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Investigation of Rheological Behavior of Silica-Based Nanofluids for Enhanced Geothermal Systems

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ABSTRACT

Geothermal energy is a vital component of the global transition to sustainable energy, offering a reliable and environmentally friendly alternative to fossil fuels. Among geothermal technologies, Enhanced Geothermal Systems (EGS) present significant potential for energy extraction through advanced heat-mining techniques. Despite their promise, EGS faces challenges such as thermal short-circuiting, where working fluids preferentially flow through high-permeability fractures, reducing heat recovery efficiency.

This study explores silica-based nanofluids as a novel solution to mitigate thermal short-circuiting and optimize fluid flow in EGS reservoirs. Nanofluids were formulated by dispersing fumed silica (Aerosil 200) at concentrations of 2–6 wt% in polyethylene glycol (PEG 6000). Rheological tests revealed that the nanofluids exhibited low viscosity at zero shear rate, facilitating ease of injection into reservoirs. Under higher shear conditions, the fluids demonstrated shear-thickening behavior, with viscosity sharply increasing. The rate of shear thickening is affected by silica concentration. Additionally, thermal conductivity improved with increased silica content.

The shear-thickening behavior of silica-based nanofluids facilitates permeability control by redirecting fluid flow toward high-temperature zones through the formation of hydroclusters. This not only enhances heat recovery but also improves the thermal conductivity of the working fluid. These findings highlight the potential of silica-based nanofluids to address critical challenges in EGS and advance geothermal energy efficiency.

1. INTRODUCTION

The continuous stringent environmental regulations and depletion of fossil fuels have led to the emergence of renewable energy as an alternative energy source. Renewable energy systems, such as solar, wind, and geothermal energy are gradually replacing fossil fuels in developing a new, carbon-free, and sustainable energy landmark as reported by Lior (2008) and Konate et al. (2024). Among the renewable energy sources, geothermal energy is swiftly gaining significant ground due to its high capacity, constant year-round energy supply, and ability to remain unaffected by seasons unlike wind and solar energies (Vivas et al., 2020 and IEA, 2011). Geothermal energy is highly versatile, with applications ranging from direct uses such as food processing, fish farming, greenhouse climate control, and space heating, to electricity generation. The diverse nature of geothermal resources allows for categorization into three main types: (1) geothermal heat pump systems, (2) hydrothermal resources, and (3) enhanced geothermal systems (EGS) as highlighted by the Geovision Report (2021). Unlike geothermal heat pumps and hydrothermal resources where the focus is on harnessing heat from shallow to medium-depth reservoirs, EGS technology focuses more on the extraction of heat from hot, dry rock at significantly deeper depths. These systems access vast heat reservoirs at depths of 5 to 10 km (16,400 to 32,800 ft). The estimated heat energy available at such depths surpasses 2000 times the total annual energy consumption of the United States, as highlighted by Tester et al. (2006) and Plummer et al. (2017). EGS relies on pre-existing fractures and artificially created fractures to extract heat from hot dry formations at deeper depths, thus facilitating its deployment over a wide range of geological settings.

Despite their huge potential, EGS technology is still either under-developed or at the demonstration and development stage, and a series of technological, economic, and environmental challenges continue to limit their use for commercialization (Tester et al., 2006; Latimer and Meier, 2017). It is imperative to address some of these challenges to optimize the development and commercialization of EGS systems. One of the most critical challenges is thermal short-circuiting (Tester et al., 2006; Pollack et al., 2021). Thermal short-circuiting occurs when the working fluid, typically water or brine, flows preferentially through high-permeability fractures within the EGS reservoir, thus preventing the fluid from reaching zones with low fracture conductivity where the thermal output could be higher. These fractures with high aperture offer less resistance to fluid flow. As a result, the fluid-rock thermal interaction is greatly reduced, leading to suboptimal heat transfer and efficiency of the geothermal system (Tester et al., 2006; Asai et al., 2018). In their report on the future of geothermal energy, Tester et al. (2006) emphasized the impact of thermal short-circuiting in the Soultz, an EGS system where one fracture with a large aperture took up 70% of the total working fluid flowing through the reservoir and ultimately reduced the useful recovered thermal energy of the entire reservoir. This emphasizes the urgent need for a solution to reduce fluid flow through large fracture pathways in order to optimize the overall thermal energy recovery of an EGS reservoir.

This work investigates the potential of silica-based nanofluids as a novel solution to mitigate thermal short-circuiting and optimize fluid flow in EGS reservoirs. Through examination of the rheological properties and thermal conductivity of silica-based nanofluids, this study explores how their behavior can be tailored to control fluid flow in large fracture zones while optimizing the reservoir heat extraction efficiency. The findings aim to contribute to the advancement of EGS development as a viable alternative to fossil fuels.

2. EXPERIMENTAL METHODOLOGY

2.1 Materials

The silica nanoparticles used in this study were Aerosil 200, a hydrophilic fumed silica with a specific surface area of 200 m²/g and a silica (SiO_2) content exceeding 99.8%. In addition, polyethylene glycol (PEG) with a molecular weight of 6000 g/mol was combined with distilled (DI) water to prepare the carrier fluid required for the dispersion and suspension of the silica nanoparticles. Various concentrations of silica were used to formulate the nanofluids for this study, and the corresponding weight percentages are detailed in **Table 1**. All materials were used in their received form without further modification.

Table 1: Composition of the formulated nanofluids.

Nanofluid ID	Concentration of PEG Solution (wt%)	Concentration of silica (wt%)
PEG6000 + 2wt% SiO_2	98	2
PEG6000 + 3wt% SiO_2	97	3
PEG6000 + 4wt% SiO_2	96	4
PEG6000 + 5wt% SiO_2	95	5
PEG6000 + 6wt% SiO_2	94	6

2.2 Methodology

The silica-based nanofluids used in this study are stable suspensions created by dispersing fumed silica (Aerosil 200) nanoparticles into a polyethylene glycol (PEG) solution. The PEG solution serves the role of carrier fluid for the nanoparticles. The nonfluids are formulated using the commonly known two-step preparation method. In this method, the nanoparticles are first produced in dry powder form and then dispersed into the carrier fluid to generate the final nanofluid, as illustrated in **Figure 1**. This method ensures a uniform dispersion of nanoparticles within the fluid, enhancing the stability, homogeneity, and consistency of the suspension. However, a key challenge of the two-step method is the risk of nanoparticle aggregation during preparation, which can undermine dispersion uniformity and reduce the overall effectiveness of the nanofluid. To mitigate this challenge, silica was used in its powdered form and added incrementally to the PEG solution to reduce the likelihood of aggregation. During the preparation, a mechanical stirrer was employed at a high rotary speed of 800 RPM, ensuring that the silica nanoparticles were well-dispersed in the PEG solution. The mixture was stirred for approximately 15 minutes, or until a homogenous fluid was obtained. To further enhance the stability of the nanofluids and eliminate potential impurities or clusters, the suspension underwent ultrasonication at high frequency for 15 minutes at room temperature. Ultrasonication helps break down any remaining agglomerates and improves nanoparticle dispersion within the fluid. Following this, the nanofluids were subjected to a vacuum treatment at 25 ºC for another 15 minutes to remove air bubbles that may have formed during mixing, ensuring a bubble-free and stable suspension.

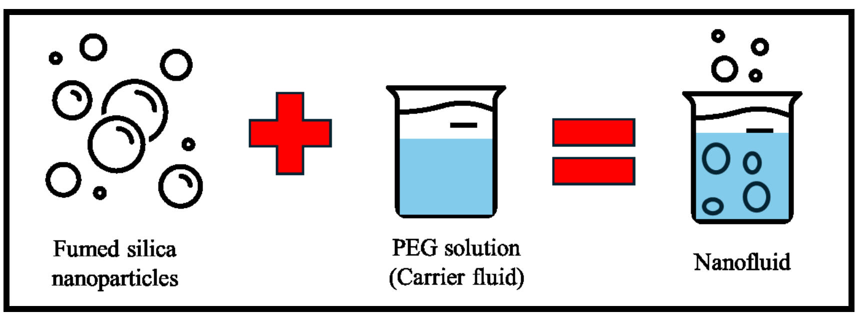

Figure 1: Schematic of the two-step preparation method of nanofluid.

Rheological experiments were conducted to analyze the viscosity behavior, gel strength, and gelation kinetics of silica-based nanofluids under varying conditions. Rheological measurements were performed using a strain-controlled Ares-G2 rheometer (shown in **Figure 2**), which is ideal for accurately capturing the nanofluid's response under controlled strain. The rheometer was equipped with a bob and cup geometry with a 25 mm diameter which was used for all rheological measurements. A volume of 5 mL of fluid was required for each test. Before conducting any rheological tests, an amplitude ramp was performed to determine the viscoelastic linear region (LVR). This is essential for ensuring that subsequent tests, such as frequency sweeps, are carried out within the LVR, where the material's internal structure remains intact and undamaged by external forces. Selecting an appropriate strain rate from this test ensured that no deformation of the nanofluid's internal structure occurred during the measurements. Next, a frequency sweep test was conducted at a temperature of 25 ºC (77 ºF), using a constant strain rate of 10% and varying the angular frequency from 0 to 600 rad/s. This test provided critical insights into the viscosity, storage modulus, and loss modulus behavior of the silica-based nanofluids, thus providing insights into the fluids' behavior under shear conditions.

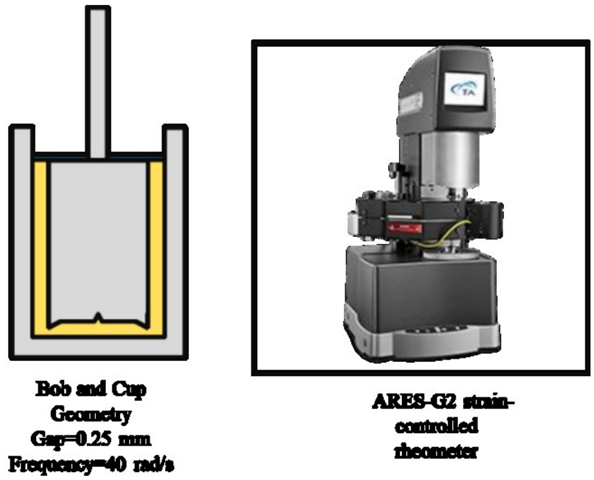

Figure 2: Illustration of ARES-G2 rheometer used for conducting the rheological tests.

Thermal conductivity is a fundamental property that quantifies a material's intrinsic ability to conduct heat. Understanding the thermal conductivity of fluids is essential for optimizing heat transfer rates in various applications, such as geothermal energy systems. In this study, the thermal conductivity of the nanofluids was measured using the Transient Hot Wire (THW) method, a technique that adheres to the American Society for Testing Materials (ASTM) standard D7896-19. Renowned for its accuracy, simplicity, and rapid measurement capabilities, the THW method is a widely adopted approach for determining thermal conductivity. The measurement process involves filling a sample cell (**Figure 3b**) with a minimum of 15 mL of the test fluid. The hot wire sensor, also shown in **Figure 3b**, is connected to the control unit (**Figure 3a**) and then immersed in the fluid. After insertion, the system is allowed to stabilize under isothermal conditions for 5 to 10 minutes before data collection begins. While the THW method is highly precise, one of its primary limitations is its restricted operating temperature range of 10 to 40°C (50 to 104°F). This limitation poses challenges in evaluating thermal conductivity at elevated temperatures. To address this issue, a temperature superposition model can be employed to create a master curve. This model enables the estimation of thermal conductivity beyond the THW method's temperature range, extending the applicability of the data to higher-temperature scenarios.

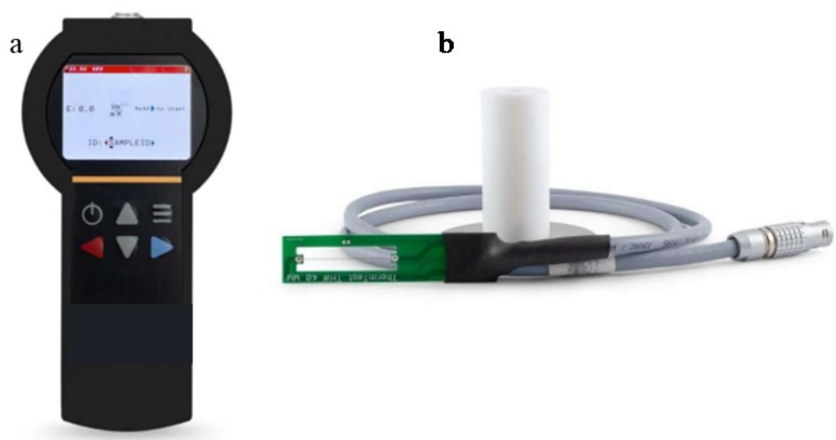

Figure 3: Thermal transient test for thermal conductivity measurement. a) Controller and b) Sensor and sample cell.

3. RESULTS

3.1 Characterization of the carrier fluid

The rheological behavior of nanofluids is strongly influenced by the properties of the carrier fluid, which acts as the medium for dispersing nanoparticles. **Figure 4** presents the viscosity behavior of the PEG-based carrier fluid used in this study. Across all tested concentrations, the PEG-based carrier fluid exhibited Newtonian behavior, characterized by a constant viscosity regardless of variations in shear rates or angular frequencies. This indicates that the fluid's resistance to flow is independent of the applied stress rate, a hallmark feature of Newtonian fluids. Such behavior is commonly observed in PEG solutions with low to moderate molecular weights and concentrations. These findings align with the research of Uzunova et al. (2015), which also confirmed the Newtonian behavior of PEG solutions under similar conditions. The PEG-based carrier fluid demonstrated a low viscosity range, which is a critical attribute for its intended application. Low viscosity enhances the fluid's flow and mixing capabilities, making it an ideal medium for dispersing nanoparticles. The reduced energy losses during flow ensure efficient heat transfer and minimize resistance in applications such as Enhanced Geothermal Systems (EGS). These observations are further corroborated by Uzunova et al. (2015), who highlighted the Newtonian behavior and low viscosity of PEG solutions with comparable molecular weights. Interestingly, the viscosity of the PEG-based carrier fluid increased with higher PEG concentrations. This increase can be attributed to enhanced molecular interactions and polymer chain entanglements, which create greater resistance to flow. As the concentration of PEG rises, these interactions become more pronounced, leading to higher viscosity. This behavior is consistent with the findings of Suzuki et al. (2020), which demonstrated that while PEG viscosity is highly dependent on concentration, it remains constant across varying shear rates, reinforcing its Newtonian nature. The hydrophilic nature of PEG plays a pivotal role in the effective dispersion and stabilization of fumed silica nanoparticles in the nanofluids. PEG molecules interact with silica particles, forming a stabilizing layer that prevents aggregation. This improved dispersion capability ensures the stability of the nanofluid by maintaining uniform particle distribution and preventing sedimentation. The selection of PEG as the carrier fluid in this study was driven by its excellent compatibility with fumed silica nanoparticles, enabling a stable suspension and enhanced overall nanofluid performance.

In summary, the PEG-based carrier fluid's Newtonian behavior, low viscosity, and concentration-dependent viscosity increase, combined with its exceptional ability to stabilize fumed silica nanoparticles, make it an optimal choice for nanofluid formulation. These properties ensure consistent rheological behavior, minimal energy losses, and enhanced nanoparticle dispersion, all of which are critical for the effective use of nanofluids in engineering applications.

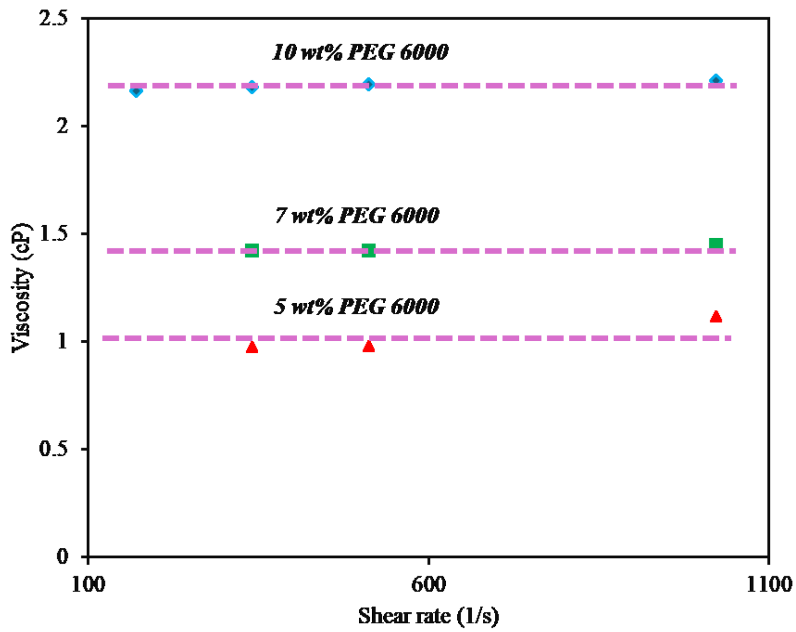

Figure 4: Viscosity of PEG solution for various concentrations of PEG.

3.2 Rheological behavior of silica-based nanofluids

The viscosity of nanofluids is a key factor in evaluating their potential to serve as flow barriers and alter the permeability of highly conductive fracture systems in Enhanced Geothermal Systems (EGS) reservoirs. For silica-based nanofluids to effectively act as a flow barrier in such reservoirs, they must exhibit an appropriate viscosity profile that allows them to be successfully pumped into the target zone. In these zones, the primary objective is to control the loss of working fluid by promoting the formation of clusters or gelation that can block, restrict, or divert fluid flow in these highly fractured zones. The rheological characterization of silica-based nanofluids provides critical insights into their viscosity behavior under varying angular frequencies or shear rates, which is essential for understanding their performance in EGS applications. **Figure 5** illustrates the complex viscosity profile of the silica-based nanofluids at 25 ºC (77 ºF), determined through frequency sweep measurements using a strain-controlled Ares-G2 rheometer. The viscosity profile shows two distinct zones that reflect different rheological behaviors of the nanofluids.

In the first zone, the nanofluids exhibit shear thinning behavior, where the complex viscosity decreases slightly as the applied angular frequency increases. This shear-thinning behavior is attributed to the alignment and rearrangement of suspended silica nanoparticles in the direction of the applied angular frequency or shear rate, which reduces internal resistance to flow. This phenomenon aligns with the findings of Wagner and Brady (2009), who observed that nanofluids tend to exhibit shear thinning at low to moderate angular frequencies due to the breakdown of particle networks. Such behavior is common in colloidal suspensions and indicates that the nanofluids can easily flow at lower shear rates, which is beneficial for injection into EGS fracture systems.

As the angular frequency increases, the nanofluids enter the second zone, where they undergo a transition from shear thinning to shear thickening behavior. In this zone, the complex viscosity rises sharply under applied angular frequency or shear rate, indicating a significant increase in flow resistance. This transition is crucial, as it reflects the shear-induced aggregation of silica nanoparticles into dense structures known as hydroclusters. These hydroclusters act as barriers within the fluid, dramatically increasing the viscosity and creating a solid-like resistance to flow. The shear thickening behavior becomes more pronounced as the concentration of silica nanoparticles increases, highlighting the importance of particle-particle interactions in the formation of hydroclusters. Higher silica concentrations lead to increased particle interaction and aggregation, resulting in a stronger shear thickening response. The observations from this study are consistent with previous research, including studies by Wagner & Brady (2009), Hoffman (1972), and Boersma et al. (1992), which demonstrated that shear thickening in nanofluids corresponds to a rapid transition from a liquid-like to a solid-like state due to the formation of hydroclusters. These dense aggregates of nanoparticles create localized resistance to flow, which can be exploited to control permeability in high-conductivity fractures.

The critical angular frequency at which the shear thickening transition occurs remains relatively stable across different concentrations of silica; however, the critical viscosity shows a noticeable increase with rising silica concentrations. **Figure 6** presents the critical viscosity as a function of silica concentration and temperature. Critical viscosity is the point at which the nanofluid's viscosity experiences a rapid, significant increase as a result of applied shear conditions. The observed increase in critical viscosity at higher silica concentrations can be attributed to enhanced particle interactions and aggregation within the nanofluid. This phenomenon aligns with the hydrocluster theory proposed by Bossis and Brady (1989), which suggests that the higher critical viscosity is due to the formation of larger hydroclusters at elevated silica concentrations. These larger hydroclusters enhance the effectiveness of the nanofluid by increasing resistance to flow, making the silica-based nanofluids more efficient for applications in Enhanced Geothermal Systems (EGS) where the mitigation of working fluid loss is crucial. The critical viscosity profile also reveals a significant decrease in viscosity as temperature increases. For all five silica concentrations tested, a reduction of approximately 50% in critical viscosity is observed when the temperature is doubled. This negative correlation between temperature and viscosity is well documented in the literature. Studies, such as those by Wagner and Brady (2009), have shown that temperature has a dilutive effect on the viscosity of nanofluids, as increased thermal energy disrupts particle interactions, reducing the overall resistance to flow. This transition to shear thickening in the silica-based nanofluids is particularly relevant for their application in EGS reservoirs. The ability of nanofluids to form hydroclusters under shear provides a mechanism for altering the permeability of fractures by blocking or restricting fluid flow through high-permeability pathways. This makes the nanofluids effective in enhancing zonal isolation and controlling the loss of working fluid in EGS reservoirs, where fluid loss can negatively impact thermal efficiency and overall system performance. Temperature is a critical factor in EGS operations, where high temperatures are necessary for effective heat extraction. However, the substantial reduction in critical viscosity at elevated temperatures presents a challenge for the use of silica-based nanofluids in such environments. While higher silica concentrations can generate sufficient viscosity for permeability alteration and zonal isolation at moderate temperatures, their effectiveness may be compromised at the higher temperatures typical of EGS reservoirs. This viscosity drop could limit the nanofluid's ability to form stable hydroclusters and maintain sufficient flow resistance, thereby reducing its capacity to act as a flow barrier or sealant in high-permeability fractures. Therefore, the optimal formulation of silica-based nanofluids for EGS applications must strike a balance between providing sufficient viscosity for fracture sealing and maintaining stability at elevated temperatures.

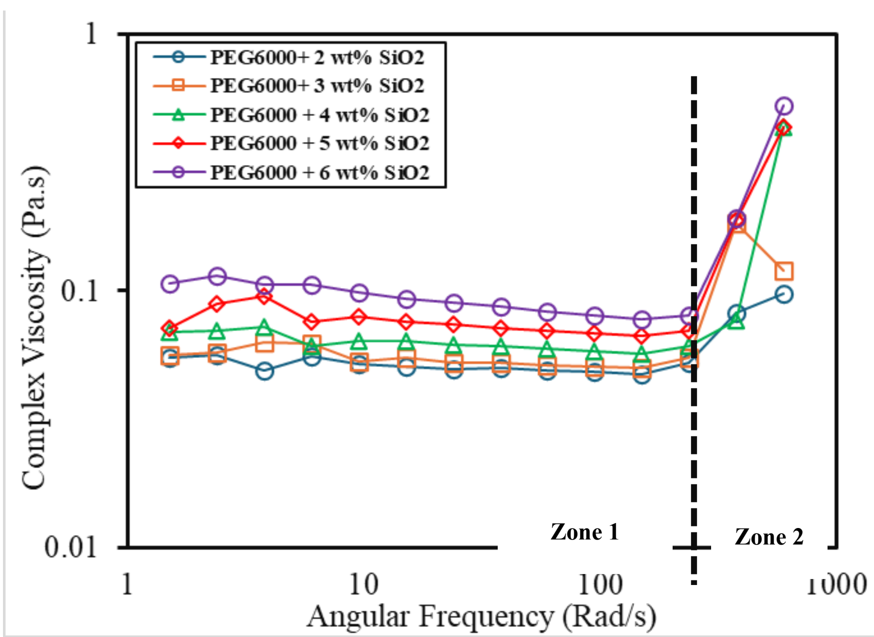

Figure 5: Rheological behavior of silica-based nanofluids of various concentrations of silica.

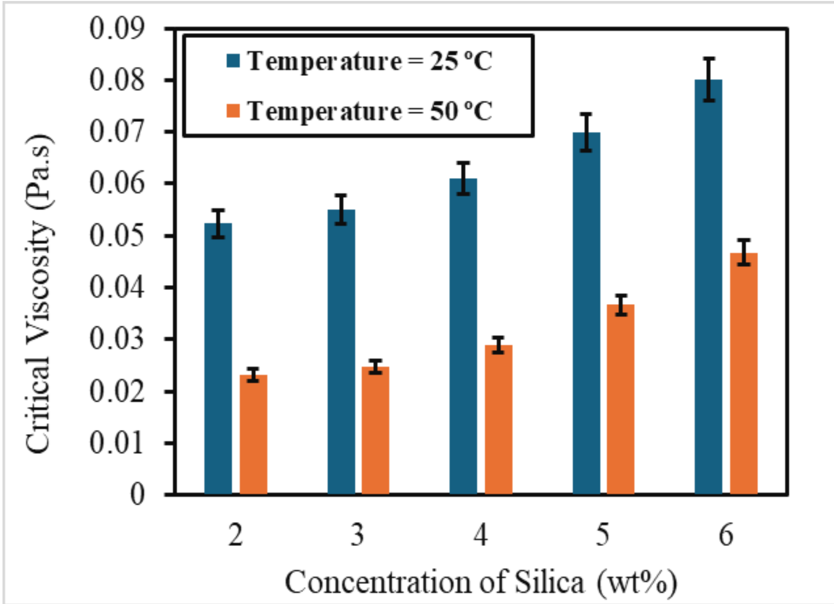

Figure 6: Critical viscosity of silica-based nanofluids with different concentrations of silica at 25 ºC (77 ºF) and 50 ºC (122 ºF).

Frequency sweep tests were conducted to investigate the viscoelastic properties of silica-based nanofluids. These properties include the storage (G') and loss (G") moduli. The storage modulus represents the elastic or energy-storing component of the fluid. While the loss modulus highlights the viscous or energy-dissipating component of the fluid. Both storage and loss moduli showed a dependence on the angular frequency. **Figure 7** shows the storage modulus (**Figure 7a**) and loss modulus (**Figure 7b**). The dependence of the viscoelastic moduli on the angular frequency indicates that the nanofluids have the potential to transition from a solid-like behavior to a more liquid-like behavior or from a liquid-state to a solid-state depending on how the storage modulus compares to the loss modulus. As depicted in **Figure 7**, both G' and G" become larger with increasing angular frequency. As angular frequencies rise, hydrodynamic interactions between silica nanoparticles amplify, causing a structural change that enhances both moduli (G' and G"). At low to intermediate frequencies, G" is larger than G' for all silica-based nanofluids investigated, indicating that the fluids start in liquid-like state. As indicated by Raghavan et al. (1997), at these frequencies, the Brownian motion dominates and the silica nanoparticles have sufficient time to rearrange and relax under stress conditions, thus minimizing the elastic response. However, as the frequency is increased beyond a critical frequency (238.86 rad/s), G' becomes the more dominant modulus, highlighting that the fluid has transitioned to a more solid-like state. At these frequencies, the time required for particle rearrangement is reduced and hydrodynamic forces dominate leading to particle aggregation, known as hydrocluster formation that enhances resistance to deformation.

The variation of G' and G" over different angular frequencies confirmed the shear thickening behavior of nanofluids as depicted by the viscosity profile in **Figure 5**. This behavior is governed by the formation of hydroclusters under shear conditions. As indicated by Astarak et al. (2023), These hydroclusters are connected and can effectively act as a barrier and significantly impede the fluid flow. This attribute can be leveraged in EGS reservoirs to control fluid flow in highly fractured zones.

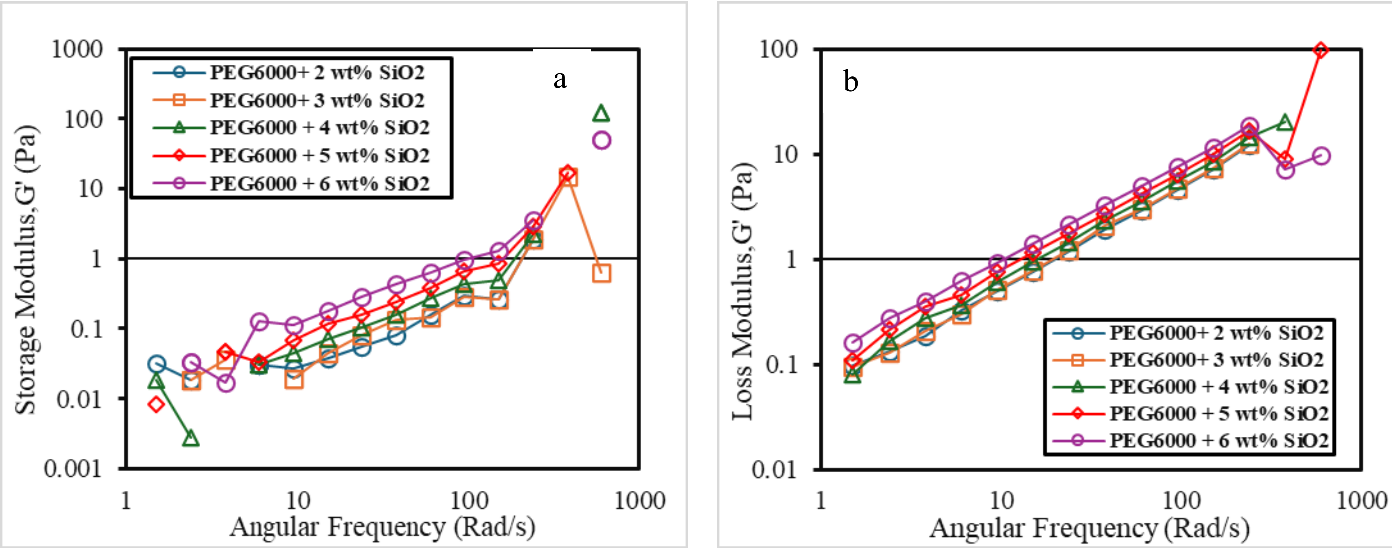

Figure 7: Storage modulus (a) and loss modulus (b) for the silica-based nanofluids tested.

The viscosity of the silica-based nanofluids at zero angular frequency or initial state was investigated to understand its implications for injection efficiency in an EGS reservoir. The complex viscosity of all tested nanofluids at zero angular frequency or initial state was found to be significantly low. This low initial viscosity is advantageous, as it facilitates the injection of the tested nanofluids into porous reservoirs, reducing the energy required for pumping the fluid downhole. This ensures that the fluids can be delivered effectively to the targeted zones. While the initial viscosity is low for all the nanofluids, it showed a linear increase as the concentration of silica nanoparticles is increased. **Figure 8** shows the relationship between the initial viscosity and the concentration of silica nanoparticles. The initial viscosity increases by 100% when the concentration of silica nanoparticles is doubled. The increase in the initial viscosity at larger silica concentrations indicates that higher silica content can compromise the injectivity of the silica-based nanofluids. This trend underscores the trade-off between nanoparticle concentration and injection efficiency. While higher concentrations improve the shear-thickening behavior of nanofluids and promote the formation of hydroclusters, which can act as flow barriers and control fluid flow in fractured EGS reservoirs, they can compromise the injectivity of the nanofluids due to higher initial viscosity. These results highlight the significance of finding a good balance between the silica content and the overall pumpability and injectivity of the nanofluid.

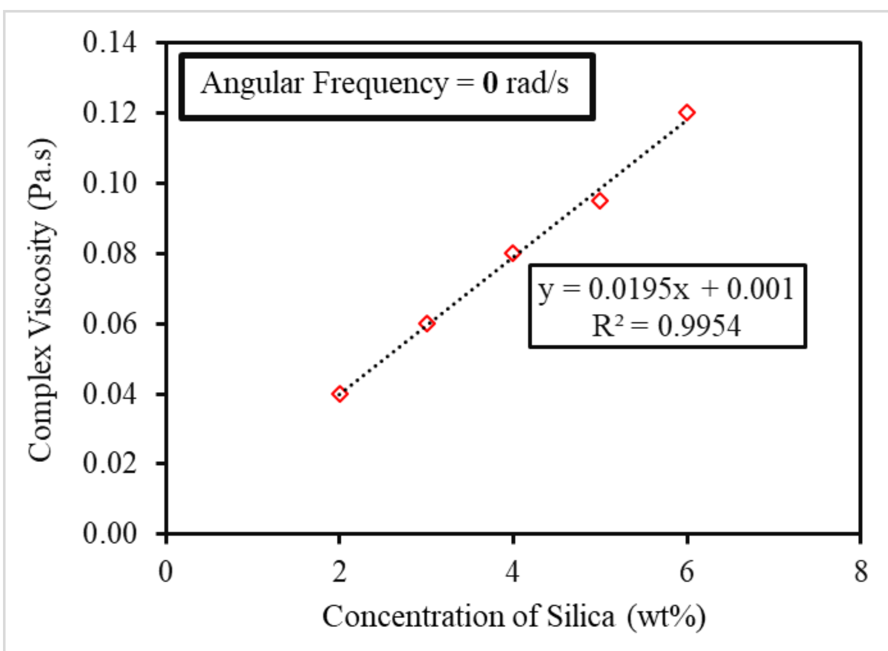

Figure 8: Complex viscosity at zero angular frequency or initial state as a function of silica content.

3.3 Thermal Conductivity of Silica-Based Nanofluids

Thermal conductivity is a critical parameter in evaluating the thermal performance of silica-based nanofluids. This property is especially important in Enhanced Geothermal Systems (EGS), as it directly influences the cooling and heating efficiency as well as the energy transfer during operation. In this study, the thermal conductivity of the formulated silica-based nanofluids was measured using the well-established Transient Hot Wire (THW) method. **Figure 10** illustrates the relationship between critical viscosity and thermal conductivity as a function of silica content at room temperature. The results demonstrate a clear increase in thermal conductivity with the increasing weight fraction of silica in the nanofluid. This enhancement can be attributed to several mechanisms, including Brownian motion, particle clustering, and ballistic photon transport, as highlighted by Pinto et al. (2016). At higher silica concentrations, the predominant factor contributing to the thermal conductivity enhancement is particle clustering. As the silica content increases, the formation of more clusters leads to the development of a network-like structure within the nanofluid. These clusters facilitate direct heat transfer across interconnected pathways, reducing thermal resistance and significantly improving the overall thermal conductivity. The correlation between critical viscosity and thermal conductivity, as shown in **Figure 10**, further supports this conclusion. Both properties increase with higher silica concentrations, indicating a shared underlying mechanism. The formation of hydroclusters under shear conditions governs the shear-thickening behavior of silica-based nanofluids. These hydroclusters create dense, interconnected networks that not only act as barriers to flow under shear but also serve as efficient heat conduction pathways. As the silica content increases, the potential for hydrocluster formation rises, resulting in higher thermal conductivity at elevated weight fractions of silica. This synergistic relationship between critical viscosity and thermal conductivity highlights the dual role of hydroclusters in enhancing both the rheological and thermal properties of silica-based nanofluids. While clustering promotes enhanced thermal properties, excessive clustering can lead to a decrease in thermal properties as indicated by Wen et al. (2009). Therefore, it is crucial to find the optimum concentration of silica that optimizes both the shear thickening behavior and thermal conductivity of silica-based nanofluids.

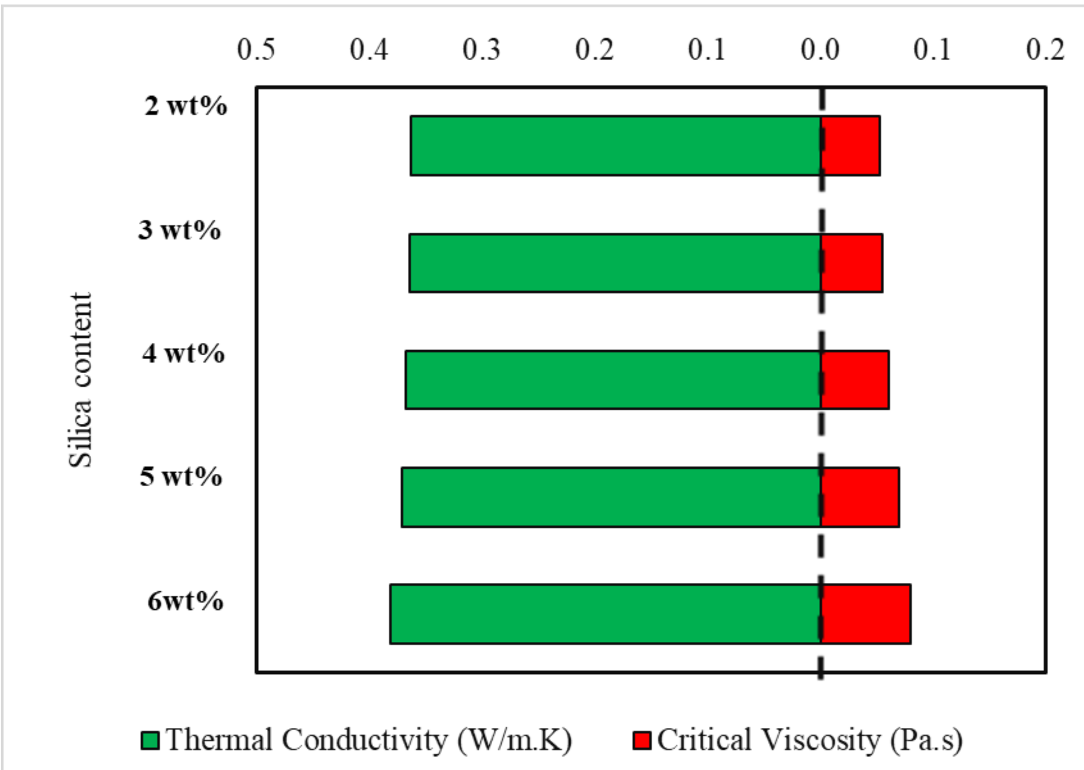

Figure 10: Thermal conductivity and critical viscosity as a function of silica concentration at a temperature of 25 ºC (77 ºF).

This study investigated the effect of temperature on the thermal conductivity of the formulated silica-based nanofluids. Due to the temperature limitations of the Transient Hot Wire (THW) method used, thermal conductivity measurements were conducted at 25°C (77°F), 30°C (86°F), and 35°C (95°F). **Figure 11** illustrates the relationship between thermal conductivity and silica content at these temperatures. The results reveal a positive correlation between thermal conductivity and temperature. For the nanofluid with a silica content of 5 wt%, the thermal conductivity increased by approximately 4.3% when the temperature was raised from 25°C (77°F) to 35°C (95°F). This trend is consistent across all tested silica concentrations, indicating that temperature plays a significant role in enhancing the heat transfer properties of silica-based nanofluids. The increase in thermal conductivity with temperature can be attributed to factors such as reduced nanofluid viscosity. At higher temperatures, the viscosity of the nanofluid is reduced, which facilitates better dispersion and mobility of nanoparticles, thus reducing thermal resistance and improving thermal conductivity. Although the THW method's operating range limits measurements to relatively low temperatures, modeling techniques, such as temperature superposition, can be utilized to estimate thermal conductivity at higher temperatures. The observed increase in thermal conductivity at lower temperatures suggests a similar trend at elevated temperatures. This hypothesis aligns with findings from Bobbo et al. (2016), who demonstrated that thermal conductivity consistently increases with temperature across both low and high-temperature ranges.

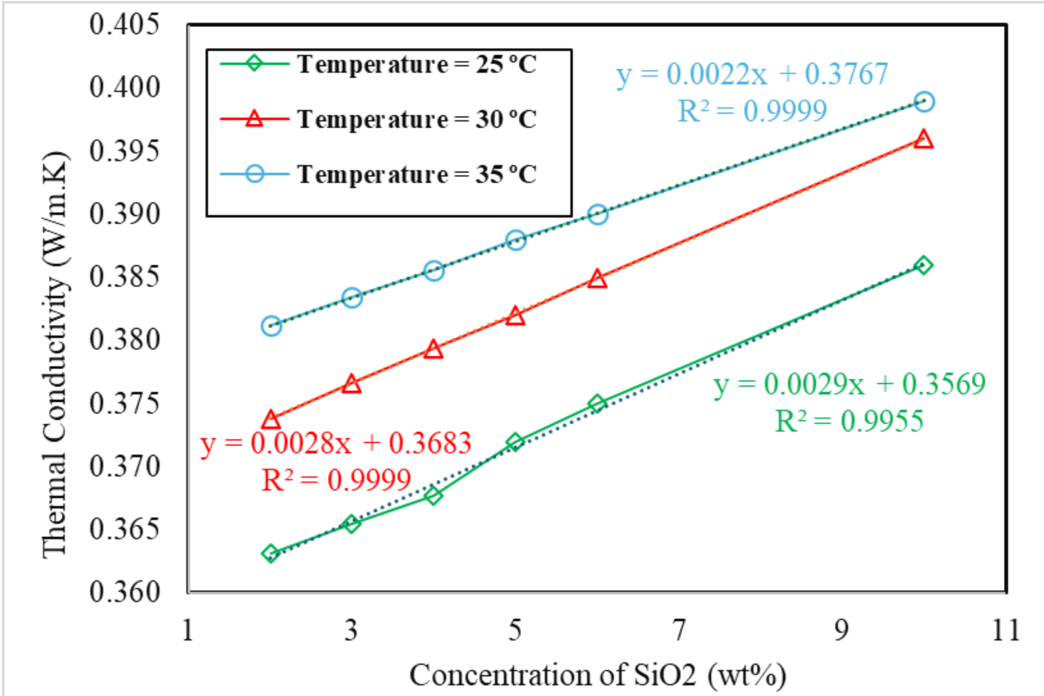

Figure 11: Thermal conductivity of formulated nanofluids at different temperatures of 25 ºC (77 ºF), 30 ºC (86 ºF), and 35 ºC (95 ºF).

4. DISCUSSION

Silica-based nanofluids, characterized by their exceptional rheological properties and enhanced thermal conductivity at elevated temperatures, present a groundbreaking solution for managing fluid flow and permeability in highly fractured Enhanced Geothermal System (EGS) reservoirsTheir unique characteristics make them particularly suitable for overcoming the challenges associated with uneven fluid distribution and inefficient heat transfer in such systems. The rheological characterization of silica-based nanofluids highlights their shear-thickening behavior, a critical property under high shear conditions commonly encountered in fractured reservoirs. This shear-thickening behavior results in a substantial increase in viscosity, which is primarily attributed to the formation of hydroclusters, which are densely packed, localized nanoparticle-rich regions that dynamically form under shear stress. These hydroclusters act as flow barriers, effectively redirecting the working fluid away from dominant, high-permeability fractures and into less-permeable zones of the reservoir. By altering the permeability of large fractures and redistributing fluid flow, silica-based nanofluids ensure that the working fluid interacts more uniformly with the geothermal formation. This enables it to access zones of high thermal potential, thereby enhancing the efficiency of heat extraction and improving overall reservoir performance. Another key advantage of silica-based nanofluids is their ability to improve thermal conductivity, particularly at elevated temperatures. This enhancement can be attributed to mechanisms such as particle clustering, Brownian motion, and the creation of efficient heat conduction networks facilitated by the nanoparticles. The interconnected pathways formed by these nanoparticles reduce thermal resistance, allowing for more effective heat transfer between the working fluid and the surrounding rock. This property ensures that silica-based nanofluids maintain or even enhance heat transfer efficiency in geothermal systems, even under the extreme temperature conditions typical of EGS reservoirs. The dual functionality of silica-based nanofluids, flow regulation through shear-thickening behavior and enhanced heat transfer through improved thermal conductivity, addresses two of the most critical challenges in geothermal reservoir management: controlling fluid flow and maximizing heat extraction. By enabling precise control over permeability and ensuring efficient energy transfer, silica-based nanofluids can significantly improve the performance and reliability of EGS systems.

5. CONCLUSION

This study investigated the rheological and thermal properties of silica-based nanofluids formulated using fumed silica (Aerosil 200**)** nanoparticles at concentrations ranging from 2 wt% to 6 wt%. The nanofluids were characterized using a strain-controlled ARES-G2 rheometer to examine their rheological behavior and a transient hot wire (THW) method to measure thermal conductivity. The findings from this work are summarized as follows:

- Silica-based nanofluids demonstrated pronounced shear-thickening behavior under high shear conditions, characterized by a significant increase in viscosity. This property is advantageous for diverting fluid flow and altering permeability in highly fractured reservoirs, enhancing the fluid's ability to target high-temperature zones.

- The shear-thickening tendency became more pronounced with increasing silica content, suggesting that higher concentrations enhance the formation of hydroclusters, which contribute to the rheological behavior.

- Storage modulus (G') and loss modulus (G") analyses revealed that silica-based nanofluids exhibit both liquid-like and solid-like behavior depending on the angular frequency or shear rate. This dual behavior underlines their viscoelastic nature, critical for flow control applications.

- All tested nanofluids exhibited low initial viscosity at zero shear rate, facilitating their injection into reservoirs without requiring excessive pumping energy.

- Thermal conductivity increased with higher silica content, with a 4.7% improvement observed when the concentration of silica was doubled. This enhancement is attributed to particle clustering and the formation of heat transfer pathways.

- Thermal conductivity also increased with temperature. For a nanofluid containing 5 wt% silica, thermal conductivity improved by 4.3% when the temperature was raised from 25°C (77°F) to 35°C (95°F), highlighting the suitability of silica-based nanofluids for high-temperature geothermal applications.

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NOMENCLATURE

EGS Enhanced geothermal systems

PEG Polyethylene glycol

LVR Viscoelastic linear region

THW Transient hot wire

ASTM American society of testing material

G' Storage modulus

G" Loss modulus

REFERENCES

Raghavan, S. R., & Khan, S. A. (1997). Shear thickening response of fumed silica suspensions under steady and oscillatory shear. Journal of Colloid and Interface Science, 185(1), 57-67

S. Astaraki, E. Zamani, M. Moghadam, M.H. Pol, H. Hasannezhad, Investigating the

Effect of Temperature, Angular Frequency, and Strain on the Rheological Properties of Shear Thickening Fluid (STF) with Different Weight Fractions of Fumed Silica, Colloid. Polym. Sci. 302 (2023) 1–11

D. Wen, G. Lin, S. Vafaei, and K. Zhang, "Review of nanofluids for heat transfer applications," Particuology, vol. 7, no. 2, pp. 141–150, 2009

Bobbo S, Colla L, Barizza A, Rossi S, Fedele L. Characterization of nanofluids formed by fumed Al2O3 in water for geothermal applications. 2016

Geovision report, 2021. Harnessing the heat beneath our feet. Department of Energy. Accessed October 29, 2024

Lior N. Energy resources and use: the present situation and possible paths to the future. Energy 2008; 33:842-57

Konate, N., Salehi, S., Salehi, M. A., Huynh, T., (2024). Geothermal Potential and Risk Assessment of Repurposing Old Wellbores for Geothermal Applications: Case Study of Oklahoma and Texas. Unconventional Resources Technology Conference (URTeC). Houston, Texas, USA, 17-19 June. DOI: 10.15530/urtec-2024-4036660

Vivas, C., Salehi, S., Tuttle, J. D., & Rickard, B. (2020). Challenges and Opportunities of Geothermal Drilling for Renewable Energy Generation. GRC Transactions, 44

IEA, 2011. Technology Roadmap: Geothermal Heat and Power. The International Energy Agency, France

Tester, J.W., Anderson, B., Batchelor, A., Blackwell, D., DiPippo, R., Drake, E., Garnish, J., Livesay, B., Moore, M.C., Nichols, K., 2006. The future of geothermal energy: Impact of enhanced geothermal systems (EGS) on the United States in the 21st century. Massachusetts Institute of Technology

Latimer, T., Meier, P., 2017. Use of the Experience Curve to Understand Economics for At-Scale EGS Projects, 42nd Workshop on Geothermal Reservoir Engineering. Stanford University, Stanford, California

Kumari, W.G.P., Ranjith, P.G., 2019. Sustainable development of enhanced geothermal systems based on geotechnical research – A review. Earth Science Reviews 199 (2019) 1012955 https://doi.org/10.1016/j.earscirev.2019.102955

Pollack, A., Horne, R., Mukerji, T., (2021). What Are the Challenges in Developing Enhanced Geothermal Systems (EGS)? Observations from 64 EGS Sites. Proceedings World Geothermal Congress 2021. Reykjavik, Iceland, April-October 2021

M. A. Plummer, E. Mattson, Y. Zhang, and Y. Xia., 2017. Methods for Selective Plugging of Geothermal 'Short Circuits.' 42nd Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 13-15, 2017 SGP-TR