

Carbon Black Suspensions as a New Alternative to Electrolytes for Increasing Fracture Electrical Conductivity in Enhanced Geothermal Systems

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ABSTRACT

Mapping propped fractures and understanding proppant distribution within fractures is critical for the success of Enhanced Geothermal Systems (EGS) projects. Borehole electromagnetic (EM) measurements offer a promising method to image proppant distribution. Electrically conductive (EC) proppant enhances the EM contrast between propped fractures and the surrounding formations. However, EC proppants are expensive, necessitating their use in small concentrations mixed with normal proppants. Electrically conductive fluids are needed to further increase the EM response. This study investigates the use of carbon black suspensions as an alternative to traditional electrolytes to enhance the electrical conductivity of fracturing fluids while addressing the challenges of salt precipitation and corrosion. In addition, the effect of carbon black on fluid rheology was evaluated under high-pressure and high-temperature conditions to reduce the thermal effect on the fracturing fluid viscosity, to improve proppant transport and distribution within EGS fractures. Laboratory systems were designed to quantify the rheological properties and electrical conductivity of EC proppants and carbon black suspensions at varying concentrations under EGS conditions. Results show that carbon black suspensions can significantly increase the electrical conductivity of fracturing fluids. Low concentrations of CB (≈ 1 wt%) were tested at varying temperatures up to 200 °C, resulting in a 40% increase in the solution's viscosity. Using 1% CB increases the electrical conductivity of the solution up to 0.5 S/m at 200 °C and 2000 psi. This study verifies the potential of carbon black suspensions for improving fracture mapping in EGS through borehole EM measurements while mitigating the drawbacks of electrolyte-based solutions and simultaneously improving the fluid viscosity performance under high-temperature geothermal conditions.

1. INTRODUCTION

Granitic formations are characterized by their low permeability, making hydraulic fracturing essential for creating artificial fracture networks that enable subsurface fluid circulation (Selvaduri et al 2020). To preserve hydraulic conductivity, proppant is injected into the fractures. However, proppant transport within fracture networks is highly complex (Bahri et al., 2025; Barboza et al., 2021; Budiman et al., 2025; Dehdouh et al 2023). Achieving uniform proppant distribution among fracture clusters is therefore critical for sustaining effective fluid circulation throughout the stimulated reservoir. Consequently, tracking and mapping proppant distribution in the subsurface is essential for optimizing stimulation design and proppant injection strategies in EGS.

Electromagnetic (EM) measurements using electrically conductive proppant have emerged as a promising approach for proppant mapping (Palisch et al., 2017, 2020; Sharma et al., 2018; Shiriyev et al., 2018). The fundamental principle of EM-based proppant mapping is to measure changes in the electrical conductivity of the subsurface before and after stimulation. Variations in electrical conductivity can be linked to the presence of fractures and proppant, enabling the detection and characterization of propped fracture networks (Sharma et al., 2018). To enhance the electrical conductivity contrast while minimizing the conductive proppant cost, electrically conductive fluids are suggested to improve the overall electrical response. Traditional electrolytes, such as sodium chloride (NaCl), are commonly used to increase fluid electrical conductivity. However, electrolytes can introduce significant drawbacks, including salt precipitation and severe corrosion of wellbore and completion components, particularly under high-temperature EGS conditions (DeBerry et al., 1978; F. Suci, 1982). In this current study, carbon black suspensions are proposed as an alternative to conventional electrolytes for enhancing the electrical conductivity of fracturing fluids. Carbon black is a highly conductive material that can be dispersed within fluids to increase electrical conductivity without introducing ionic species that promote corrosion (Sánchez-González et al., 2005). In addition to electrical considerations, fluid rheology plays a critical role in proppant transport (Budiman et al., 2025). At high temperatures, fluid viscosity decreases significantly, which can result in poor proppant lifting capacity and accelerated proppant settling. Carbon black suspension has the potential to increase fluid viscosity and reduce its temperature sensitivity, thereby improving proppant suspension and transport performance at high temperatures (Bahri and Miskimins, 2021). In this study, new experimental systems were designed to measure both the electrical conductivity and rheological properties of fluids mixed with varying concentrations of carbon black suspensions under EGS conditions of high pressure and high temperature. The objective is to evaluate the feasibility of carbon black suspensions as an alternative to electrolyte-based solutions for enhancing fluid electrical conductivity while simultaneously improving the fluid viscosity and proppant transport performance in high-temperature geothermal conditions.

2. MATERIALS AND METHODS

2.1 Electrical conductivity measurements

A custom experimental system was developed to measure the electrical conductivity of fluids under high temperature and pressure conditions (Figure 1). To ensure thermodynamic stability and prevent fluid evaporation during measurements, the fluid was maintained under high pressure using a syringe pump. The pressurized fluid was contained within a stainless-steel cylindrical cell. The pressure cell is equipped with four feedthroughs; one feedthrough is dedicated to real-time temperature measurement using a temperature sensor. The remaining feedthroughs are used to connect the inductance–capacitance–resistance (LCR) meter to measure the fluid resistivity.

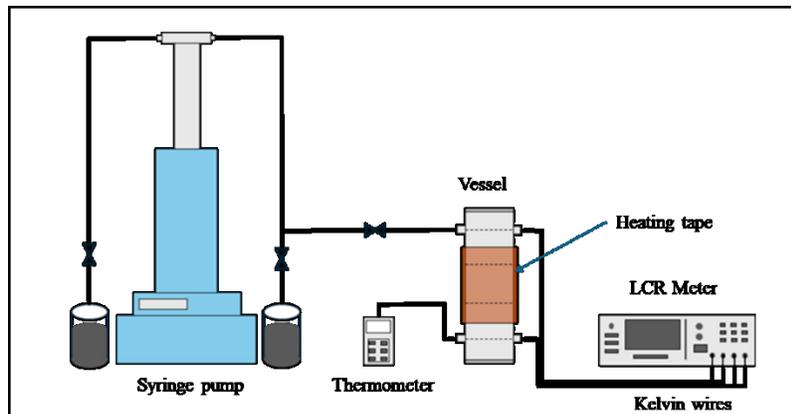


Figure 1: Schematic of high-temperature, high-pressure electrical conductivity system.

To minimize electrode polarization, four-wires Kelvin was used to measure fluid resistivity. The two force electrodes are used for the alternating current, while the two sense electrodes are used to measure the resulting voltage drop across the fluid. The sensing electrodes are wrapped around the internal surface of the cylinder with a known spacing. The internal surface of the stainless steel cylinder is covered with high-temperature electrical insulation tape to reduce interference from the metallic pressure vessel. Heating tape is wrapped around the external surface of the pressure cell to elevate the fluid temperature for high temperature measurements. The system allows controlled heating of the fluid up to 200 °C while maintaining constant pressure.

To improve particle dispersion and ensure stable measurements, a small concentration of surfactant (0.03 wt% cetyltrimethylammonium bromide (CTAB)) was added to the base fluid. The addition of CTAB enhances the dispersion stability of carbon black particles. For each experiment, the pressure inside the cell was first increased to 2,000 psi before heating. Pressurizing the system before temperature ramping prevents fluid evaporation. After the target pressure was reached, the fluid temperature was gradually increased.

2.2 High-pressure and high-temperature viscosity measurements

Fluid viscosity under high-pressure and high-temperature conditions was measured using pressure-drop data obtained under laminar flow conditions and interpreted using Hagen–Poiseuille’s law. A high-pressure flow loop was constructed in which a syringe pump injects the fluid at low flow rates through a coiled slim tube placed inside a high-temperature oven, allowing temperatures to exceed 200 °C. System pressure is maintained using a back-pressure regulator, which also establishes a pressure gradient along the tube. High-resolution pressure transducers installed at the inlet and outlet of the slim tube measure the steady-state differential pressure (ΔP). The setup was calibrated using fluids with known viscosities to validate measurement accuracy, assuming incompressible Newtonian behavior (Kelessidis et al., 2011; Chhabra).

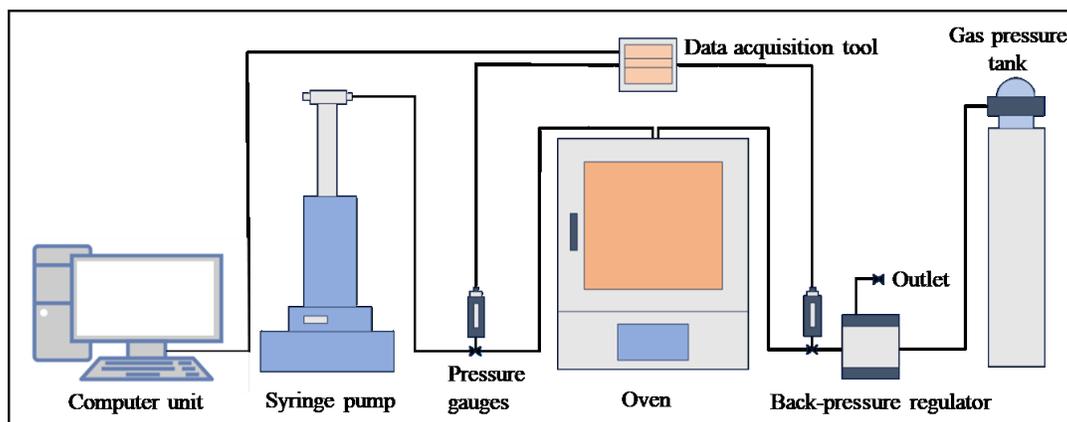


Figure 2: Schematic of the high-pressure and high-temperature viscosity measurement setup.

Viscosity measurements were performed by recording the pressure drop across the slim tube at multiple flow rates. The measured pressure drop, normalized by tube length ($\Delta P/L$), was plotted as a function of flow rate, and the fluid viscosity was calculated from the slope of the resulting linear trend. This approach allows viscosity to be determined directly from experimental measurements while minimizing uncertainty. The viscosity of fluids with different concentrations of carbon black suspension was measured at a pressure of 2,000 psi and temperatures up to 200 °C to evaluate the influence of carbon black on fluid rheology under EGS conditions.

3. RESULTS AND DISCUSSIONS

3.1 Electrical conductivity measurements

Figure 3 shows the pressure dependence of electrical conductivity for CB suspensions at three concentrations (0.1, 0.5, and 1 wt%). The electrical conductivity increases rapidly with pressure at low pressures, indicating significant improvement in charge transport as pressure increases. At high pressure, the electrical conductivity reached a plateau. The plateau conductivity increases with CB concentration, confirming that higher carbon black concentration creates more conductive networks.

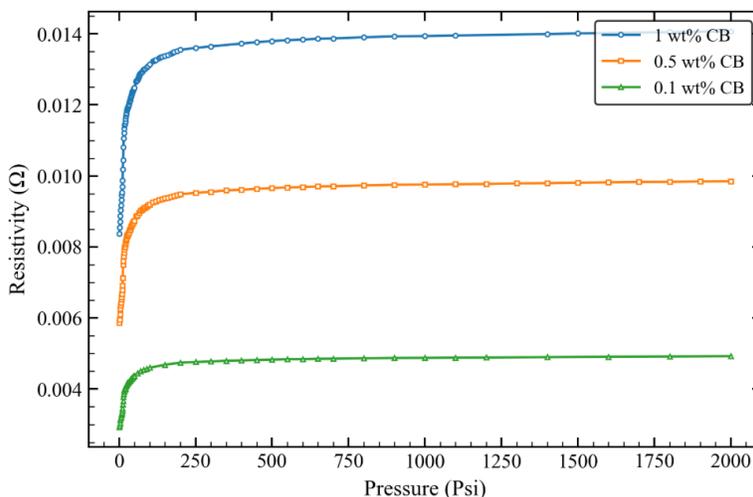


Figure 3: Pressure-dependent electrical conductivity of carbon black suspensions.

The observed increase in electrical conductivity with increasing pressure is attributed to the pressure effect on the microstructural arrangement of CB particles within the suspension. Electrical charge transport in CB suspensions occurs primarily through a conductive particle network, where electrons move through direct particle-to-particle contacts and short-range tunneling between closely spaced conductive particles. As pressure increases, weakly bound CB aggregates rearrange, reducing void space and increasing the number of particle-particle contacts. This structural reorganization, rather than compression of the liquid phase, leads to a decrease in the average separation between conductive particles. This reduction in inter-particle spacing enhances particle-particle contact and shortens electron tunneling distances, both of which significantly reduce electrical resistance. The increased confinement promotes the formation of a denser and more interconnected conductive network, allowing electrical charges to move more efficiently through the suspension.

Figure 4 summarizes the temperature effect on the electrical conductivity for CB suspensions at three concentrations. Across all datasets, increasing temperature produces an increase in electrical conductivity. The conductivity increases with temperature for all concentrations, with a higher rise at higher temperatures (roughly above ~120–150 °C). The 1 wt% CB suspension exhibits the highest conductivity over the full temperature range, reflecting the higher density of conductive particles, which results in forming more continuous conductive pathways. The 0.5 wt% CB case shows intermediate results, while 0.1 wt% CB remains the least conductive. These results indicate that temperature increases the electrical conductivity response for all suspensions, but the absolute magnitude is controlled primarily by CB concentration.

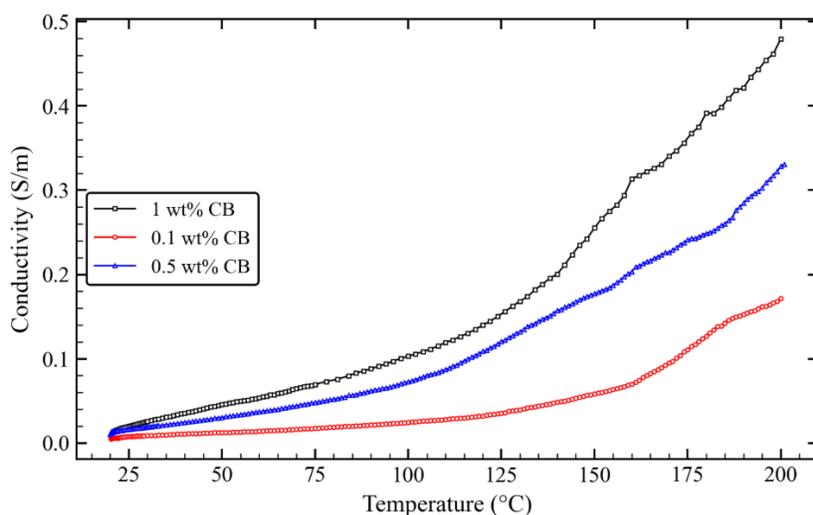


Figure 4: Temperature-dependent electrical conductivity of carbon black suspensions.

3.2 High-pressure and high-temperature viscosity measurements

To calibration measurements conducted using water to validate the viscosity measurement setup and account for the errors associated with the slim tube geometry, fittings, and flow connections, a series of calibration measurements was conducted. An effective tube radius was used to ensure accurate measurements. Multiple experimental runs were performed over a range of low flow rates to maintain laminar flow conditions. For each run, the pressure gradient ($\Delta P/L$) was plotted as a function of flow rate, and the viscosity was determined from the slope of the linear relationship using the Hagen–Poiseuille equation under low Reynolds number conditions.

As shown in Figure 5, all three calibration runs exhibit a strong linear relationship between pressure gradient and flow rate, with R^2 exceeding 0.99. The viscosities calculated from the fitted slopes are in excellent agreement with the known viscosity of water at standard conditions (~ 1 cP). The close match between measured and reference values, together with the high linearity of the data, confirms the reliability of the experimental setup.

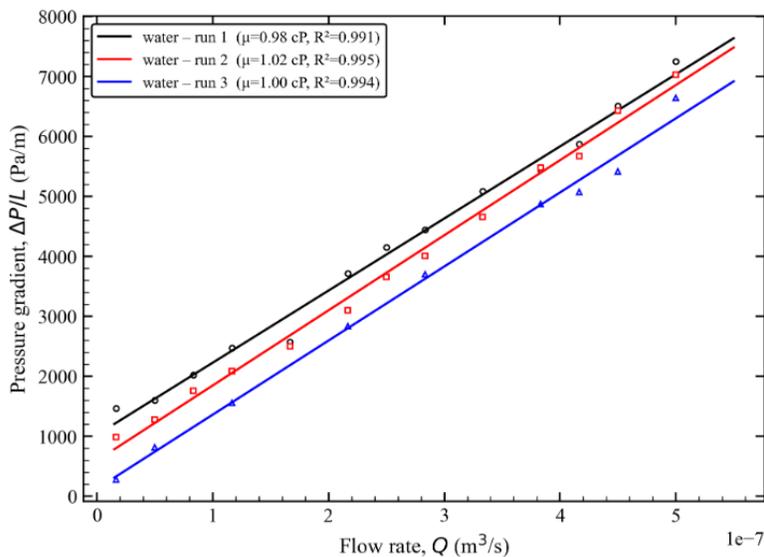


Figure 5: Water viscosity calibration using pressure-driven laminar flow in a slim tube.

Polymer viscosity measurements were conducted using a partially hydrolyzed polyacrylamide (HPAM) solution to further validate the viscosity measurement system and to assess the effect of carbon black addition under high-pressure and high-temperature conditions. Based on the results shown in Figure 6, a polymer fluid with a viscosity of 5 cP under standard conditions. The viscosity of the polymer solution was first measured at standard laboratory conditions using the calibrated slim-tube setup. The measured viscosity was 4.94 cP, in excellent agreement with the reference value of ~ 5 cP. These results further confirm the accuracy of the corrected tube radius and the reliability of the experimental methodology for polymeric fluids.

The polymer solution was tested under high-pressure and high-temperature conditions (2000 psi and 200 °C). Under these conditions, a significant reduction in viscosity was observed, reflecting the strong temperature sensitivity of polymer solutions and the thermal degradation of intermolecular interactions at high temperatures. To investigate the influence of CB on the high-temperature rheological behavior, the polymer was mixed with 1 wt% of CB suspension. The results indicate that the addition of CB increased the viscosity of the polymer solution by approximately 40% compared to the polymer-only case at high temperature and pressure. This viscosity enhancement suggests that carbon black particles introduce additional hydrodynamic resistance.

These findings demonstrate that incorporating a small concentration of CB can significantly improve the viscosity of polymer-based fluids at high temperatures. This behavior is important for hydraulic fracturing and proppant transport applied to EGS projects, where reduced fluid viscosity at high temperatures can lead to rapid proppant settling and poor proppant distribution. The results indicate that CB suspensions may play a dual role by enhancing both the electrical conductivity and the rheological stability of injected fluids under extreme subsurface conditions.

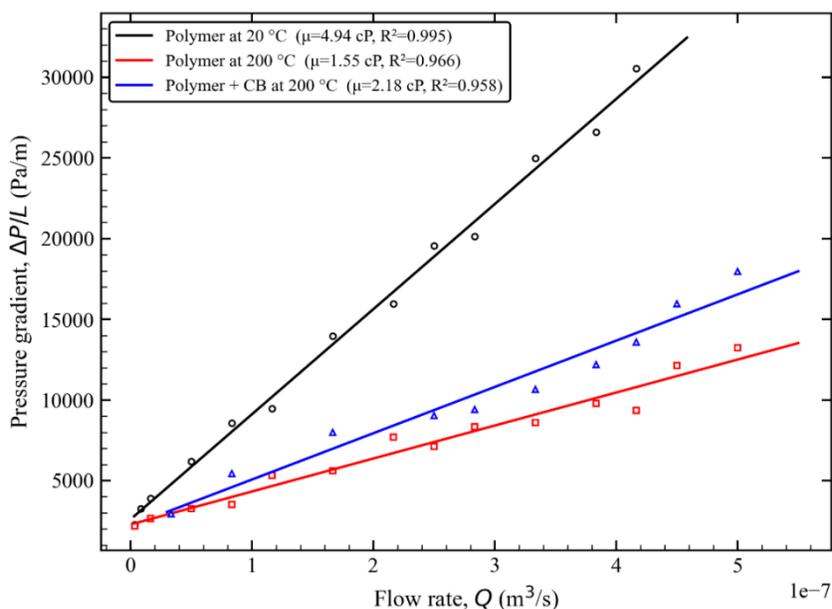


Figure 6: Polymer fluid viscosity measurements under 2000 psi and 200 °C.

4. CONCLUSION

This study demonstrates that carbon black suspension is a good alternative to traditional electrolyte-based solutions for enhancing the electrical conductivity of fracturing fluids under EGS conditions. Laboratory measurements conducted at high pressures (up to 2,000 psi) and temperatures (up to 200°C) show that low CB concentrations (≈ 1 wt%) can generate electrical conductivities on the order of 0.5 S/m, exceeding the conductivity of granitic formations by more than three orders of magnitude. When combined with electrically coated conductive proppants, the electrical contrast is expected to be much higher, which improves the electromagnetic mapping of the proppant. The observed increases in conductivity with pressure and temperature indicate that CB suspensions are particularly well suited for high-temperature geothermal environments, where conventional electrolytes suffer from precipitation and corrosion risks. The use of low concentrations of surfactants improves CB dispersion, resulting in stable, homogeneous suspensions with high electrical conductivity at small CB concentrations. In addition to their electrical benefits, CB suspensions provide favorable rheological effects. The addition of small amounts of CB (≈ 1 wt%) increases fluid viscosity by 30–40% at high temperature and pressure, partially reducing the strong thermal thinning typically observed in polymer solutions, which enhances the proppant suspension capacity and reduces settling velocity under EGS conditions.

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