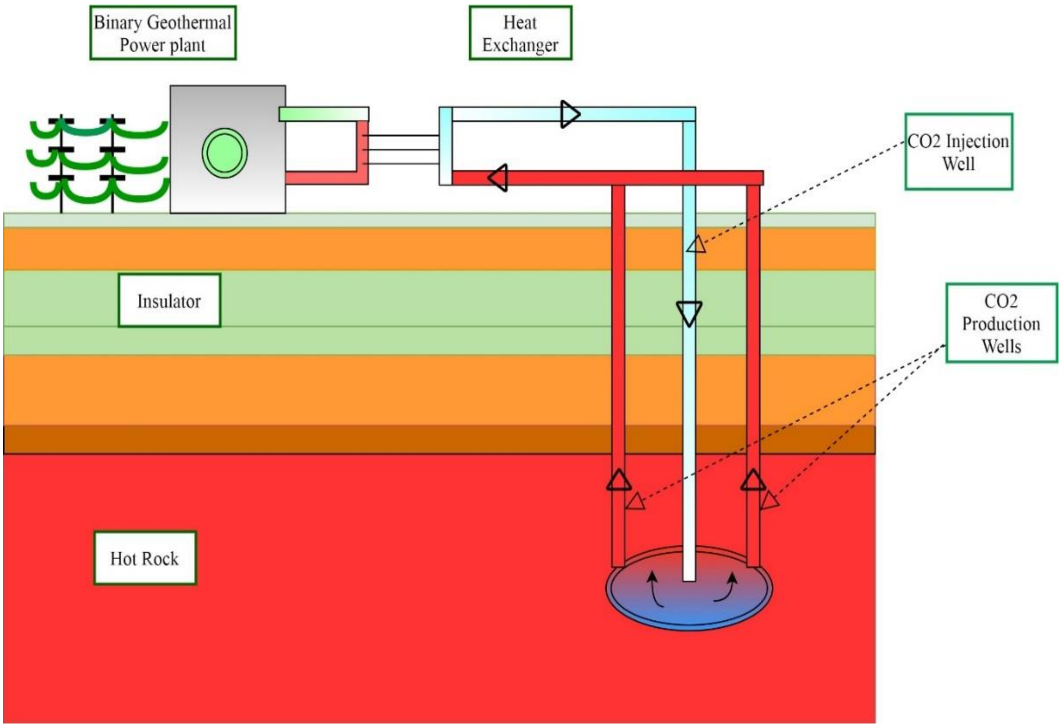

Fig. 7. CO_2 as a heat transmission fluid in EGS (modified after Yao *et al.,* 2018)

In order to model the subsurface fracture network, an effective continuum approach with thermodynamic equilibrium is one of the efficient methods. However, this method is valid only when fracture spacing is less than 2-3 meters or hydraulic conductivity of the rock is low. But in the case of artificial fracture network the fractures are widely spaced making explicit modelling of the fractures more appropriate. Discrete fracture networking can provide an appropriate design of the subsurface fracture network rather than the effective continuum approach. Based on the desired parameters for EGS reservoirs, researchers have demarcated the reservoir simulators in two categories which are hydrothermal simulators and HDR simulators. These simulators can have applications in the field of EGS reservoirs. HDR simulators and hydrothermal simulators are discussed in the following sections.

3.6.1 HDR reservoir simulators

The HDR system modelling is complicated and expensive task as it involves the understanding between key rock properties during reservoir operations. Along with this it also requires long term reservoir performance prediction. A numerical modelling tool is required to understand the interactions between various complex phenomena going on inside the reservoir. There has been extensive work going on in the field development of 1D, 2D, 3D geometric models using stochastic fracture network model for prediction of thermal performance of HDR systems under long term simulation (Robinson and Kruger, 1998; Jupe *et al.* 1995a; Kolditz and Clauser 1998). GEOPHIRES v2.0, GEOTH3D, FRACTure, Geocrack2D, and FRACSIM-3D simulators are currently being used to model HDR geothermal systems.

FRACTure stands for Flow, rock and coupled Temperature effects. It is a 3D finite-element algorithm that handles discrete-fracture problems and predicts the long-term trends of a HDR reservoir (Kohl and Hopkirk, 1995). This simulator uses FOTRAN77 as the programming language. The simulator is able to simulate all the major interactions and processes such as hydraulic (laminar and turbulent), thermal (various transport materials) and mechanical (elastic) (Kohl *et al.*, 1997). It can also simulate non linear stress dependent features or linear elastic effects. The software is able to model the experimental injection steps in a stepwise linear time flow fashion. This simulator is useful in various industries such as geothermal, oil and gas, radioactive etc. This simulator however is not suitable for multiphase flow or chemical processes (Sanyal *et al.*, 2000).

The GEOTH3D simulation has been tested on the Ogachi, Hijiori, and other reserves. It uses micro seismic data patterns as a reference for permeability variation. (Yamamoto *et al.*, 1997). GEOTH3D uses a three-dimensional relatively limited methodology based on Darcy's law to resolve mass balance. When searching for non-uniform pore sizes corresponding to micro seismic strength in a geological formation, easily available micro seismic data sets should be employed. As a consequence, flow is substantially higher in reservoir sites with the most micro seismic events all through the activation (Chen *et al.*, 2020). This model however is not applicable to discrete fractures and overestimates energy production with respect to porous media models

GEOCRACK is another HDR simulator which is a finite-element-based method, focusing on fracture flow (Swenson and Hardeman, 1997). The software has been validated at places like Hijori, Fenton Hill etc. for reservoir modelling. The program is able to perform simulations at the geometry level by handling features like fractures and wellbore area (Swenson, 1998). This method is however not applicable to porous medium. The method also lacks ability to couple shear displacement with the fracture aperture.

The *FRACSIM-3D* is a 3D simulation code program (Xu *et al*., 2014). It's a fracture network-based convective heat transfer concept (Zhenzi, 1998; Jing *et al*., 1998; Tezuka and Watanabe, 2000). The simulator is helpful in understanding about the effects of stimulation and fluid circulation on shear stress of a fracture. It also simulates the changes in the thermo elastic properties and chemical changes due to fluid circulation. FRACSIM-3D is an important tool in both reservoir simulation and stimulation. It can help in understanding about the quality of well stimulation operation.

GEOPHIRES v2.0 is an updated version of techno economic tool GEOPHIRES. It combines the technical and economic calculation capabilities. The technical models can help to assess the correlations from reservoir to the surface. Along with this cost calculation can also be done via this software. The code is publically available making it modifiable for various scenario-based usages (Beckers and McCabe, 2019).

3.6.2 Hydrothermal reservoir simulators

In order to optimise geothermal reservoir utilization, analysis of hydrothermal processes is critical. Reservoir simulators help to understand about the reservoir geometry including structural geology, reservoir behaviour, long term reservoir characteristics, well path design, wellbore planning and pressure drawdown in a producing well. Various simulators are developed for modelling of hydrothermal reservoirs such as TOUGH2, TETRAD, FEHM etc. Some of them are discussed below.

For non-isothermal flows in porous and fractured media of multi-component and multi-phase fluids numerical simulation software *TOUGH2* is used. This simulator also offers features such as capability to handle different fluid mixtures, an inbuilt internal version control system to make sure reference ability of code applications and the ability to process geometric data (Pruess, 1991). TOUGH2 has inbuilt software potential to model the partition of the rock matrix in a linear way. 1-D, 2-D, and 3-D structure of porous or fractured medium can be modelled in TOUGH2. This code goes into great detail into gas, including the principal gas species living in geothermal resources. For soluble substances, the impacts of NaCl on permeability, porosity, and precipitating impacts are discussed. Deformation and high flexibility of rocks mimic the effect of temperature and pressure on essential reservoir parameters like porosity and permeability, consistent characteristics are used.

TETRAD is another numerical engine based on finite difference algorithm. It is used to increase the prediction capabilities which are very useful in geothermal reservoir management. TETRAD evaluates reservoir properties as input parameters and simulates an accurate model. It can investigate major properties such as geological structures inside the reservoir, fluid relative permeabilities, porosity parameters etc. It can predict the importance of placement of new wells on the present reservoir geometry. However, the effects of flow-channelling are not factored into the numerical engine of the software. TETRAD has a reputation for being one of the most user-friendly simulators in the business.

FEHM stands for Finite-Element Heat and Mass Transfer algorithm that has been used to model many hydrothermal situations such as groundwater, oil and gas, chemical, nuclear waste etc. (Zyvoloski *et al.,* 1997; Bower, 1996). It can simulate dynamic conditions such as non-isothermal, multiphase, multi-component flow. The porosity and permeability of the media can be affected by pressure and temperature. In FEHM, you may model two-dimensional, two-dimensional radial and three-dimensional geometries. Because it can simulate water and steam phases, as well as heat transfer via convection and conduction, FEHM is well-suited for EGS simulations. FEHM doesn't have any mechanical connections, but it does include a tracer-test modelling interface that facilitates in calibration.

To mimic hydrothermal reserves, the STAR simulator was created. Oil and gas reserves can also be modelled using this simulator. It employs the bounded approach to partition the continuity equation. It can model in one dimension, two dimensions, and three dimensions. The simulator can be used to mimic the impacts of temperature and pressure variations on material deformation, porosity, and permeability, among many other things (Bower 1996; Zyvoloski *et al*., 1997). To explain the shift in equilibrium between the rock matrix and cracks, a grid street system is employed to describe temperature and pressure fluctuations. However, the software is not able to model the effects of flow channelling and stress on fracture diameter (Bower, 1996; Zyvoloski *et al.,* 1997).

4. Discussion

Three basic aspects, namely heat, fluid and permeability constitute an in-situ geothermal system, known as a hydrothermal system. Whenever hot rock occurs but natural permeability or moisture content is insufficient, an EGS is created. Fluid is pumped into the ground under precisely regulated conditions, causing previously closed cracks to re-open, resulting in permeability. Water can move through the fractured formation and convey heat to the surfaces, wherein power can be produced, using the enhanced permeability. A large amount of the total cost of an industrial EGS plant is spent on the ground power plant. Artificially built subsurface thermal reservoirs are mostly used for EGS research and developments. EGS services can range from enhancing traditional geothermal sources, in which additional liquid is discharged through a hydrothermal system. Whereas in HDR EGS increases permeability with the help of stimulation in location where no natural geothermal possibilities exist.

There are several methods now a days which are being used to exploit EGS. Hydraulic fracturing (HF) is one such method which is most promising in nature to extract EGS. New technologies in the fields of supercritical geothermal plants and hot sedimentary reservoirs have the potential to reduce cost and challenges, broaden the geographic relevance of new geothermal resources and significantly boost geothermal energy output share (AbuAisha *et al.,* 2016). Carbon dioxide as a storage heat transfer medium for EGS can increase reservoir storage performance with time due to the high density and low viscosity at supercritical situations. The geochemical activities of SCCO2-rock combination have a significant impact on dissolution of minerals and precipitation, according to studies (Pan *et al*., 2017). This has consequences for increased energy recovery and CO2 capture in the ground (Brown, 2000; Yao et al., 2018). Mini earthquakes are created by HF-induced seismic activity. However, the size of these events is quite minimal, inflicting very little harm to the people and facilities on the ground (Majer *et al.,* 2007). There have been a bunch of new technology innovation for reservoir simulation that have come to market. In this study, numerous simulators including such as hydrothermal simulations and HDR simulators were reviewed. It’s been discovered that each simulator model has its own set of advantages and disadvantages. An individual model may not be sufficient for all EGS procedures or for each construction project.

FRACTure is a distinct fracture numerical simulation code that simulates the interaction of hydraulic, thermal, and mechanical behaviour in fragmented media. Flow pattern through a porous host rock and discontinuous fractures is shown in the concept. Darcian and turbulent management formulas can be used to describe the flow behaviour. Porous mediums are subjected to thermo - elastic and porous elastic processes, with crack opening being nonlinearly linked to rock strain. Heat transfer in rock formations and transfer in fluids are examples of heat transfer, which is linked to flexibility and pyrolysis via thermal expansion and nonlinear stress - strain relationships.

Micro seismic information was used as a guideline for permeability dispersion in their GEOTH3D simulator, which was used to the Hijiori, Ogachi, and Fenton Hill basins. GEOTH3D solves mass balance as per Darcy's law using a 3D finite differential approach. The Hijiori and Soultz reservoirs were modelled using FRACSIM-3D algorithms (which included fracture network topologies of flowing fluid and heat transmission). Thermal heat transmission in porous material can be described using this model. The existing seismic data information would be used to determine non-uniform porosity proportionate to the seismic data strength whenever used to geothermal resources. The Hijiori and Soultz basins were modelled using FRACSIM-3D algorithms (which included fracture network topologies of flowing fluid and heat transmission).

Swenson and Hardeman (1997) created Geocrack2D, a bounded simulation that concentrates on fracturing circulation which has been used to study the Fenton Hill and Hijiori basins. When the flow occurs in cracks, the program can address associated thermal, hydrostatic, and mechanical issues. A Geocrack2D model is made up of nonlinearly connected rock pieces with distinct fluid channels between them. TOUGH2 is a multi-phase, multi-component fluid flow and heat flow in porous and cracked medium numerical modelling programme developed by the Lawrence Berkeley National Laboratory in the United States. TOUGH2 can simulate the geometries of pores or fractures media in 1-D, 2-D, and 3-D (Sanyal *et al*., 2000). The mechanisms of heat and mass transmission are inextricably linked. TETRAD is a bounded numerical simulator created by the Calgary Computer Modeling Group in Alberta, Canada, which has been widely utilised in the modelling of hydrothermal, oil, and natural gas reserves. Traditional mathematical expressions are used to express continuity equation, which are then segmented.

The simulation can replicate 1D, 2D, and 3D heat and mass transfer in porous or fractured media because the formulas are fully connected. Hydrothermal, oil, and gas reserve simulations have been performed using the STAR simulator built by Maxwell Technologies in San Diego, California. A numerical solution approach is used in the linearization of the conservation equations. It's a 1D, 2D, or 3D simulator with all of the features found in typical thermal reservoir simulations, such as tracer module, NaCl deposit and dissolving, and non-condensable gasses. At Fenton Hill Reservoir, the Los Alamos National Laboratory's FEHM (Finite Element Heat and Mass Transfer) programme has been used to model thermal liquids, oil and gas basins, nuclear waste segregation, groundwater models, and HDR storage tanks. In porous materials, it replicates non-isothermal, multistage, and multi - component movement. The heat and mass transport coefficients of fluid flows in highly permeable mediums are addressed using the controllable volumes finite element model. In porous materials, it models non-isothermal, multistage, and multi component flow. The heat and mass transport coefficients of fluid flows in porous and permeable mediums are addressed using controllable volumes finite element model. Temperature and pressure affect the medium's porosity and permeability.

However, EGS stimulation can have negative environmental impacts. EGS programs are still in the early stages of development, with challenges to overcome, expertise to gain, and complex technologies to deploy. A technically and economically viable geothermal project will require methodical risk analysis and early thorough feasibility studies. Acid activation or hydraulic treatment processes aid in the development of artificially improved hydraulic permeability in low-permeability reservoirs. As a consequence, the EGS concept aims to make geothermal utilisation feasible in a wide range of settings, thereby unlocking a huge untapped resource (Huenges, 2016). EGS-induced seismic activity is not a challenge in the development of geothermal energy sources. As per, the research $SCCO_2$ instead of freshwater as a thermal transfer fluid in EGS, could enhance overall heat recovery (Pan *et al*., 2017). Fluid loss in a "traditional" EGS operation would have been inconvenient and costly. Fluid loss in a CO_2-fueled EGS system would allow for the geological storage of this “green - house” gas. Eventually for carbon management situations, this storing creates financial rewards and incentives. It will help to improve the EGS's profitability (Pruess, 2006). All of the simulators listed in the techniques section above could model fractures to some extent and include a tracer component. The use of EGS offers a huge potential in terms of geothermal energy extraction yields.

5. Conclusion and future research

The present research reviews the progress in enhanced geothermal system. It evaluates the progress in the domain of reservoir characterization, resource classification, drilling technologies, hydraulic fracturing and reservoir simulation. It also discusses the impact of the same on electricity generation. The paper reviews the aspect of seismic and micro-seismic activities associated with hydraulic fracturing for exploitation of deep geothermal prospects. It has been found that although small scale tremors are generated while HF, the consequences of the same on human life or buildings is insignificant. However, the components of fracturing fluids pose a hazard to ground water. The present study discusses about the usage of super critical CO_2 as HF fluid instead of water to mitigate the issues of CO_2 emissions. The usage can also remediate the threats that the fracturing fluid pose. Our carbon footprint will decrease as the share of geothermal energy sectors grows, and our ecosystem will benefit from the same.

The present study recommends that the future of EGS lies in mitigating the risk associated with micro seismic events and developing technologies for safe practices. Exploring and exploitation of EGS is still in nascent stage and research on the same will definitely reduce the risk associated with the same. Systematic risk assessment and early and extensive feasibility studies are implemented essentially nowadays. These implementations would make sure technological and commercial success of geothermal project.

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Conflict of interest statement

On behalf of all the authors, the corresponding author states that there is no conflict of interest.

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