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Impact of Fluid Thermophysical Properties on Long-Term Fluid Circulation and Heat Production in Enhanced Geothermal Systems

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ABSTRACT

Enhanced Geothermal Systems (EGS) are a promising technology for harnessing Earth's heat for energy production. Most previous studies simulating EGS processes have assumed constant thermophysical properties, such as density and viscosity, for the circulating fluid. In this study, we modeled several cases with varying fracture geometries to assess the impact of temperature-dependent thermophysical properties, particularly density and viscosity. The results indicate that although density variations with temperature are relatively small, they can still influence simulation outcomes due to their effect on gravity-driven fluid movement. This impact is more pronounced when wells are aligned vertically, leading to predominantly vertical fluid flow. In contrast, viscosity exhibits a significant reduction with increasing temperature. At the high temperatures typical of the Utah FORGE site, viscosity can decrease by an order of magnitude. Incorporating temperature-dependent viscosity in the simulations significantly lowered production temperatures and slowed fracture propagation. Based on these findings, it is crucial to account for temperature-dependent density and viscosity variations when conducting EGS reservoir simulations to ensure more accurate predictions.

1. INTRODUCTION

Enhanced Geothermal Systems (EGS) concept represents a promising technology for harnessing the earth's heat for energy production, particularly in Superhot reservoirs. EGS involves creating or enhancing subsurface fracture networks to allow fluid circulation and heat extraction. Reservoir growth by fracturing is a critical step and is dominated by stress regime, rock structure and fabric as well injection conditions. In addition, reservoir stability is a major concern during circulation as it impacts fluid loss which can be detrimental to power production. The efficiency and sustainability of EGS depend significantly on the complex interplay between thermo-poro-mechanical processes and fracture deformation and growth.

When simulating EGS problems, it has been often assumed that the density and viscosity of the circulating fluid remain constant (e.g., Okoroafor & Horne, 2022; Xia et al., 2017; Ghassemi et al., 2007; 2008; Safari and Ghassemi, 2015; Rawal and Ghassemi, 2014). However, it is well known that viscosity varies significantly compared to the other thermophysical properties, particularly for liquids like water and can impact pressure and flow channel deformation (e.g., Ghassemi and Tao, 2016). Although density does not change with temperature as drastically as viscosity, it is still important to access its effect during circulation (JI et al., 2022). Therefore, it is essential to account for variations in viscosity and density with temperature when simulating long term fluid circulation in EGS.

In this work, we carry out a detailed study to investigate the effect of thermophysical properties (specifically density and viscosity) on long term fluid circulation in an EGS.

2. EFFECT OF DENSITY AND VISCOSITY DURING LONG TERM CIRCULATION

In geothermal reservoirs injection fluid density can be reduced due to the high temperature as a result of increase in the fluid volume. On the other hand, the viscosity of most fluids decreases as temperature increases. This means the fluid becomes thinner and flows more easily at higher temperatures. In hydraulic fracture stimulation in hot rocks, if the fluid viscosity drops too low, it can reduce fracture propagation due to high leak-off and can also affect the proppant carrying capacity (Liu and Ghassemi, 2024). These effects are also important during circulation.

The focus of this study is circulation for heat production purposes. To assess the effect of density and viscosity during circulation two fracture geometries are considered. First being a circular fracture with a radius of 500m and the second a rectangular fracture with dimensions 400×150m. For each fracture geometry two sub cases are considered, one with the effect of variable density/viscosity, other without the effect of variable density/viscosity. The circular fracture is discretized into 640 four node quadrilateral elements while the rectangular fracture is discretized into 840 elements. The position of injection well and extraction wells in both fractures are shown in Figure 1.

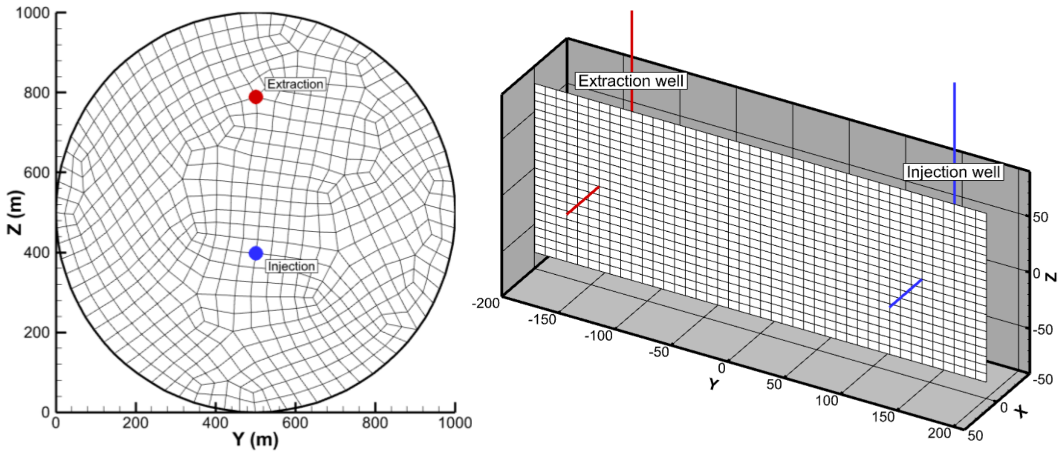


Figure 1: (a) Circular (b) rectangular fractures with injection and extraction well positions.

The value of in-situ stresses and other formation properties used are listed in Table 1 for both fracture geometries. It is important to note that in situ stress, pore pressure and formation temperature gradients are used for the rectangular fracture case, which means these properties change for each element based on their depth (z-coordinate). Additionally, the possibility of fracture propagation during circulation is allowed for the rectangular fracture example.

Table 1: In situ stresses and formation properties (Ratnayake & Ghassemi, 2024).

Parameter	Circular	Rectangular	Units
Fluid injection rate (Q_i)	0.144	0.008	m^3/s
Fluid extraction rate (Q_{ex})	0.142	0.0079	m^3/s
Initial fracture aperture (w_0)	1×10^{-3}	1×10^{-4}	m
Shear modulus (G)	20.88	20.88	GPa
Rock permeability	1.20×10^{-17}	1.20×10^{-17}	m^2
Poisson's ratio (υ)	0.29	0.29	-
Biot's coefficient (α)	0.69	0.69	-
Rock density(ρ_R)	2650	2650	kg/m^3
Fluid heat capacity (C_F)	4200	4200	J/kg.K
Rock heat capacity (C_R)	800	800	J/kg.K
Rock thermal conductivity (K_R)	2.9	2.9	-
Rock linear thermal expansion coefficient (α_T)	6.6×10^{-7}	6.6×10^{-7}	-
Injection of fluid temperature (T_i)	353	353	K
Initial rock temperature (T_0)	470	448	K
Initial joint stiffness (K_n)	1×10^{10}	1×10^{10}	Pa/m
Mode I critical fracture toughness	-	1.8×10^{6}	$Pa.m^{0.5}$
In situ stress vertical	65.13	65.13	MPa
In situ stress maximum horizontal	55.88	55.88	MPa
Insitu stress minimum horizontal	45.81	45.81	MPa
Vertical stress gradient	-	-0.02556	MPa/m
Maximum horizontal stress gradient	-	-0.02182	MPa/m
Minimum horizontal stress gradient	-	-0.01651	MPa/m
Pore pressure gradient	-	-0.00979	MPa/m
Formation temperature gradient	-	-0.17230	K/m

Case 1: Effect of density and gravity

The impact of density is more visible when the extraction well is above the injection well as in the circular fracture example. On the other hand, in the second configuration, where a rectangular fracture is used, the impact of density (gravity) can be clearly observed on fracture growth. Since our main goal in this section is to find the possible effects of density on fluid flow and temperature distribution, a constant viscosity of 0.001 Pa.s was used. Fluid was circulated for 6 months based on the boundary conditions listed on Table 1 and the result of density variation at the end of 6 months is shown in Figure . As depicted the density varies from a minimum of 910 to a maximum of 990 kg/m^3. Notably, the highest-density fluid is concentrated near the injection well. Due to this distribution and the influence of gravity, the high-density fluid is expected to migrate downward as circulation progresses.

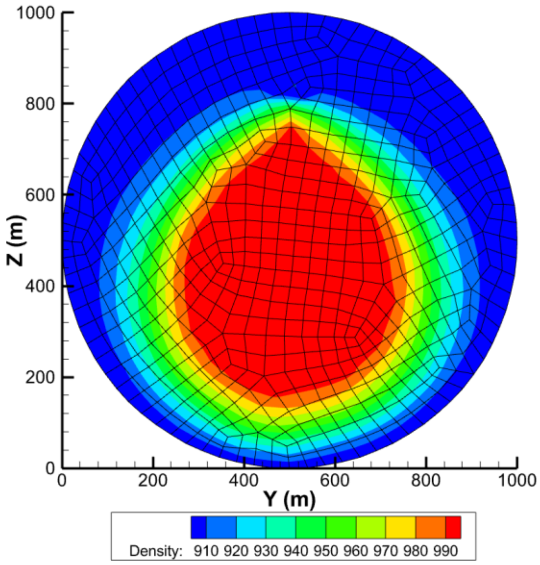
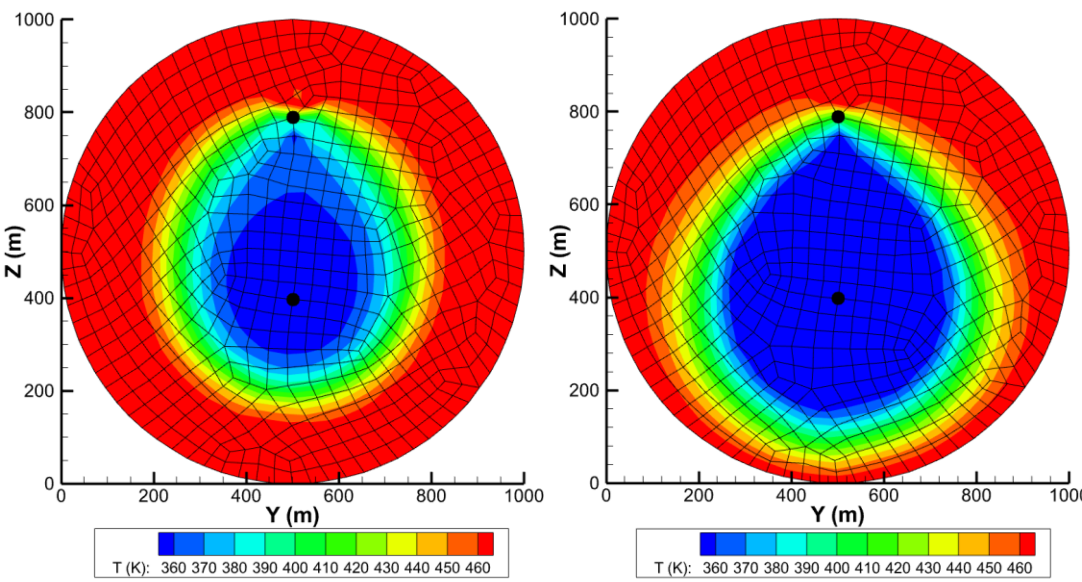


Figure 2: Variation of density (kg/m^3) inside the fracture at 6 months of fluid circulation.

The main objective of incorporating variable density into fluid flow is to introduce the effect of gravity. When the variable density option is not included in these simulations, the gravitational force effect disappears. In order to understand how the introduction of gravitational forces change the fluid flow pattern, a similar case was done without the effect of variable density and gravitational force and a comparison of results are presented in the subsequent figures.



(a) **(b)**

Figure 3: Temperature distribution in the fracture (a) without gravity effect, (b) with gravity effect after fluid circulation for 6 months.

When the gravity force is introduced to the fluid flow equation what we should expect is an additional force that is acting downward. For example, in the case that we consider, the fluid is expected to travel more to the -Z direction before travelling upwards toward the extraction well. Figure (a), (b) shows a comparison of temperature distribution in the fracture after 6 months when the gravity force is not included and when it is included respectively. As can be clearly seen when the gravitational force is introduced, the fluid travels more towards the

-Z direction. As a result, a larger region beneath the injection well experiences cooling. This behavior significantly impacts the production temperature despite having the same production rates (see Table 1), as depicted in Figure 4. The downward fluid movement causes the lower part of the fracture to cool before the region near the extraction well. Consequently, the extraction temperature is higher when the gravity effect is present. However, this trend may differ when the wells are aligned horizontally, which will be analyzed in the rectangular fracture case.

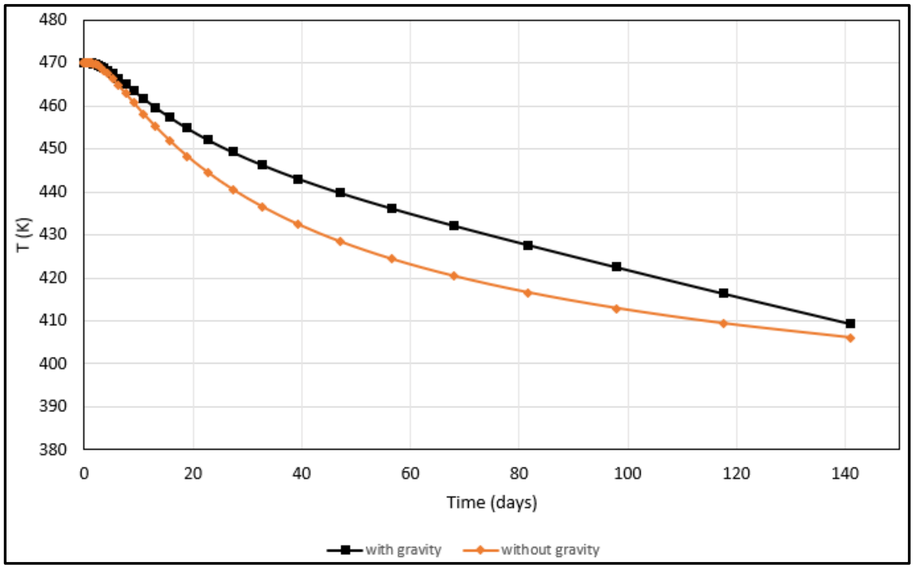


Figure 4: Variation of extraction temperature (K) with time (days) when gravity effect is present and when it's not for circular fracture.

As the effect of gravity is introduced the fluid falls down before starting to move upwards as mentioned earlier. As a result of this, the pressure in the lower part of the fracture increases resulting in a larger fracture width. The propagation status of the fracture is affected by this larger fracture width in the lower portion. Figure shows the mode I propagation status of the two cases. When that is no gravity effect present it can be observed that the KI/KIc values are uniform all around the fracture. Whereas in Figure (b) it can be seen that when gravity effect is present, the lower portion of the fracture has a higher possibility to propagate. Further the value of KI/KIc is higher in this scenario when compared with no gravity effect result.

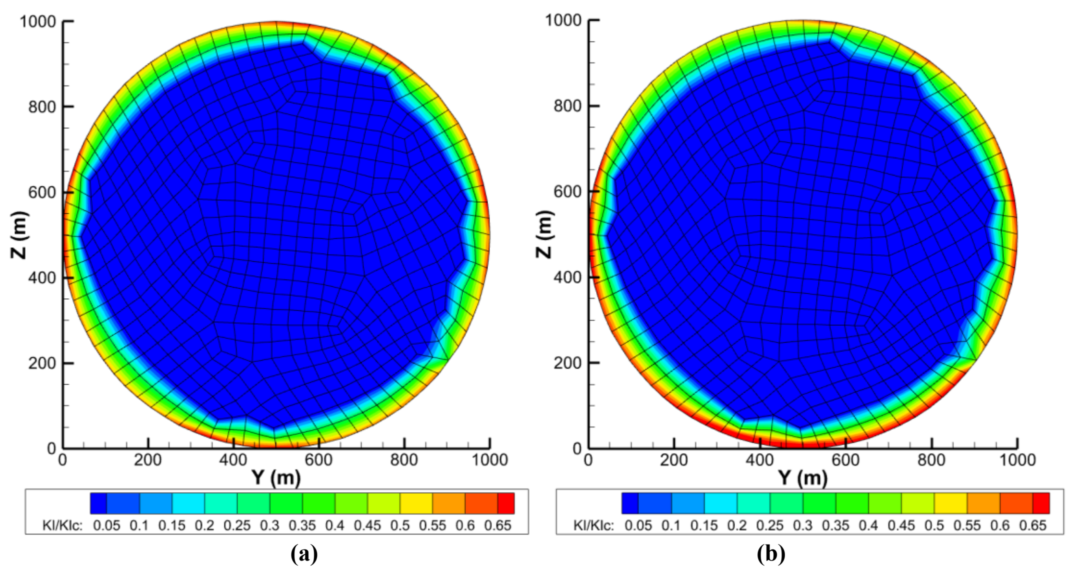
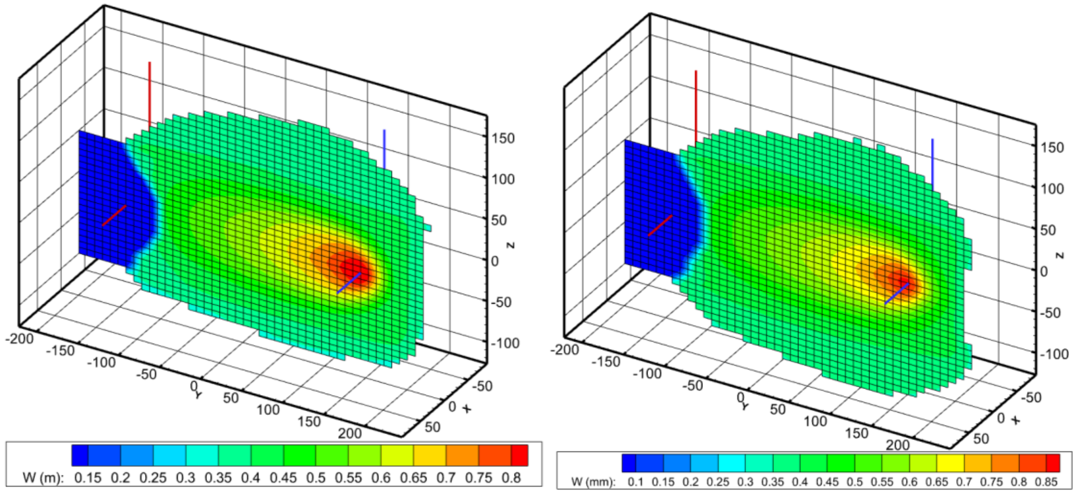


Figure 5: Mode I propagation status of the fracture (a) without gravity effect, (b) with gravity effect after fluid circulation for 6 months. Note that the condition for propagation is not met at this time.

The rectangular fracture setup shown in Figure (b) was used next to find out the effect of density/gravity on fracture propagation. The two main differences of this setup when compared with the circular fracture configuration discussed earlier is the use of stress gradient as mentioned in Table 1and allowing the fracture to propagate. As a result of this, the elements in the upper half of the fracture (+Z) experience a lower normal stress value. The fluid circulation was carried out for 13 years using the boundary conditions lister in Table 1.

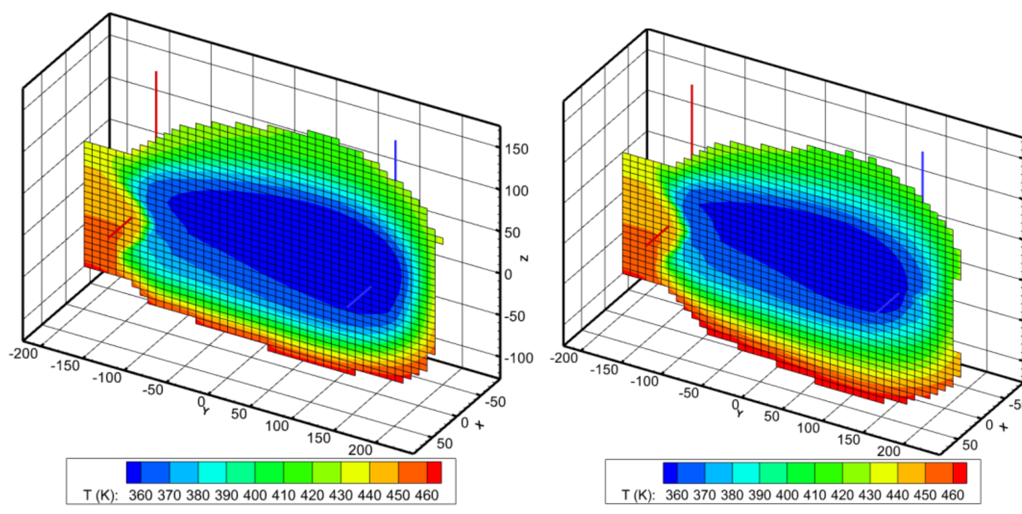


(a) **(b)**

Figure 6: Fracture width distribution (a) without gravity effect, (b) with gravity effect after fluid circulation for 13 years.

Figure (a) and Figure (a) show the fracture width and temperature distribution in the fracture after 13 years when there is no gravity effect. As can be seen the propagation of fracture was primarily upward (+z) direction. The reason for this is the lower normal stress (compared to the driving pressure and thermal stress) that the elements in the upper half of the fracture experience as explained earlier. Due to the lower normal stress, the fluid tends to move in that direction resulting in fracture propagation. Figure (a) also confirms this as the upper portion of the fracture is cooled more when compared with the lower portion.

Figure (b) and Figure (b) show the fracture aperture and temperature distribution after 13 years when the effect of gravity is introduced. In this scenario two forces are being applied on the fluid in two opposite directions. The upward force due to the low normal stress in that direction and the downward force due to the effect of gravity. As a result, the fluid movement happens towards both directions unlike in the previous case. This can be confirmed by Figure (b), which shows the propagation of the fracture occurred in both upward (+Z) and downward (-Z) directions. Figure 8 compares the variation of production temperature over time for scenarios with and without gravity. Although there is a slight difference in production temperatures, it is less significant than in the previous circular fracture case with vertically aligned wells. This indicates that the effect of gravity is more pronounced when fluid movement predominantly occurs in the vertical direction.



(a) **(b)**

Figure 7: Temperature distribution in the fracture (a) without gravity effect, (b) with gravity effect after fluid circulation for 13 years.

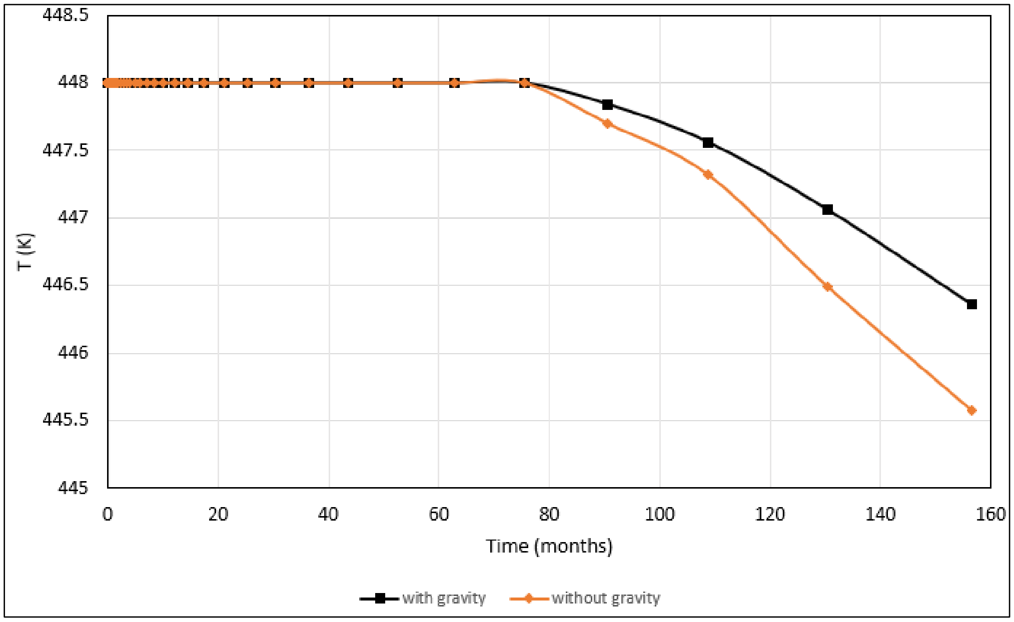


Figure 8: Variation of extraction temperature (K) with time (days) when gravity effect is present and when it's not for the rectangular fracture.

Case 2: Effect of viscosity

The same fracture setup and formation properties were used to find the effect of temperature dependent viscosity. The density of injected fluid is kept constant at a value of 1000 kg/m^3. Figure shows the distribution of viscosity values in the fracture after 6 months of fluid circulation.

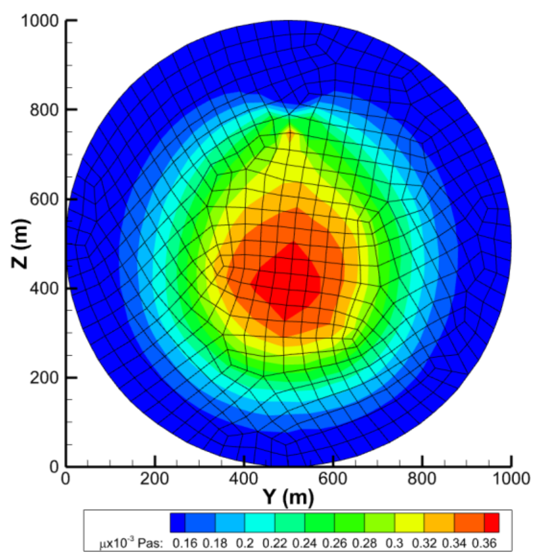
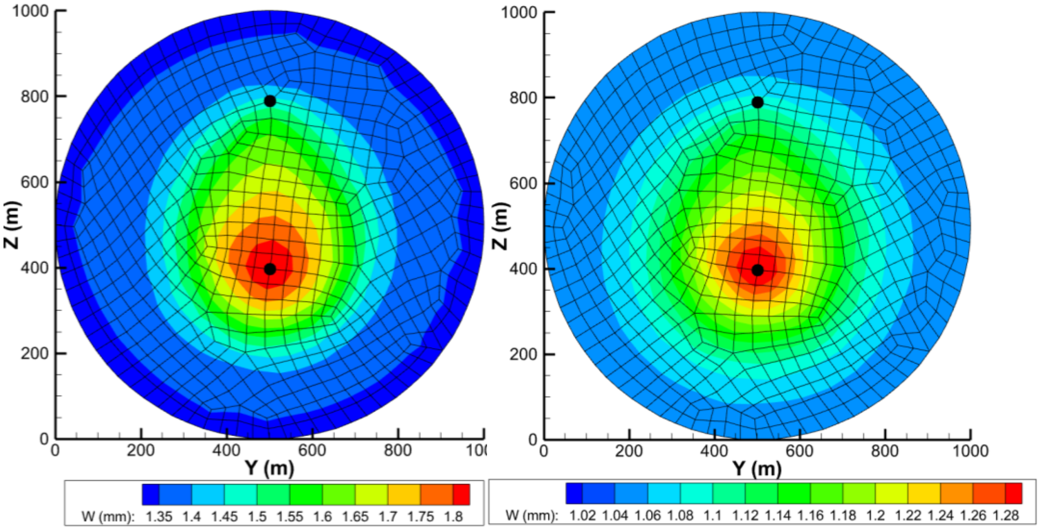


Figure 9: Variation of viscosity inside the fracture at 6 months of fluid circulation

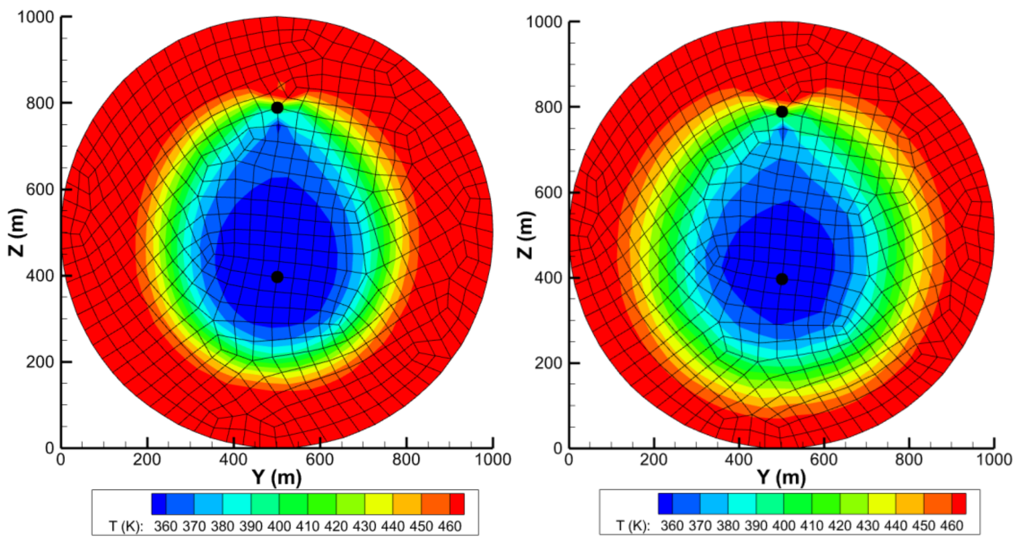
The viscosity values observed here are nearly an order of magnitude lower than that of water at room temperature (0.001 Pa·s). As a result, water flows more easily within the fracture, reducing pressure differences and increasing fluid leak-off. Notably, the change in viscosity with temperature is far more significant than the corresponding change in density. This suggests that viscosity variations are likely to have a substantial impact on fracture propagation and temperature distributions, unlike the relatively minor influence of density changes.



(a) (b)

Figure 10: Fracture width distribution (a) without variable viscosity, (b) with variable viscosity, after fluid circulation for 6 months.

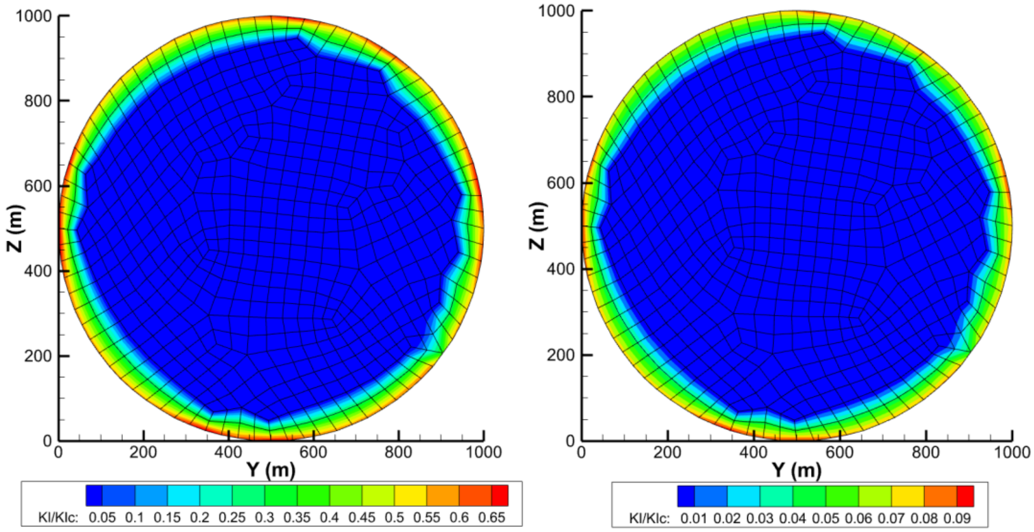
Figure shows a comparison of fracture apertures obtained when using a constant viscosity of 0.001 Pa.s and when the viscosity changes with temperature, respectively. It is clearly observed that when the temperature dependence on viscosity is considered, the fracture aperture reduces significantly as a result of high leak off. This low fracture aperture affects the fracture propagation status as shown in Figure . The KI/KIc values when the viscosity is temperature dependent becomes nearly one order of a magnitude lower when compared to using a fixed viscosity. This effect on fracture propagation is analyzed further for the case of a rectangular fracture next.



(a) (b)

Figure 11: Temperature distribution in the fracture (a) without variable viscosity, (b) with variable viscosity, after fluid circulation for 6 months.

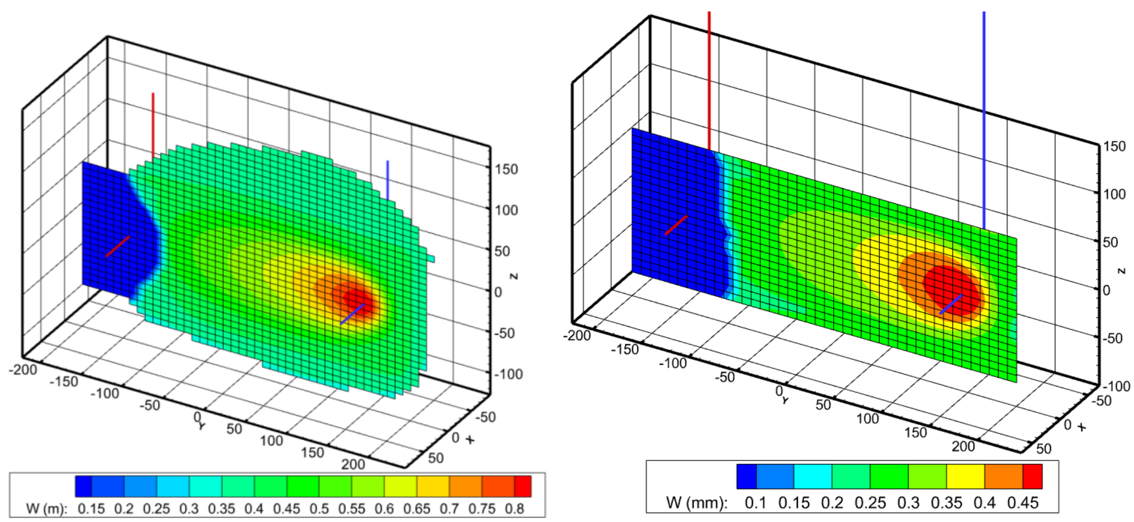
Figure shows how the temperature distribution is affected by viscosity. As can be seen although there is no significant difference as in previous parameter, the area being cooled is larger when viscosity is temperature dependent.



(a) **(b)**

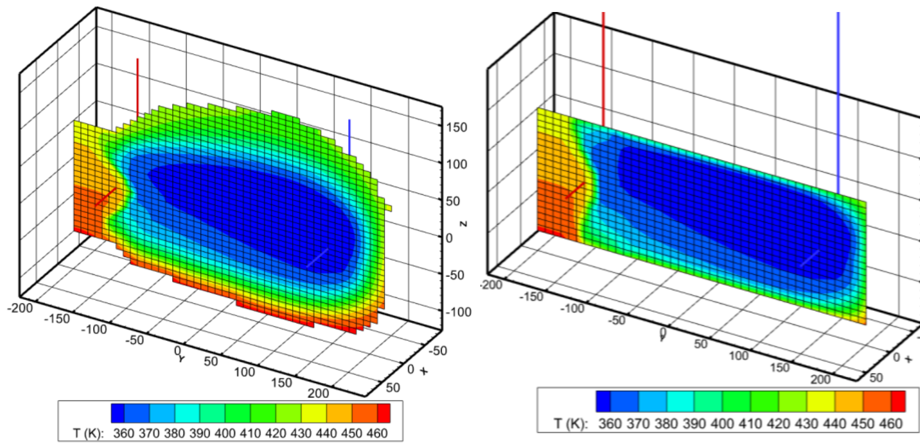
Figure 12: Mode I propagation status of the fracture (a) without variable viscosity, (b) with variable viscosity, after fluid circulation for 6 months.

Now we consider a different arrangement, namely two laterally situated wells connected by a rectangular fracture. The injection, extraction rates along with boundary conditions are listed in Table 1. The results after circulation of 13 years are shown in Figure (b) and 14(b) showing the shape of the final fracture with fracture aperture and temperature distribution. As can be seen from the plots, in the case of variable viscosity the fracture did not propagate at all even though it was circulated with cold fluid for 13 years. The reason for this is the lower fracture pressure and aperture resulting from lower viscosity and high fluid leak off. In fact, this can be seen when comparing the fracture apertures in Figure 13 (a) and (b) where it is significantly low when temperature dependent viscosity is used. Figure shows the induced pressure distribution in a cross section around the fracture after 13 years of fluid circulation. As can be seen, for constant viscosity the pressure build up in the surrounding rock is significantly higher than variable viscosity. In variable viscosity when it drops low at high temperatures, fluid flows easily though the pore space dissipating the pressure quickly. As a result of this pressure buildup in the vicinity of the fracture is minimal.



(a) **(b)**

Figure 13: Distribution of fracture width of the fracture after fluid circulation of 13 years for (a) constant viscosity, (b) variable viscosity.



(a) **(b)**

Figure 14: Distribution of temperature inside the fracture after fluid circulation of 13 years for (a) constant viscosity, (b) variable viscosity cases.

Referring to Figure 13, it is observed that the fracture has cooled more in the variable viscosity case. Importantly, this contrast is reflected in the production temperature vs time plot shown in Figure . The temperature of the extracted fluid begins to decline around six years in the constant viscosity case, while in the variable viscosity case, it starts to decline within the first few months. There are two possible reasons for this discrepancy. First, when temperature reduces the viscosity, the fluid's ability to flow freely increases, allowing it to move quickly towards the extraction well and cool it rapidly. Second, in the constant viscosity case, the propagation of the fracture exposes more hot rock, resulting in a longer cooling time. (there is no propagation observed in variable viscosity case).

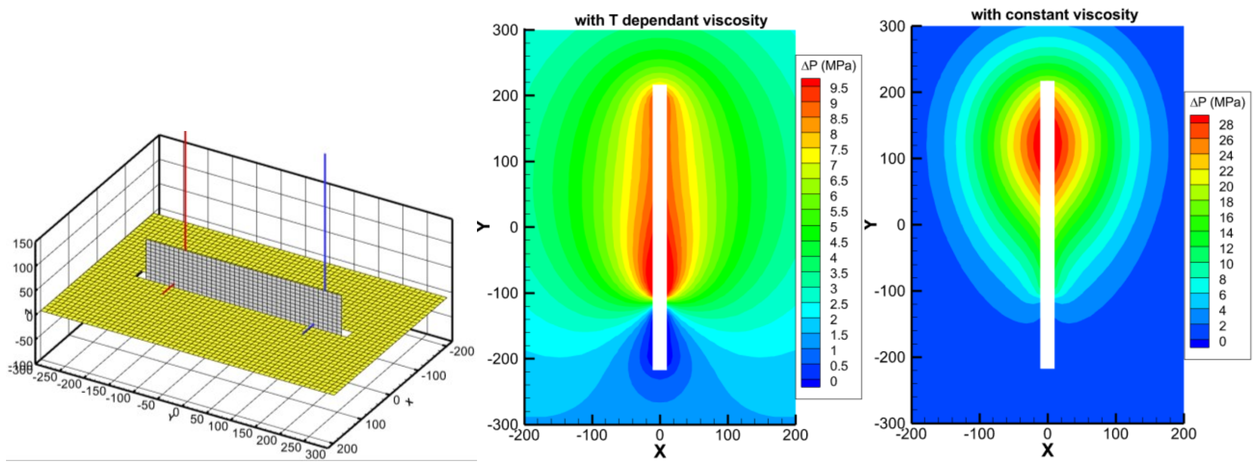


Figure 15: Pressure distribution around the fracture for constant and temperature dependent viscosity cases after fluid circulation of 13 years.

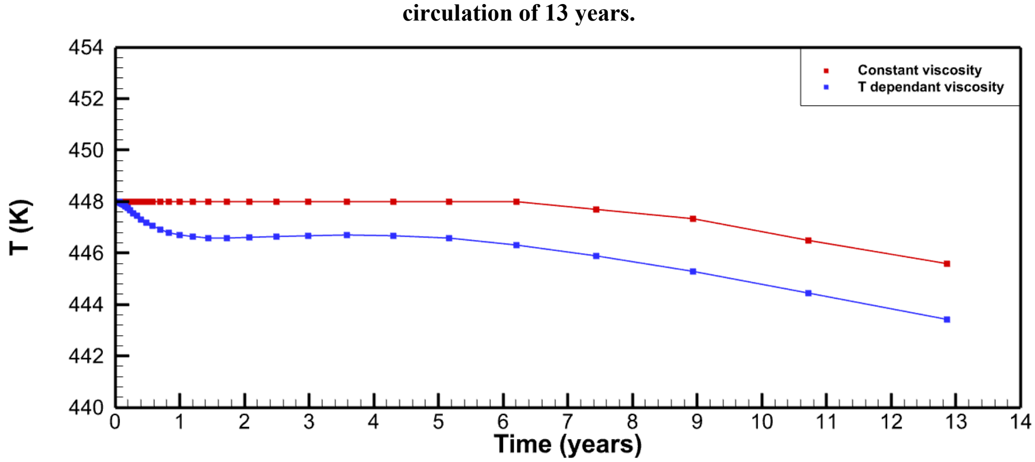


Figure 16: Extraction temperature vs time plot for constant viscosity and variable viscosity cases.

CONCLUSION

The study highlighted the crucial roles of fluid density, gravity, and temperature-dependent viscosity in hydraulic fracture simulation. Gravity introduced a downward force, influencing fracture propagation direction, while lower fluid viscosity at high temperatures significantly reduced fracture propagation due to increased leak-off. These effects were directly linked to heat production, showing that fracture propagation delays temperature decline by exposing new hot rock, enhancing geothermal energy extraction efficiency. However, it was found that this advantage will not happen if the fluid viscosity falls too low due to high temperature.

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