EXPERIMENTAL INVESTIGATION OF PROPPED FRACTURE CONDUCTIVITY IN TIGHT GAS RESERVOIRS USING THE DYNAMIC CONDUCTIVITY TEST

A Thesis

by

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ABSTRACT

Hydraulic Fracturing stimulation technology is used to increase the amount of oil and gas produced from low permeability reservoirs. The primary objective of the process is to increase the conductivity of the reservoir by the creation of fractures deep into the formation, changing the flow pattern from radial to linear flow. The dynamic conductivity test was used for this research to evaluate the effect of closure stress, temperature, proppant concentration, and flow back rates on fracture conductivity. The objective of performing a dynamic conductivity test is to be able to mimic actual field conditions by pumping fracturing fluid/proppant slurry fluid into a conductivity cell, and applying closure stress afterwards. In addition, a factorial design was implemented in order to determine the main effect of each of the investigated factors and to minimize the number of experimental runs. Due to the stochastic nature of the dynamic conductivity test, each experiment was repeated several times to evaluate the consistency of the results.

Experimental results indicate that the increase in closure stress has a detrimental effect on fracture conductivity. This effect can be attributed to the reduction in fracture width as closure stress was increased. Moreover, the formation of channels at low proppant concentration plays a significant role in determining the final conductivity of a fracture. The presence of these channels created an additional flow path for nitrogen, resulting in a significant increase in the conductivity of the fracture. In addition, experiments performed at high temperatures and stresses exhibited a reduction in fracture

conductivity. The formation of a polymer cake due to unbroken gel dried up at high temperatures further impeded the propped conductivity.

The effect of nitrogen rate was observed to be inversely proportional to fracture conductivity. The significant reduction in fracture conductivity could possibly be due to the effect of polymer dehydration at higher flow rates and temperatures. However, there is no certainty from experimental results that this conductivity reduction is an effect that occurs in real fractures or whether it is an effect that is only significant in laboratory conditions.

DEDICATION

I would like to dedicate this thesis to my mother, Nancy Lugo. There is no doubt in my mind that without her continued support and love I could not have completed this process.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Zhu, and my committee members, Dr. Hill, and Dr. Sun, for their guidance and support throughout the course of this research. Thank you very much for giving me the opportunity to work in this wonderful research group.

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CHAPTER I

INTRODUCTION AND

LITERATURE REVIEW

1.1 Background and Purpose of Research

The elevated demand for natural gas resources has led to the development of different stimulation techniques to optimize production in unconventional reservoirs such as coalbed methane, shale gas and tight gas reservoirs. Developing these types of unconventional gas reservoirs improves our energy security, and benefits the overall economy. Also, natural gas is one of the cleanest and most efficient energy sources available producing lower levels of greenhouse gas emissions than other energy sources such as coal and heavy oil. Tight gas reservoirs are characterized by permeability values of 0.01 md or less and are not expected to produce at a high rate even after a stimulation procedure. They also do not cleanup quickly after a stimulation treatment (Rahim, 2012). Over the years, hydraulic fracturing has been used as one of the preferred stimulation techniques to maximize production and economic flow rates in tight gas reservoirs by increasing the final conductivity of the reservoir. The primary objective of performing a hydraulic fracturing job is to create a long conductive flow path from the wellbore extending into the formation.

The process of performing a hydraulic fracturing job involves a series of steps. The first step is when the pad (water and additives) is pumped at high pressures around the wellbore. The main purpose of the pad is to break down the formation and initiate the

creation of fractures. After the pad is pumped, the next step is to pump the slurry (water, proppant and additives). The main purpose of pumping the slurry is to hold the fractures created by the pad open. This process is repeated multiple times in stages to reach optimum and extended areas around the wellbore.

The first fracturing treatment specifically designed to stimulate well production was conducted in the Hugoton gas field, in July 1947, on Kelpper Well 1 located in Grant County, KS (Gidley, 1989). This well was chosen to be optimized for hydraulic fracturing due to low production rates and would offer a direct comparison between an acidizing stimulation and a fracturing stimulation. Fracturing has made a significant contribution in stimulating the gas production rates and recoverable reserves (Gidley, 1989). Over the years, much progress been made in optimizing the deliverability of tight gas reservoirs using hydraulic fracturing. The proper selection of gel concentration, polymer loading, proppant type/size and concentration, and the use of breaker have all contributed to successful and improved gas recovery. Also, new design models and analytical methods have emerged increasing the complexity and the economics of performing a successful fracturing job. For this reason, there is a need to continue the investigation of the behavior of fractures and be able to estimate with more accuracy the conductivity of a proppant pack.

1.2 Literature Review

Hydraulic Fracturing stimulation technology is used to increase the amount of oil and gas produced from low permeability reservoirs. The primary objective of the process is to increase the transmissibility of the reservoir by the creation of fractures deep into the formation in order to achieve economic production rates. There are several different parameters that have a significant influence on fracture conductivity: proppant concentration, polymer loading, reservoir temperature and closure stress. Since the technology of hydraulic fracturing was developed, there has existed a need to investigate optimization strategies to improve the effectiveness of the process.

Laboratory conductivity tests are commonly used to investigate the effects of different parameters in hydraulic fracturing operations. One of the first investigations to measure conductivity using a conductivity cell in proppant packs was conducted by Cooke (1973). Cooke investigated the effects of temperature and closure stress on the conductivity of vertical fractures filled with proppant using a conductivity cell. This research concluded that fracture conductivity has an inverse relationship with closure stress and reservoir temperature. Also, it was observed that both the polymer and proppant concentration after closure were different from the initial concentrations and the importance of Non-Darcy flow at high gas flow rates was indicated. Cooke (1975) later investigated how to predict the fluid effects on fracture conductivity, such as reduction in pore volume, effects on polymer and breaker loading. The factors that he considered to be detrimental to fracture conductivity were the amount of residue in the fluid, the porosity of the proppant, and the fraction of residue retained in the fracture as

fluid leaks off. He also found that the presence of fluid-loss additives had a negligible effect at normal concentrations (Cooke 1975).

Van der Vlis et al., investigated the effect of proppant placement on fracture conductivity to predict improvements in productivity (Van der Vlis et al., 1975). Empirical relations were developed allowing for an accurate estimate of conductivity for fractures propped with sand. For low-viscosity fracturing fluids and proppant concentrations up to 5 lb/gal, this research recommended a value of 2.0 for the ratio between fracture width and maximum proppant diameter. High-viscosity fracturing fluids require a ratio of 2.6 for proppant concentrations up to 8 lb/gal.

McDaniel conducted several experiments evaluating the effect of elevate temperatures and/or closure stresses to determine their combined effect on fracture conductivity for long time periods using a conductivity cell (McDaniel, 1986). This investigation concluded that laboratory measurements of fracture conductivity at room temperature were more optimistic compared to the measurements that were exposed to high closure stress and temperature for long periods of time.

Penny (1987) conducted one of the first investigations of propped fracture conductivity using dynamic testing. Penny investigated the effect of closure stress, temperature, fracturing fluid additives, and proppant embedment on conductivity. This investigation concluded that both closure stress and temperature have deleterious effects on fracture conductivity.

Hawkins performed a laboratory study to determine the critical physical parameters and fracturing fluid characteristics affecting permeability in proppant packs (Hawkins,

1988). The parameters selected for gelling agent concentrations were in the range of 500 lbm/1000 gal, and 140° to 200 °F for temperature range. This investigation concluded that temperature alone had little effect on the proppant pack permeability and an increase in the proppant size improved the permeability of the fracture. Also, the use of breaker and the reduction of cross-linker and polymer concentrations improved the permeability of the fracture.

Fredd et al., studied the effect of proppant strength at elevated temperatures on conductivity (Fredd et al, 2001). They conducted a series of conductivity experiments at 250 °F using horizontal fractures and sand concentrations of 0, 0.1 and 1.0 lb/ft^2. The conductivity was measured after approximately 20 hours of flowback at closure pressures ranging from 1000 to 7000 psi. For this set of experiments proppant type, proppant distribution and the alignment of the fractures surfaces were varied. This investigation concluded that conductivity can be proppant dominated, depending on the proppant concentration, proppant strength, and formation properties. Also, this investigation determined that the conductivity varied by several orders of magnitude when low-strength proppants were used at low concentrations.

The large demand for optimal exploitation from unconventional reservoirs has created the need to further investigate the behavior of conductivity in propped fractures. Marpaung (2007) developed an experimental setup called the dynamic conductivity test to simulate field conditions for fracture behavior in tight gas reservoirs. The dynamic conductivity test is able to simulate field conditions by pumping proppant/slurry between the fracture surfaces through an API conductivity cell. Previous experiments were

conducted using what is called a static conductivity test where proppant is loaded manually between the fracture surfaces. The main advantage of performing the dynamic conductivity test is to be able to more accurately examine the behavior or proppant placement inside the fracture, the effect of different proppant concentrations, the effect of gel damage, and the effect of closure stress on conductivity.

Marpaung later conducted a series of dynamic conductivity experiments by varying the polymer concentration of the fracturing fluid, the presence of breaker, flow-back rates at a constant temperature, and closure stress to evaluate the effects of gel residue in the fracture (Marpaung, 2008). This investigation concluded that a higher polymer concentration will decrease cleanup efficiency and that increasing flow-back rates optimizes gel cleanup efficiency.

Several authors have established improvements in the experimental designs for evaluating the effects of different parameters on proppant pack conductivity. Most of these authors have focused on testing the effect of one parameter on fracture conductivity. These parameters include reservoir temperature, closure stress, proppant size and concentration, fluid properties, and flow-back rates. The objective of this research is to evaluate the individual effect of these parameters on fracture conductivity by using the dynamic conductivity test. This experimental study evaluates different combinations of the different design parameters. Every parameter is tested at two levels (high and low). These design conditions were selected based on literature review and typical field conditions. By implementing this experimental design, it will be easier to identify optimal settings of parameters, and optimize field condition design.

1.3 Research Objectives

The principal objectives of this research are the following:

- Conduct a series of experiments with an 850kN load frame, a conductivity cell, and low permeability tight gas sandstone core samples using the dynamic conductivity test to determine the effects of proppant loading, closure stress, gas flow rate, and reservoir temperature on proppant pack conductivity.
- Evaluate the effect of the fracturing fluid considering proppant, and polymer concentration on propped pack conductivity.
- Evaluate the effects of the parameters investigated and their levels. Each factor would be tested at a low and high setting. The settings of the design parameters would be selected according to typical field conditions and based on previous literature review.

The process to accomplish the principal objectives will involve the development of specific objectives:

- Allow researchers and engineers to be able to identify the effects of parameters such as polymer concentration, proppant concentration, gas flow rate, reservoir temperature, and closure stress on proppant pack conductivity.
- Be able to predict the behavior of propped fracture conductivity in a tight gas reservoir based on the results from the dynamic conductivity test.
- Be able to optimize fracturing design on proppant pack conductivity in tight gas reservoirs by evaluating the effects of the parameters investigated, and be able to predict well performance and production rates.

CHAPTER II

EXPERIMENTAL SETUP, PROCEDURES AND CONDITIONS

2.1 Experimental Setup

The objective of performing a dynamic conductivity test is to be able to mimic actual field conditions in a fracturing job by pumping the slurry fluid instead of loading the proppant manually in the fracture (static testing). Marpaung (2007) developed a laboratory procedure for dynamic conductivity testing, to simulate field conditions. The experimental dynamic conductivity setup is divided into three different units, the pad/slurry pumping unit to simulate fracturing, the gas flow-back unit to simulate flow-back and production, and the proppant pack conductivity measurement unit.

Pumping Equipment and Procedure:

- 5 gallon bucket and paddle mixer (Caframo ZRZ50) for fracturing fluid preparation and mixing.
- Mixing drum (55 gallons) to mix the total volume of pad/slurry to be pumped through the fracture.
- Ph meter (SM102 Milwaukee).
- Plastic drum (30 gallons) to separate the pad from the slurry fluid that is to be pumped through the fracture.
- 2 jet pumps to be able to displace the pad/slurry volume through the system.

- High pressure centrifugal pump (TONKAFLO Model No. AS445HZ) with a 400 psi maximum pressure, and 400 gpm flow rate.
- A modified API RP-61 fracture conductivity cell and 2 tight gas sandstone rock sample cores.
- Heating jacket (GlasCol).
- Load frame (GCTS 1646 FRM-1000-50S).
- Stainless steel pipes (OD 1/2 in).
- Fracturing fluid disposal drum (55 gallons).

The schematic for the fracturing fluid pumping unit is shown in Fig. 2.1. To start each experiment, two pieces of core samples are assembled in the conductivity cell with a fracture width of 6.5mm. A heating jacket is used to heat the conductivity cell for two hours before pumping to ensure that the desired temperature for the experimental condition is reached. Approximately 12 gallons of pad are prepared for each experiment, the pad is mixed in 4 gallon batches to ensure proper mixing. The mixer contains the fluid with proppant (slurry) and the plastic drum contains the base gel (pad). The two jet pumps are used to displace the base gel and slurry mixture from the tanks to the line where the inlet of the multistage centrifugal pump (Fig. 2.2) is located. The base fluid is pumped first to recreate the effect of the pad injection into the formation. Meanwhile, 4 gallons of slurry fluid is mixed in the bucket with the paddle mixer by adding the desired amount of proppant (based on proppant loading) and cross-linker.

After the base gel is pumped through the conductivity cell, the slurry was then pumped. Both fluids are pumped through the conductivity cell for 1-2 minutes with a pumping back-pressure of 200 psi. After pumping, the inlet and outlet of the conductivity cell are closed; trapping the slurry within the conductivity cell. After this, a desired closure stress is applied through the load frame. Finally, the system is flushed with base fluid and water to prevent blockage of the pump by the cross-linked propped slurry.

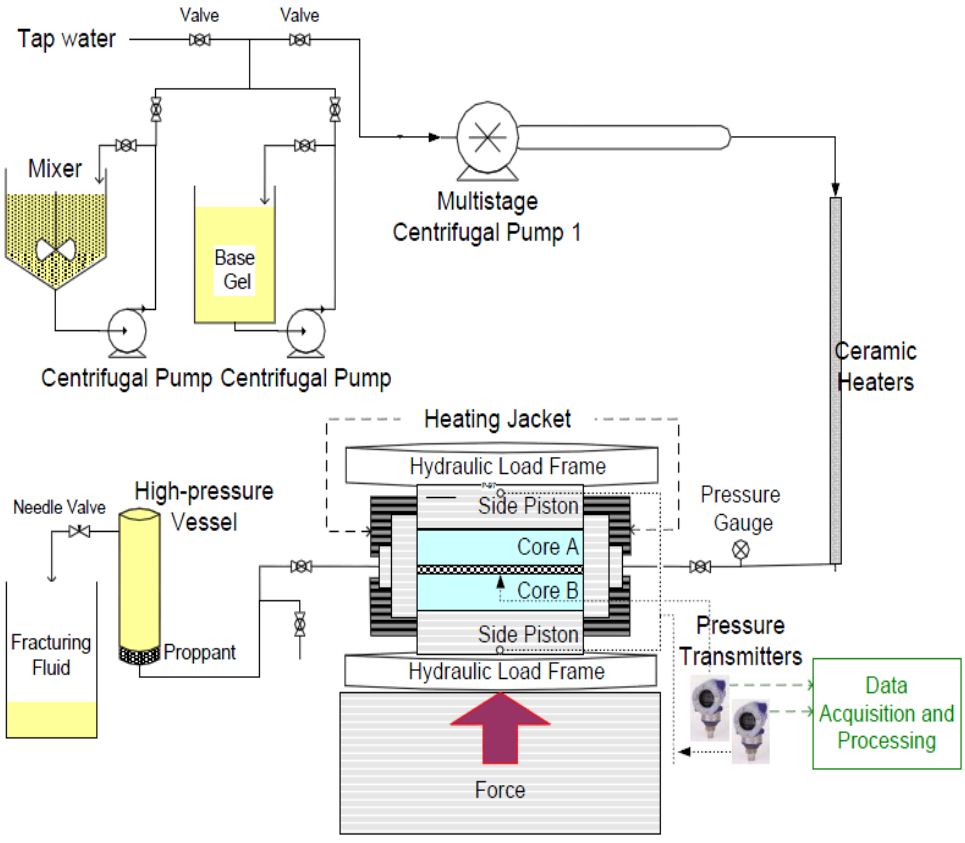

Fig 2.1: Pumping Procedure of Dynamic Conductivity Test (After Marpaung 2007)

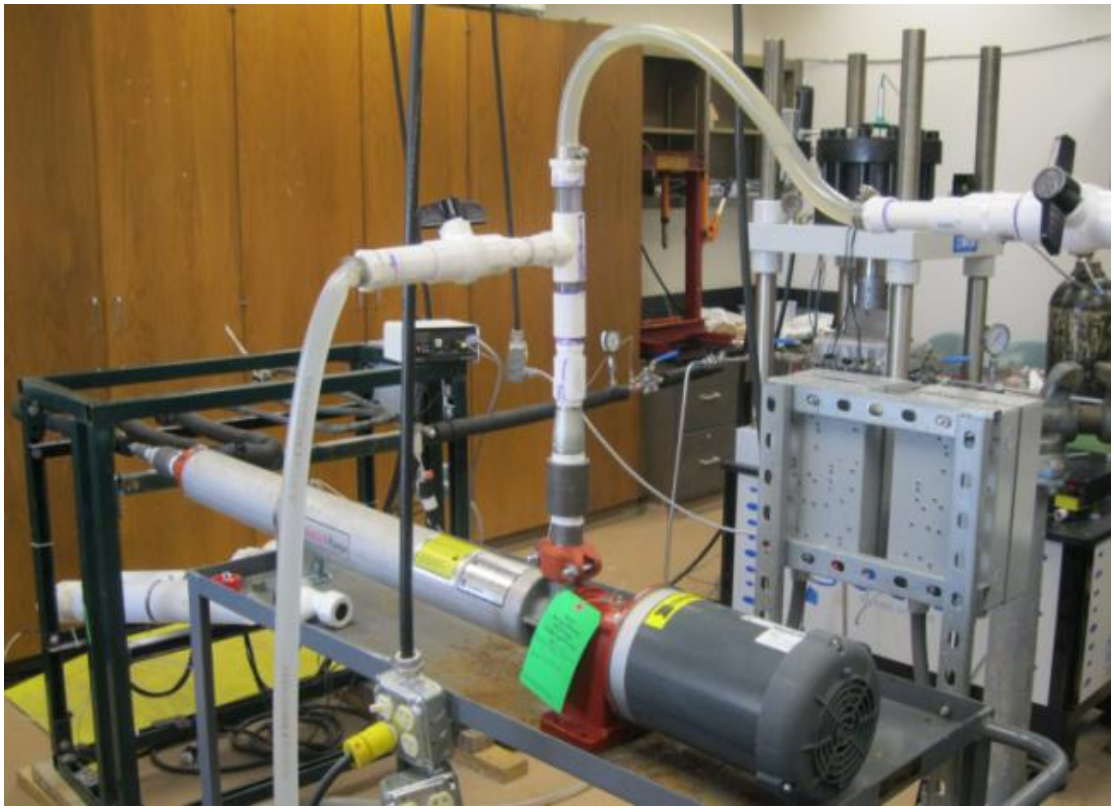

Fig 2.2: High Pressure Centrifugal Pump

Simulated Gas Production and Conductivity Measurement Equipment and Procedure:

- A modified API RP-61 fracture conductivity cell and 2 tight gas sandstone rock sample cores.
- Heating jacket (GlasCol).
- Load frame (GCTS 1646 FRM-100-50S).
- Back-pressure regulator to control the desired nitrogen rate.

- Pressure transducers to measure the absolute and differential pressure across the conductivity cell.
- GCTS C.A.T.S. data acquisition system and control software to obtain accurate readings for the pressures inside the cell.
- Nitrogen cylinder to simulate gas flow rates.
- Water chamber used to wet the gas before flowing into the conductivity cell.
- Mass flow controller to measure the desired nitrogen flow rate.

After the pumping procedure is finished, the gel is allowed to break for approximately 12 hours and then the next experiment procedure is initiated. The schematic for the fracture conductivity measurement and simulated gas production is shown in Fig. 2.3. Nitrogen flow is initiated through the water chamber before reaching the conductivity cell to wet the gas before it reaches the propped fracture. The fracture conductivity cell consists of two side pistons that ensure that the cores inside the cell stay in place while stress is applied, and three pressure ports where the pressure transducers are connected. The middle transducer measures absolute pressure inside the conductivity cell and the other two transducers measure the pressure drop across the conductivity cell. Finally, these pressures are measured from the GCTS C.A.T.S data acquisition system at regular time intervals through the pressure transducers. Fracture conductivity is calculated with either Forcheimer's equation or Darcy's law. The equation used depends on whether the Non-Darcy flow effect is significant or not.

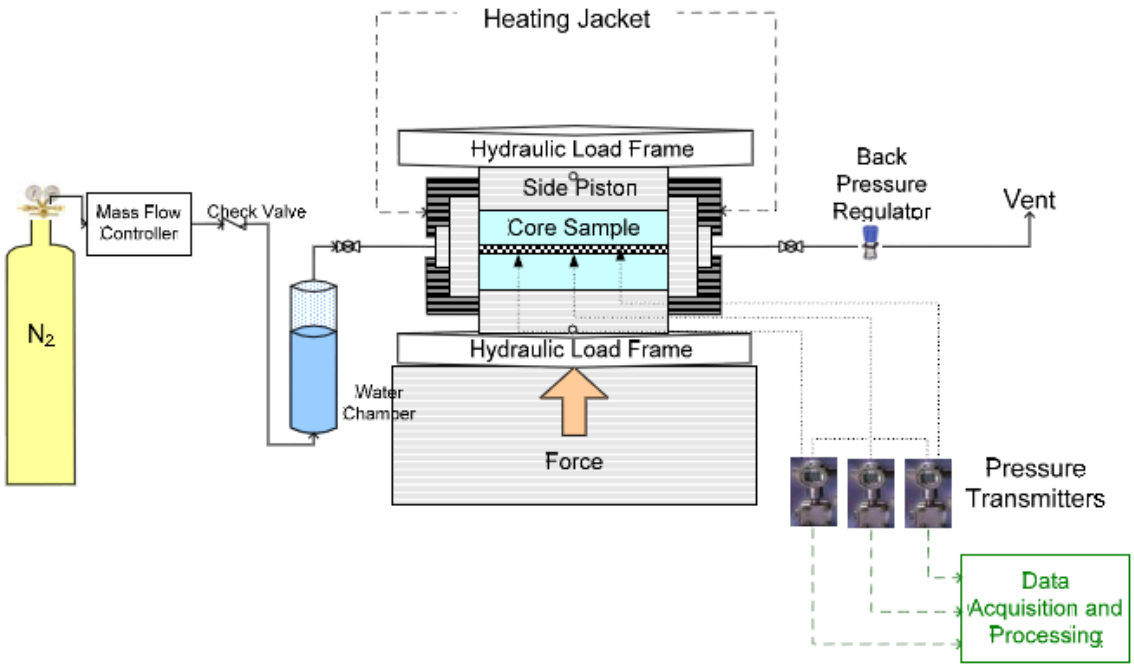

Fig 2.3: Conductivity Measurement and Simulated Gas Production (After Marpaung 2007)

Figure 2.4 shows the conductivity cell used during this project. The modified API RP-61 conductivity cell is made of 316 grade stainless steel and is able to accommodate core samples with the following dimensions: 7 in. length, 1.7 in width, and 3 in. height with two 12 in. height side pistons, leak-off ports are available, but sealed for this set of experiments. The permeability of the core samples is around 0.01 to 0.1 md. Figure 2.4 also illustrates how the heating jacket is used to increase the temperature of the cell.

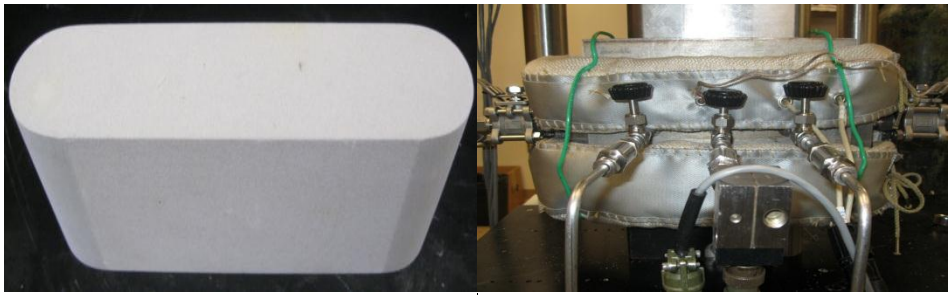

Fig 2.4: Dynamic Conductivity Test Equipment

The load frame (GCTS 1646 FRM-1000-50S) is shown in Fig. 2.5. The frame can easily apply a desired closure stress to the conductivity cell. The maximum static axial load capacity is 225000 psi and the maximum dynamic axial load capacity is 180000 kN. The frame is controlled by the GCTS C.A.T.S software and data acquisition system. The software allows the user to control the closure stress applied to the load frame, monitor the absolute and differential pressure inside the cell, and also the axial displacement of the pistons which are correlated to the propped fracture width. Fig. 2.6 shows an example of the control panel of the software.

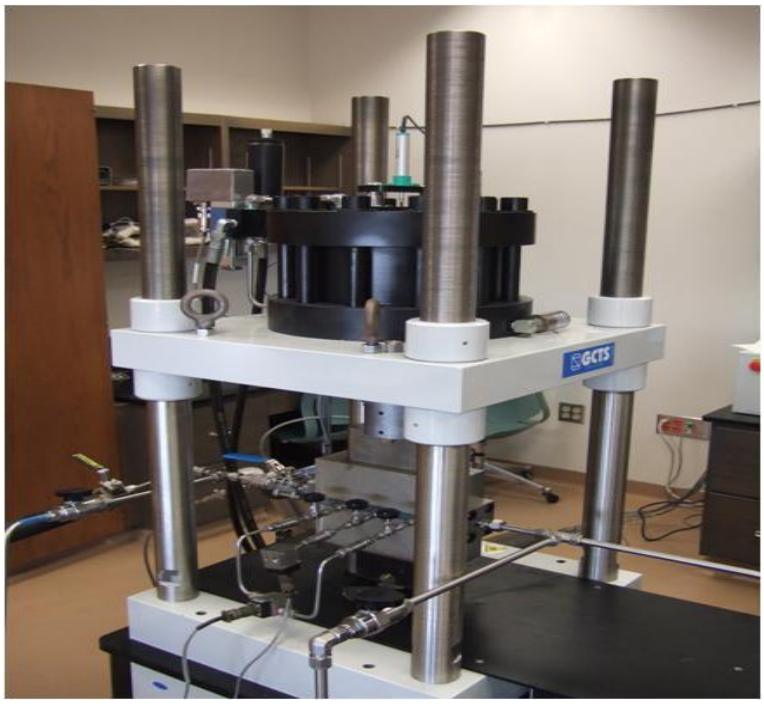

Fig 2.5: Load Frame (GCTS 1646 FRM-1000-50S)

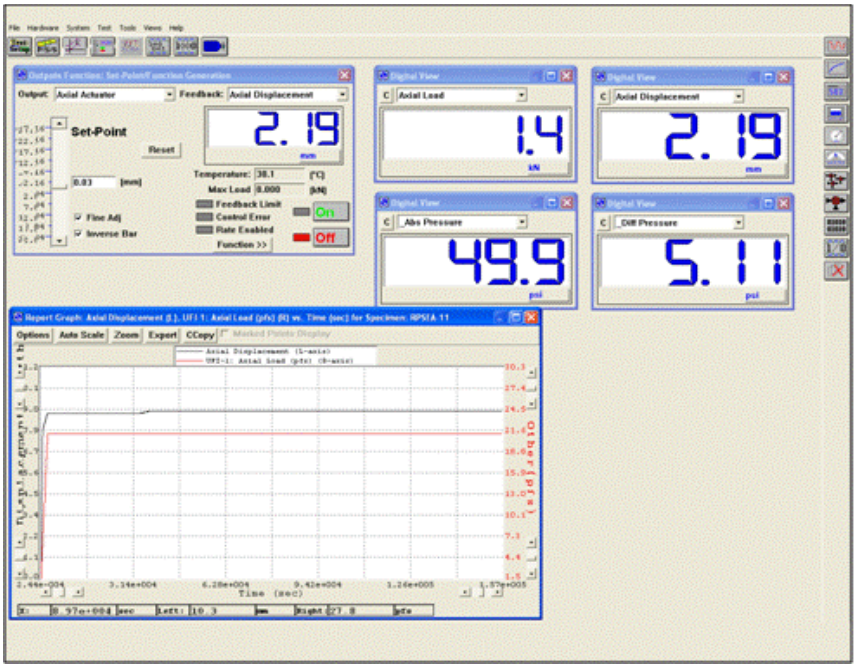

Fig 2.6: GCTS C.A.T.S Software and Data Acquisition System

Preparation items are listed below:

- 5 gallon bucket and paddle mixer (Caframo ZRZ50) for fracturing fluid preparation and mixing.
- Mixing drum (55 gallons) to mix the total volume of pad/slurry to be pumped through the fracture.
- Ph meter (SM102 Milwaukee).
- Plastic drum (30 gallons) for the pad fluid.
- 2 jet pumps to be able to displace the pad/slurry volume through the system.
- High pressure centrifugal pump (TONKAFLO Model No. AS445HZ) with a 400 psi maximum pressure, and 400 gpm flow rate.
- A modified API RP-61 fracture conductivity cell and 2 tight gas sandstone rock sample cores.
- Heating jacket (GlasCol).
- Load frame (GCTS 1646 FRM-1000-50S).
- Fracturing fluid disposal drum (55 gallons).
- Back-pressure regulator to control the desired nitrogen flow rate.
- Pressure transducers to measure the absolute and differential pressure across the conductivity cell.
- GCTS C.A.T.S. data acquisition system and the control software to obtain accurate readings of the pressures inside the cell.
- Nitrogen cylinder to simulate gas flow rates.
- Water chamber used to wet the gas before flowing into the conductivity cell.

- Mass flow controller to measure the desired nitrogen flow rate.

2.2 Experimental Procedures

Fracture conductivities representing field conditions in tight gas reservoirs were determined via a series of experiments using the dynamic conductivity test. This experimental procedure is divided into a series of steps:

- Core sample preparation.
- Pressure transducers calibration.
- Fracturing conductivity cell Setup.
- Pad and slurry fluid preparation.
- Fracturing fluid pumping.
- Closure stress shut-in.
- Proppant pack conductivity measurement.

2.2.1 Core Sample Preparation

The core samples used for these experiments are the low permeability Ohio Scioto Sandstone with dimensions: 7 in. length, 1.7 in width, and 3 in. height. The purpose of the core sample preparation is to cover the sides of the cores with a silicon mixture to provide a perfect seal between the rock sample and the conductivity cell. It is very important to create a perfect seal inside the conductivity cell to avoid any type of leakage that might lead to an erroneous reading of the pressure drop in the propped fracture. Fig. 2.7 shows a comparison of the rock samples before and after the preparation procedure.

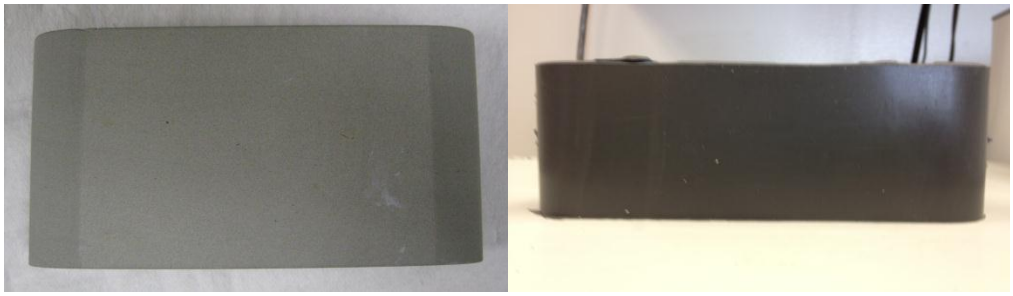

Fig 2.7: Core Sample Preparation

Core Sample Preparation Procedure:

- Place tape on the top and the bottom surfaces of the core sample, edges should be removed with a razor cutter.
- Use a brush to apply 3 layers of silicon primer (SS415501P), allowing 15-minute time intervals between layers.
- Clean the metal molds and the bottom plastic piece with acetone and a cloth.

- Spray 3 layers of Sprayon S000315 (silicon mold release) on the molds, allowing 5-minute time intervals between layers.
- Assemble the mold with 3 bolts on the side and 4 on the bottom. Make sure all the bolts are properly tightened to avoid silicon leakage.
- Place the core sample in the mold, making sure that is properly centered.
- Weight 60 grams of silicone potting compound and 60 grams of silicon curing agent. Mix and stir thoroughly.
- Pour the silicon mixture into the void space between the mold and the core sample until it reaches the surface of the core sample.
- Let the mold dry at room temperature for 3 hours.
- Place the mold in the oven at 200 °F for 3 hours.
- Take the mold out of the oven and wait for the temperature to decrease to room temperature.
- Unscrew all the bolts from the mold and dissemble it to remove the core sample.
- Cut off the extra silicon on the edges with a razor cutter.
- Label the core sample

2.2.2 Pressure Transducers Calibration

Pressure measurements inside the conductivity cell are crucial in calculating the final conductivity of the propped fracture. The pressure transducers used for these experiments are shown in Fig. 2.8 need to be calibrated and tested before every experiment. A T-140 Pressure Calibrator and the GCTS C.A.T.S software are used to calibrate the transducers.

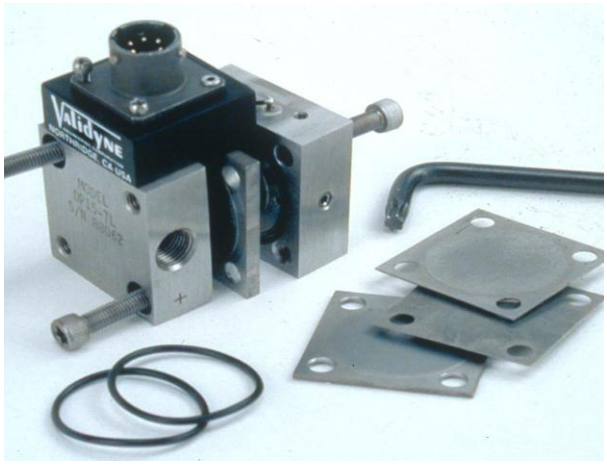

Fig 2.8: Pressure Transducers

Pressure Transducer Calibration Procedure:

- Start the GCTS C.A.T.S software.
- In the upper panel, proceed to System/Inputs/Analog.
- Fig. 2.9 shows the Analog Input Menu. Select the desired transducer to calibrate (Absolute/Differential).

- After selecting the transducer to calibrate. Click on Edit and the Editing Analog Input AI-4 screen will appear. Select Calibrate option (Fig. 2.10).
- Select 2 point calibration from the Calibration Type selection menu.
- Connect the pressure transducer to the T-140 Pressure Calibrator (Fig. 2.11).
- Set the pressure manometer to 0 psi pressure by selecting the vacuum mode.
- Set the “First Calibration” point to 0 psi and click “Next”.
- Switch the pressure calibrator to pressure mode and apply the desired calibration pressure for the transducer.
- Set the Second Calibration Point equal to the pressure in the calibrator and click Next.
- Repeat First and Second Calibration point if necessary for accuracy.
- Click Close and then OK. Make sure that the pressure values from the calibrator are equal to the measured values in the C.A.T.S software.

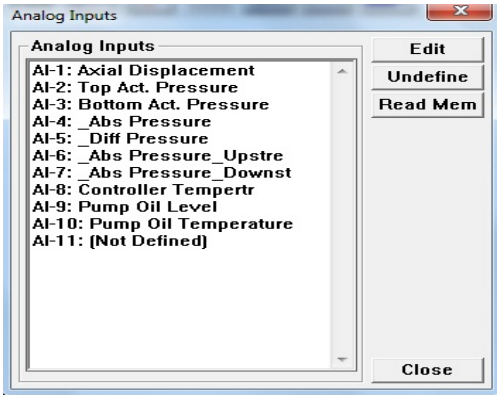

Fig 2.9: Analog Input Menu

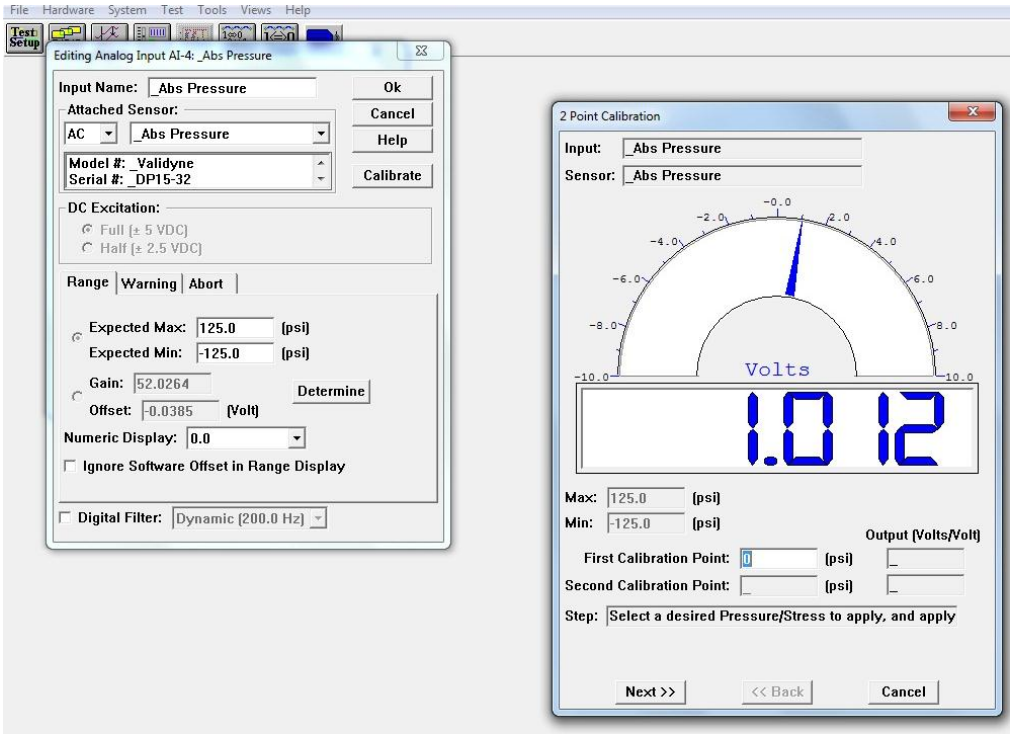

Fig 2.10: Calibration Data Input Screen

Fig 2.11: T-140 Pressure Calibrator

2.2.3 Fracture Conductivity Cell Setup

To start each experiment, two pieces of core sample are assembled in the conductivity cell with a preset fracture width of 6.5mm. Fracture width is an important parameter used to determine the final permeability of the fracture. The following procedure shows how to assemble the conductivity cell with a fracture width of 6.5mm.

Fracture Conductivity Cell Setup Procedure:

- Select a pair of cores prepared following the guideline in section 2.2.1.
- Wrap each core with Teflon tape to prevent leakage inside the conductivity cell.
- Apply vacuum grease to each layer placed around the core sample.
- Make sure that the conductivity cell is properly cleaned before starting the loading process.
- Insert the bottom core sample into the bottom opening of the fracture conductivity cell with help of hydraulic press.
- Insert the bottom piston with the support pushing the bottom core sample until it reaches the end of the pressure reading ports. This will ensure that the fracture is placed in the middle of the conductivity cell.
- Plug the lower leak off port of the piston with a cap.
- Insert the top core sample into the top opening of the fracture conductivity cell with help of hydraulic press.
- Push the top core sample until there is enough room to place the top piston.
- Using the C.A.T.S software, activate the output function tool and select the Axial Displacement option.

- Displace the load frame upwards to a distance of -45 mm.
- Place the conductivity cell in the center of the load frame.
- Insert the top piston into the top of the conductivity cell.
- Once the conductivity cell is placed in the middle of the load frame with the top piston in place, start displacing the frame downwards to a distance of -21mm. This will ensure that the fracture created has a width of 6.5mm inside the conductivity cell.
- Plug the top leak off port of the piston with a cap.
- Assemble the inlet and outlet ports of the conductivity cell making sure they match with the number/letter of the conductivity cell. Make sure the bolts are tight enough to avoid leakage.
- Connect the outlet and the inlet pipelines to the ports of the conductivity cell making sure all the connections are tight to avoid leakage.
- Connect the absolute and differential pressure transducers to the conductivity cell.
- Wrap the heating jacket around the conductivity cell and connect it to the temperature controller.
- Turn on the temperature controller and select the desired temperature for the experiment.
- Wait for 2 hours for the conductivity cell to heat up and reach the desired temperature.

- The conductivity cell is now ready for the experiment. Fig. 2.12 shows the final assembly of the conductivity cell.

Fig 2.12: Final Assembly of the Conductivity Cell

2.2.4 Pad and Slurry Fluid Preparation

The fracturing fluid used in these experiments is a water-based guar containing polymer, gel stabilizer (necessary for experiments at high temperatures), breaker, buffers, and cross-linker. A detailed description of the fracturing fluid composition will be discussed in Section 2.3.2. The recipe used for the mixing of the fracturing fluid resembles the characteristics of those used in field treatments. Approximately 12 gallons of the pad fluid are prepared for each experiment; the pad is mixed in 4 gallon batches to ensure proper mixing.

Pad preparation procedure:

- Use a 5 gallon bucket and a paddle mixer (Caframo ZRZ50).

- Fill the bucket with 4 gallons of water at room temperature.
- Add the buffering agent (BA-20) to decrease the Ph of the water to 6.5, to ensure proper hydration.
- Add 54.4 g of Guar gelling agent to the mixture.
- Transfer the 4 gallons of base gel to the mixer drum.
- Repeat previous steps until 12 gallons are mixed in the mixing tank.
- Mix thoroughly in the mixing tank for 30 minutes.
- Transfer the 12 gallons of pad from the mixing tank to the plastic drum.

Slurry preparation procedure for low-temperature experiments:

- Use a 5 gallon bucket and a paddle mixer (Caframo ZRZ50).
- Fill the bucket with 4 gallons of high temperature water.
- Add the buffering agent (BA-20) to decrease the Ph of the water to 6.5 to ensure proper hydration.
- Add 54.4 g of Guar gelling agent to the fluid and mix for 30 minutes.
- Add the buffering agent (BA-40) to increase the Ph of the fluid to 10.
- Add 138.90 ml of ViCon NF, 13.81 ml of CAT-OS1 for breaker and breaker activator.
- Measure the desired proppant weight based on concentration and add it to the mixture.
- Add 12.43 ml of CL-28M (Cross-linker) to the propped mixture.
- After the propped fluid is fully cross-linked, transfer the slurry to the mixing tank.

Slurry preparation procedure for high-temperature experiments:

- Use a 5 gallon bucket and a paddle mixer (Caframo ZRZ50).
- Fill the bucket with 4 gallons of high temperature water.
- Add the buffering agent (BA-20) to decrease the Ph of the water to 6.5 to ensure proper hydration.
- Add 54.4 g of Guar gelling agent to the fluid and mix for 30 minutes.
- Add the buffering agent (BA-40) to increase the Ph of the fluid to 10.
- Add MO-67 to increase the Ph of the fluid from 10 to 11.5
- Add 41.43 ml of Gelsta-L to stabilize the gel at high temperatures.
- Add 69.05 ml of ViCon NF for breaker.
- Measure the desired proppant weight based on concentration and add it to the mixture.
- Add 16.57 ml of CL-28M (Cross-linker) to the propped mixture.
- After the propped fluid is fully cross-linked, transfer the slurry to the mixing tank.

2.2.5 Fracturing Fluid Pumping

The fracturing fluid pumping procedure unit consists of 2 different jet pumps and a high-pressure centrifugal pump. The main function of the 2 jet pumps is to displace the slurry and the pad to the line connected to the centrifugal pump. After the pad and the slurry are properly mixed, both fluids are pumped with a back-pressure of 200 psi for proper proppant transport and to replicate actual pumping conditions occurring in the field.

Fracturing fluid pumping procedure:

- The 12 gallons of pad and the 4 gallons of slurry need to be stored in the plastic drum and in the mixing tank before starting the pumping procedure.
- The first step is to pump the pad volume from the plastic drum to the conductivity cell, maintaining a pumping pressure of 200 psi by operating the back-pressure valve.
- Leave the remaining 5 gallons of pad to flush the pipelines, clean the system, and extend the operating life of the pump.
- Make the necessary changes by switching the valves to start pumping the slurry volume from the mixing tank to the conductivity cell.
- After pumping the total slurry volume, close the outlet and the inlet valves of the conductivity cell respectively to trap the slurry inside.
- Make the necessary valve changes and start pumping the remaining 5 gallons of pad volume to clean the pipes.
- Fill up the mixing tank with tap water.
- Pump the full tank volume of water to make sure the pipelines and the centrifugal pump are completely clean.

2.2.6 Closure Stress Shut-In

An 850kN load frame is used to apply a desired closure stress to the conductivity cell. After finishing the pumping procedure, closure stress is applied to the conductivity cell for a period of time, using the GCTS C.A.T.S software to operate the frame.

Closure stress shut-in procedure:

- Start the GCTS C.A.T.S software.
- In the top menu, go to File/Projects.
- Create a new project schedule.
- Create a new sample for the experiment.
- Click on “new specimen” and input the design parameters for the experiment.
- Select the desired program from the Universal Test Setup Screen (high or low closure stress). Click on New to create a new program if the pressure/rate needs to be changed.
- Click Run to start applying closure stress to the conductivity cell. The GCTS C.A.T.S software saves data automatically.

2.2.7 Propped Pack Conductivity Measurement

After closure stress is applied to the cell, the slurry inside the cell is allowed to break for approximately 12 hours. The next step is to start nitrogen flow at a desired constant flow rate for a time period of at least 6 hours. Finally, pressure and flow rate are measured at regular intervals to calculate fracture conductivity using either Forcheimer’s equation or Darcy’s law. The equation used was selected whether the Non-Darcy flow effect is significant or not.

Proppant pack conductivity measurement procedure:

- Open the inlet of the conductivity cell.
- Turn on the mass flow controller and start flowing nitrogen into the conductivity cell until a cell pressure of 50 psi is reached.

- Make sure to check the pressure lines and conductivity cell for leakage. If leakage is found repair the leak and continue with the procedure.
- Open the valves of the pressure transducers and the outlet of the conductivity cell, while keeping the back-pressure valve closed so the pressure is maintained inside the cell.
- Wait for the system to stabilize for 5 minutes and record the baseline absolute and differential pressure.
- Start varying the nitrogen flow rate from 1 slm to 9 slm to get 9 sets of data, keeping the pressure inside the cell around 50 psi. For each data set, record absolute and differential pressure.
- For every measurement, wait 2 minutes for each flow rate to stabilize before recording the absolute and differential pressure inside the cell.
- To vary the flow rate, operate either the nitrogen flow regulator or the back pressure valve.
- Shut down the nitrogen flow and release the pressure in the system very carefully.
- Disconnect all the lines from the conductivity cell.
- Dissemble the conductivity cell and remove the core samples from the cell with the help of a hydraulic jack.
- Collect and measure the weight of the amount of proppant in the fracture.
- Calculate fracture conductivity by using either Forcheimer's equation (Eq. 2.1) or Darcy's equation (Eq. 2.2).

$$\frac{(p_1{}^2-p_2{}^2)Mh}{2ZRTL\mu\rho q} = \frac{1}{k_f w} + \frac{\beta\rho q}{w^2\mu h} \tag{2.1}$$

$$\frac{(p_1{}^2-p_2{}^2)M}{2ZRTL} = \frac{\rho q\mu}{h}\frac{1}{wk} \tag{2.2}$$

To calculate the conductivity of the fracture from the experimental data, Eq. 2.1 and Eq. 2.2, shown above, were set up as straight line equations of the form y = mx + c, where $\frac{\rho q}{\mu h}$ or $\frac{\rho q\mu}{h}$ is the x-axis, and $\frac{(p_1{}^2-p_2{}^2)Mh}{2ZRTL\mu\rho q}$ or $\frac{(p_1{}^2-p_2{}^2)M}{2ZRTL}$ is the y-axis for Forcheimer's equation and Darcy's law respectively. The y intercept of the straight line represents the inverse of fracture conductivity. The final conductivity used as a result for the experiment depends whether Non-Darcy flow effects are significant or not. Fig. 2.13 shows an example of a good data fit for an accurate measurement of fracture conductivity.

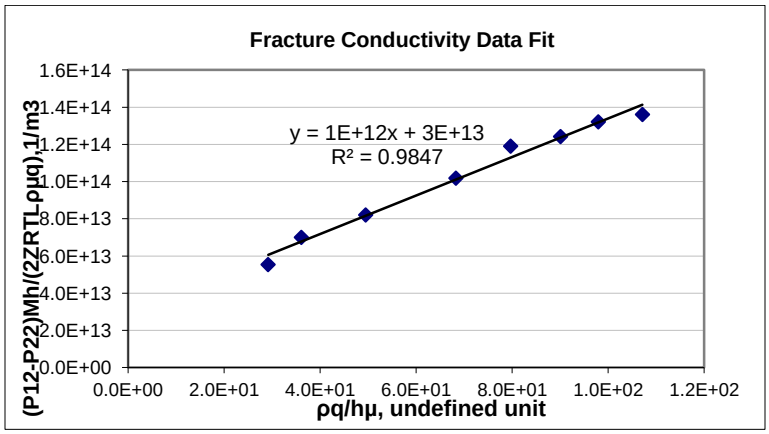

Fig 2.13: Forcheimer's Conductivity Data Fit Example

The parameters used in the conductivity calculation in this study are listed in Table 2.1.

Table 2.1 Conductivity Parameters

Parameter	Value	Units
Length, L	5.25	In
Compressibility Factor, Z	1	
Universal Constant, R	8.3144	J/mol K
Temperature, T	293.15	K
RMM of Nitrogen, M	0.028	Kg / kg mole
Viscosity of Nitrogen, μ	1.795E-05	Pa.s
Density of Nitrogen, ρ	1.16085	Kg/m^3
Height of fracture face, h	1.61	In

2.3 Experimental Conditions

The parameters tested are closure stress, proppant concentration, reservoir temperature, and flow back rates. The values used for the experiments are based on a literature review and common field conditions for tight gas reservoirs. For every experiment, each factor is tested at two levels/ or settings (high and low).

2.3.1 Tight Gas Sandstone Core Sample

The core samples used for these experiments are low permeability Ohio Scioto Sandstone. Table 2.2 shows the petrophysical and mechanical properties of the core samples used in these experiments.

Table 2.2 Core Properties of Ohio Scioto Sandstone

Property	Value
Permeability, md	0.01 – 0.1
Porosity, fraction	0.175
Young's Modulus @ 1500/2500psi confining pressure, psi	2.5E6/2.43E6
Average Poisson's ratio @ 1500/2500psi	0.163/0.189

2.3.2 Fracturing Fluid Composition

The fracturing fluid selected for these experiments is a water-based guar cross-linked fluid consisting of a mixture of polymer, gel stabilizer, breaker, breaker activator, cross-linker, and pH buffers. The fracturing fluid composition was previously to resemble typical fracturing fluids of an actual tight gas fracturing operation. The steps for preparing the fracturing fluid were given in Section 2.2.4. A detailed breakdown of the fracturing fluid components is shown in Table 2.3.

Fracturing Fluid Components:

- Polymer: Guar polymer is used to create a linear gel. The main function of the polymer is to increase the viscosity of the fluid.
- Buffers: the main functions of the buffers are to reduce the pH of the fluid to allow for proper hydration and to raise it to allow for proper cross-linking.

- Gel Stabilizer: The main function of the stabilizer is to increase the stability of the viscosity of the gel for experiments at high temperatures.
- Breaker: The main function of the breaker is to reduce the viscosity of the fracturing fluid by breaking the long-chain molecules into shorter segments for proper gel cleanup.
- Breaker Activator: The main function of the activator is to activate the breaker for experiments with low temperature conditions.
- Cross-linker: The main function of the borate cross-linker is to increase the viscosity of the fracturing fluid for proper proppant transportation.

Table 2.3 Fracturing Fluid Components

Component	**Loading**
Polymer	30 pounds/1000 gallons of fracturing fluid
Buffer 1	Variable
Buffer 2	Variable
High Temperature Buffer	Variable
Gel Stabilizer	1.5-3 gallons/1000 gallons of fracture fluid
Breaker	5-10 gallons/1000 gallons of fracture fluid
Breaker Activator	0-1 gallons/1000 gallons of fracture fluid
Cross-Linker	0.1-0.4 gallons/1000 gallons of fracture fluid

2.3.3 Proppant Description

The proppant used in the experiments is 30/50 ceramic proppant provided by Carbo Ceramics. The proppant concentration for these experiments was varied from 0.5 to 2 ppg. This is equivalent to 0.075-0.3 lb/ft^2 in cores with a 12.5 in^2 surface area. These concentrations were selected to resemble fracturing operations in tight gas reservoirs with a low viscosity fracturing fluid. The weight of this type of proppant is considered optimal for proppant transportation in common fracturing operations using low viscosity fracturing fluids.

2.3.4 Polymer Concentration

A polymer concentration of 30 lbs/1000 gallons of fracture fluid is used for this set of experiments. The main purpose of the polymer concentration is to increase the viscosity of the fluid for optimum proppant transportation. This concentration is commonly used for tight gas or slick-water fracturing operations.

2.3.5 Temperature

A range of temperatures between 150 °F and 250 °F were selected for study to replicate typical tight gas reservoir temperatures. Temperature is a very important factor because it affects the proppant's physical properties, the way the polymer dehydrates, and the way the breaker reacts inside the propped fracture. A heating jacket, attached to the conductivity cell, is used to reach the desired temperature for the experiments.

2.3.6 Closure Stress

Closure stress was varied between 2000 psi and 6000 psi to study the effect on propped fracture conductivity. The closure stress affects how the proppant is crushed inside the fracture. Also, proppant embedment is highly dependent on closure stress. Proppant embedment can cause a significant reduction in fracturing width leading to a reduction in the proppant pack conductivity.

2.3.7 Flow Back Rates

The laboratory flow back rates for this set of experiments were chosen to resemble actual producing rates from field data. Table 2.4 shows the parameters selected to calculate flow rates under laboratory conditions.

Table 2.4 Laboratory and Field Data

	Laboratory Data	**Field Data**	**Units**
Fracture Height, h	0.133	100	Ft
Fracture Width, w	0.04	0.25	In
Temperature, T	150-250	250	°F
Flowing Pressure, pwf	50	1000	Psi

Based on the selected input parameters, a laboratory flow rate calculation example is shown below:

$$q_{sc} = 3\ \frac{sl}{min}\left(0.0353\ \frac{SCF}{sl}\right) = 0.1059\ \frac{SCF}{min} \tag{2.3}$$

$$B_g = \frac{\frac{zt}{p}}{\frac{Z_{sc}T_{sc}}{p_{sc}}} = \frac{(1)(150+460)/50}{(1)(60+460)/14.7} = 0.3448\ \frac{ft^3}{SCF} \tag{2.4}$$

$$q = B_g q_{sc} = 0.1059\ \frac{SCF}{min}\ 0.3448\ \frac{ft^2}{SCF} = 0.0365\ \frac{ft^3}{min} \tag{2.5}$$

$$v_{lab} = \frac{q}{w\ h} = \frac{0.0365\ \frac{ft^3}{min}}{(1.6\ in)(0.04\ in)}\ 144\frac{in^2}{ft^3} = 82.125\ \frac{ft}{min} \tag{2.6}$$

Using the gas flux under laboratory conditions, gas flux under reservoir conditions is calculated. Assume the temperature is 250 °F and Pressure is 1000 psi.

$$B_g = \frac{(1)(250+460)/1000}{(1)(60+460)/14.7} = 0.0201\ \frac{ft^3}{SCF}$$

$$q = v_{frac}A = (82.13\frac{ft}{min})(100\text{ ft})(0.25\text{ in})(\frac{1\ ft}{12\ in}) = 171.104\ \frac{ft^3}{min} \tag{2.7}$$

$$q_{sc} = \frac{q}{B_g} = \frac{171.104\ \frac{ft^3}{min}}{0.0201\ \frac{ft^3}{SCF}} = 8525.36\ \frac{SCF}{min} \tag{2.8}$$

$$\frac{q_{sc}}{wing} = 8525.36\ \frac{SCF}{min}\frac{(24)(60)}{1}\frac{min}{day} = 12.28\ \frac{MMSCF}{day}$$

CHAPTER III

RESULTS AND DISCUSSION

3.1 Experimental Design

The objective of this investigation is to determine the key factors affecting proppant pack conductivity using the dynamic conductivity test. The parameters evaluated in this investigation were temperature, flow back rate, closure stress, and proppant concentration. The polymer concentration used for the fracturing fluid is 30lb/1000gal. A fractional factorial design was implemented in order to determine the main effect of each of the investigated factors and to minimize the number of experiments. Due to the stochastic nature of the dynamic conductivity test, every experiment was repeated several times to evaluate the consistency of the results. Table 3.1 shows the factor levels and parameters evaluated for this experimental design. Table 3.2 and Table 3.3 show the number of experiments that were performed at the high and low settings respectively after screening bad experiments and outliers.

Table 3.1 Parameters Evaluated in the Experimental Design

Parameter	**Low Setting**	**High Setting**
Temperature, °F	150	250
Flow Back Rate, SL/min	1	3
Closure Stress, psi	2000	6000
Proppant Concentration, ppg	0.5 for Low Temperature 1 for High Temperature	2

Table 3.2 Experiments Performed at High Closure Stress/Temperature

Proppant Concentration, ppg	**Nitrogen Rate, SL/min**	**Number of Iterations**
2	1	4
2	3	2
1	1	4
1	3	2

Table 3.3 Experiments Performed at Low Closure Stress/Temperature

Proppant Concentration, ppg	**Nitrogen Rate, SL/min**	**Number of Iterations**
2	1	6
2	3	5
0.5	1	5
0.5	3	5

3.2 Experimental Results

Results from the high closure stress/high temperature and low closure stress/low temperature experiments are shown in Table 3.4 and Table 3.5 respectively. Two different measures of central tendency were used to analyze the conductivity results. The high standard deviation in the experimental data can be attributed to the fact that both the proppant weight and distribution inside the fracture play a significant role in fracture conductivity.

Table 3.4 Conductivity Results for High Settings Experiments

Proppant concentration, ppg	N2 Rate, SL/m	Conductivities, md-ft				Average Conductivity, md-ft	Standard Deviation, md-ft
2	1	87	201	130	20	109	66
1	1	153	91	5	220	117	79
1	3	57	21			39	18
2	3	34	13			23	10

Table 3.5 Conductivity Results for Low Settings Experiments

Proppant concentration, ppg	N2 Rate, SL/m	Conductivities, md-ft						Average Conductivity, md-ft	Standard Deviation, md-ft
2	1	2565	2717	1581	1663	1742	122	1732	845
0.5	1	3321	3252	3058	3669	472		2754	1158
0.5	3	436	650		5883	3152	66	2037	2209
2	3	453	583	575	51	70		346	238

3.2.1 Effect of Temperature

Temperature has a significant effect on the mechanical properties of the proppant and the breaking time of the fracturing fluid. Based on experimental results in Table 3.4 and Table 3.5, the relationship between temperature and fracture conductivity was observed to be inversely proportional. An increase in temperature from 150 °F to 250 °F in the conductivity cell decreased the fracture conductivity significantly. One of the reasons attributed for this type of behavior could be related to polymer dehydration inside the conductivity cell at high temperatures. Fig. 3.1 shows a common phenomenon in high closure stress and high temperature experiments in which a dense proppant cake forms in the simulated fracture, significantly reducing the conductivity of the proppant pack. Further investigation is recommended in order to ascertain whether or not this is a common effect observed in actual field conditions, or if it is related to the way the dynamic conductivity test is performed under laboratory conditions.

Fig 3.1: Proppant Cake Formed at High Temperature Experiments

3.2.2 Effect of Closure Stress

The effect of closure stress used in these experiments was designed to replicate realistic conditions in tight gas reservoirs. Closure stress was increased from 2000 to 6000 psi to evaluate the effect of this factor on fracture conductivity. From the results shown in Table 3.4 and Table 3.5, closure stress is observed to have a negative effect on fracture conductivity. This effect can be attributed to the reduction in fracture width as closure stress was increased. Additionally, at high closure stresses the proppant loses optimal physical properties due to crushing, leading to a reduction in conductivity. Fig 3.2 shows an example of dried and crushed proppant after a 6000 psi closure stress is applied. This effect is more noticeable in experiments where low concentrations of proppant are used, resulting in significantly lower fracture conductivity. Table 3.6 shows a comparison between the average conductivities of experiments with high and low closure stress values. Fig 3.3 shows the conductivity values for low and high closure stresses.

Fig 3.2: Dried and Crushed Proppant at High Closure Stresses

Table 3.6 – Average Conductivity for High and Low Settings

Parameter	Average Conductivity, md-ft
High Setting	86
Low Setting	1718

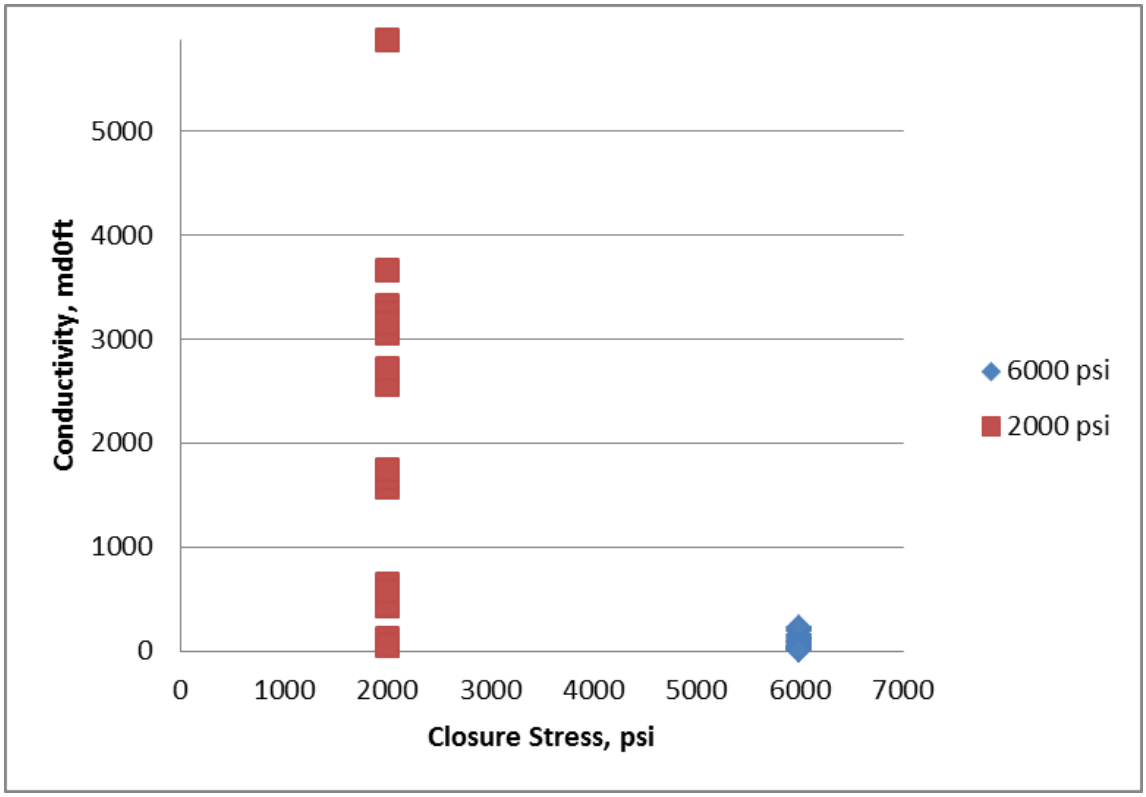

Fig 3.3: Conductivity for High and Low Closure Stresses

3.2.3 Effect of Flow Back Rates

Fracture conductivity was observed to decrease with an increase in the flow back rate from 1 SL/min to 3 SL/min. This result contradicts the original expectation that an increase in nitrogen flow rate would aid the cleanup process, causing a reduction of gel damage in the fracture and resulting in a higher conductivities. The significant reduction in fracture conductivity might be due to the effect of polymer dehydration at higher flow rates and temperatures. However, there is no certainty based on the experimental results that this conductivity reduction is an effect that occurs in real fractures; it could be an artifact that is only occurring in laboratory conditions, unlikely to have an impact in real fracturing treatments. Further, more detailed investigation on the effect of flow back rates is recommended in order to validate these results. Table 3.7 shows the average conductivity values for the low and high flow rate cases.

Table 3.7 – Average Conductivity Values for Low/High Nitrogen Rates

Nitrogen Rate, SL/min	Closure Stress, Psi	Temperature, °F	Average Conductivity, md-ft
1	2000	150	2197
3	2000	150	1192
1	6000	250	113
3	6000	250	31

3.2.4 Effect of Proppant Concentration

The effect of proppant concentration is studied during these experiments. For the experiments with low closure stress and low temperature, the proppant concentrations used are 0.5 ppg and 2.0 ppg. For the high closure stress and high temperature scenario however, the proppant concentrations used are 1.0 ppg and 2.0 ppg. The difference in design for the two cases was due to the fact that in experiments with high and closure stresses, a proppant concentration of 0.5 ppg is not enough to keep the fracture open for nitrogen to flow through it, thus compromising the ability to measure the pressure drop across the fracture.

Based on experimental results, conductivity is observed to decrease with a decrease in proppant concentration from 2 ppg to 1 or 0.5 ppg. This effect can be attributed to the difference in the amount of proppant that is deposited inside the fracture, and related to fluid transport properties and the back-pressure imposed when the fracturing fluid is being pumped. Additionally, the proppant distribution inside the fracture had a significant effect on conductivity due to the formation of channels, which were found in some of the experiments conducted at low proppant concentration. These channels create a high path for gas to flow through the fracture, causing a significant reduction in the pressure drop, leading to an increase in fracture conductivity. Table 3.8 shows the average conductivities for the low and high proppant concentrations. Fig 3.4, Fig 3.5, and Fig 3.6 show the different scenarios in experiments containing channels, experiments homogenously distributed, and experiments containing void spaces.

Table 3.8 – Average Conductivity Values for Low and High Proppant Settings

Setting	**Average Conductivity, md-ft**
High	742
Low	1532

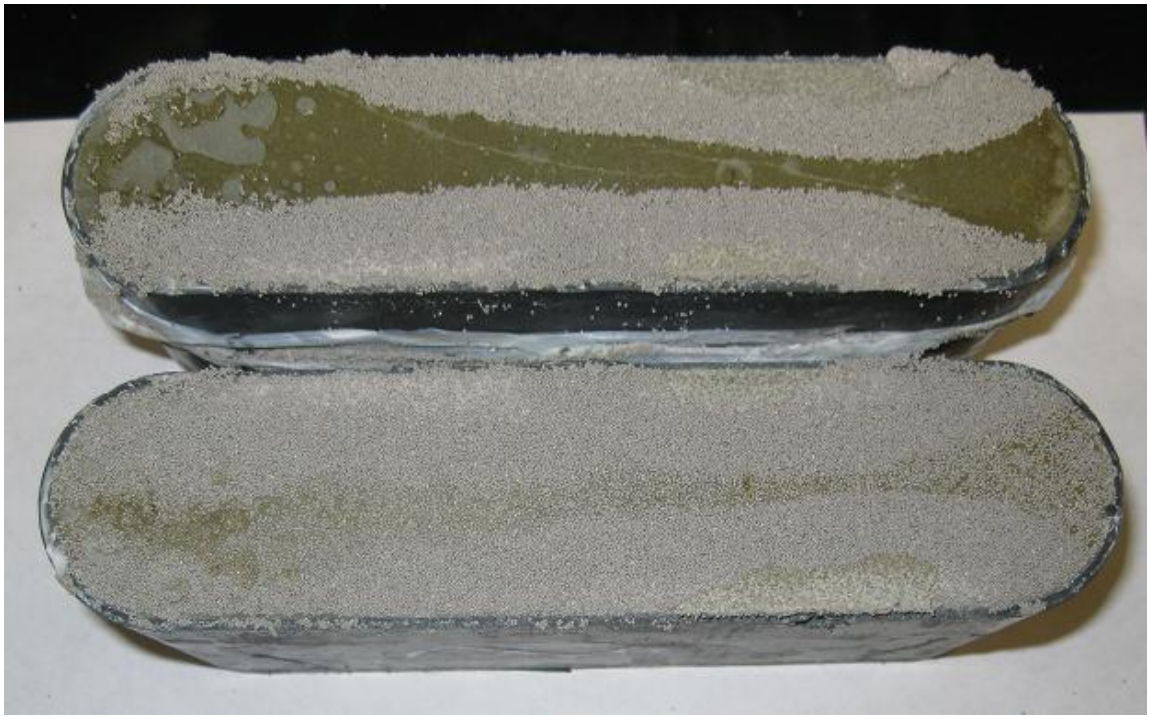

Fig 3.4: Experiment Containing Channels

Fig 3.5 Experiment with Uniform Proppant Distribution

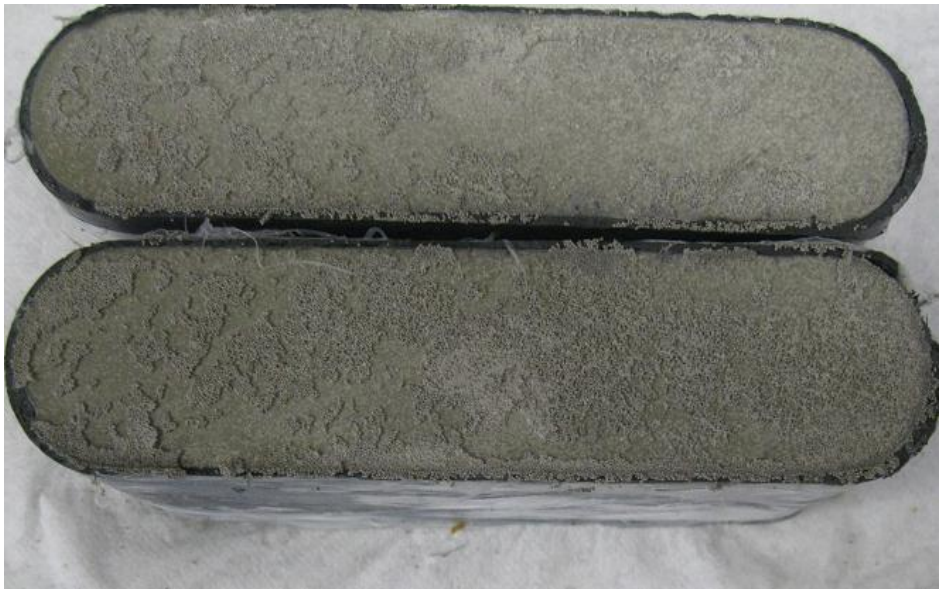

Fig 3.6: Experiment with Void Spaces

3.2.5 Static Test

Static conductivity experiments were developed by API to measure proppant conductivity. The main difference of a static conductivity test compared to a dynamic conductivity test is that the proppant is loaded manually inside the created fracture. A series of experiments using the static conductivity test were conducted to evaluate differences in final conductivity between the static conductivity test and the dynamic conductivity test. Table 3.9 shows a comparison of the dynamic and static final conductivity results at high closure stress and temperature conditions.

Table 3.9 – Comparison of Dynamic and Static Test

Proppant Concentration, ppg	Nitrogen Rate, SL/min	Static Test Average Conductivity, md-ft	Dynamic Test Average Conductivity, md-ft
2	1	162	110
2	3	118	23

As shown from the table above, fracture conductivity is relatively higher in static conductivity testing compared to dynamic conductivity testing. This effect can be attributed to the absence of gel damage in static testing. Dynamic experiments at high closure stress and temperature experienced the formation of a dense proppant cake in the simulated fracture, significantly reducing the conductivity of the proppant pack.

CHAPTER IV

CONCLUSIONS

A series of experiments were conducted to determine the effect of various factors on fracture conductivity. The factors investigated are closure stress, flow back rates, temperature, and proppant concentration. The most relevant conclusions following our experimental design and analysis are:

1. An increase in closure stress has a detrimental effect on fracture conductivity. This effect can be attributed to the reduction in fracture width as closure stress was increased. In addition, at high closure stresses and temperatures proppant loses its optimal physical properties due to crushing, leading to a reduction in conductivity.
2. The formation of channels plays an important role in determining the final conductivity of a fracture. The formation of these channels is related to the amount of proppant distributed inside the conductivity cell and the back-pressure imposed while pumping. The presence of these channels resulted in a significant increase in the conductivity of the fracture using the dynamic conductivity experimental setup.
3. Experiments performed at high temperatures exhibited a reduction in the fracture conductivity. The formation of a proppant-polymer cake due to dehydration of the polymer at high temperatures was a critical factor for this reduction in the conductivity.

4. The effect of the nitrogen flow rate was observed to be inversely proportional to fracture conductivity. The significant reduction in fracture conductivity was possibly due to the effect of polymer dehydration at higher flow rates and temperatures; however, there can be no certainty based on the experimental results that this reduction in conductivity is an effect that occurs in real fractures or whether it is an effect that is only significant under laboratory conditions.
5. Static conductivity test resulted in higher fracture conductivity when compared to dynamic conductivity testing. This effect can be attributed to the absence of gel damage in static testing. Dynamic experiments at high closure stress and temperature experienced the formation of a dense proppant cake in the simulated fracture, significantly reducing the conductivity of the proppant pack.

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APPENDIX A

Table A.1 Low Settings Conductivity Experimental Schedule

N2 Rate, SL/min	Temperature, °F	Closure Stress, psia	Proppant Concentration, Ppg	Conductivity, md-ft
1	150	2000	2	2565
1	150	2000	2	2717
1	150	2000	2	1581
1	150	2000	2	1663
1	150	2000	2	1742
1	150	2000	2	122
1	150	2000	0.5	3321
1	150	2000	0.5	3252
1	150	2000	0.5	3058
1	150	2000	0.5	3669
1	150	2000	0.5	472
3	150	2000	0.5	436
3	150	2000	0.5	650
3	150	2000	0.5	5883
3	150	2000	0.5	3152
3	150	2000	0.5	66
3	150	2000	2	453
3	150	2000	2	583
3	150	2000	2	575
3	150	2000	2	51
3	150	2000	2	70

Table A.2 High Settings Conductivity Experimental Schedule

N2 Rate, SL/min	Temperature, °F	Closure Stress, psia	Proppant Concentration, Ppg	Conductivity, md-ft
1	250	6000	2	87
1	250	6000	2	201
1	250	6000	2	130
1	250	6000	2	20
1	250	6000	1	153
1	250	6000	1	91
1	250	6000	1	5
1	250	6000	1	220
3	250	6000	1	57
3	250	6000	1	21
3	250	6000	2	34
3	250	6000	2	13

Table A.3 High/Low Settings Conductivity Experimental Schedule

N2 Rate, SL/min	Temperature, °F	Closure Stress, psi	Proppant Concentration, ppg	Conductivity, md-ft
0.5	150	6000	2	598
0.5	150	6000	2	542
0.5	250	2000	2	3945
0.5	250	2000	2	3210
0.5	250	2000	2	3674
0.5	250	2000	2	3543
3	150	6000	0.5	1120
3	150	6000	0.5	448
3	250	2000	0.5	216

APPENDIX B

B.1 Effect of Temperature on Fracture Conductivity

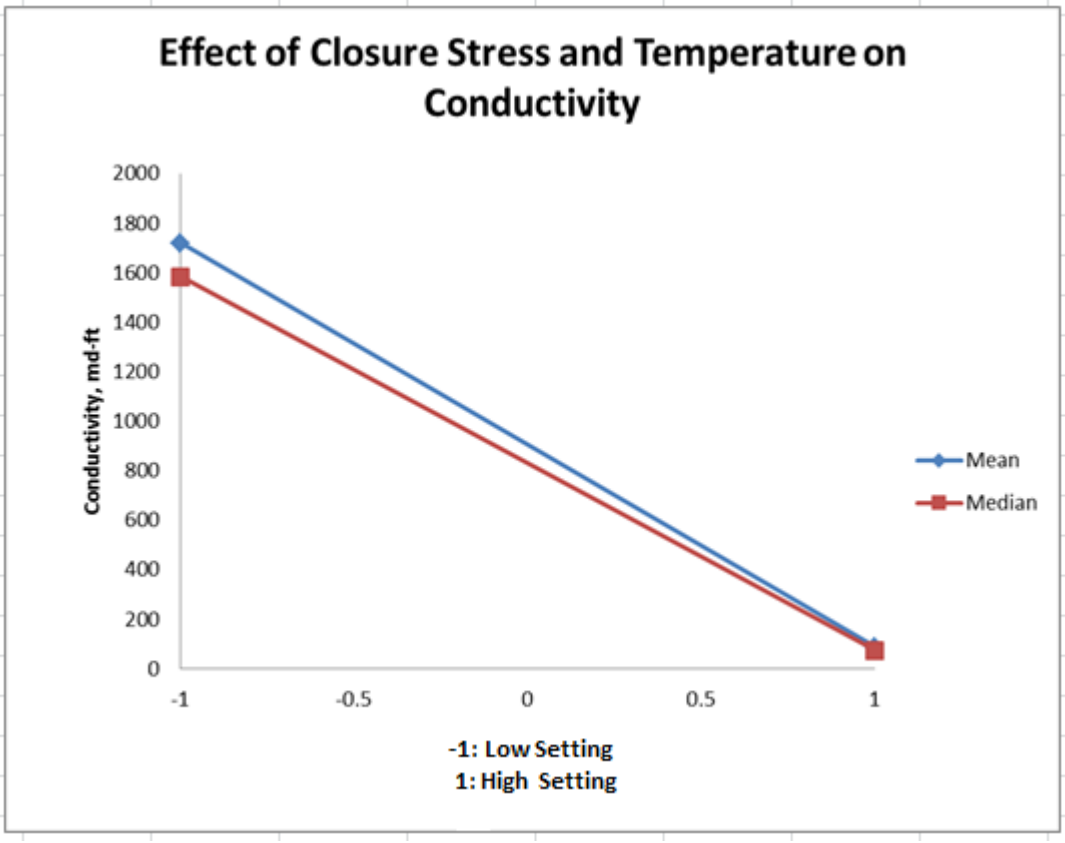


Fig B.1: Effect of Closure Stress and Temperature on Conductivity

B.2 Effect of Flow Back Rates on Fracture Conductivity

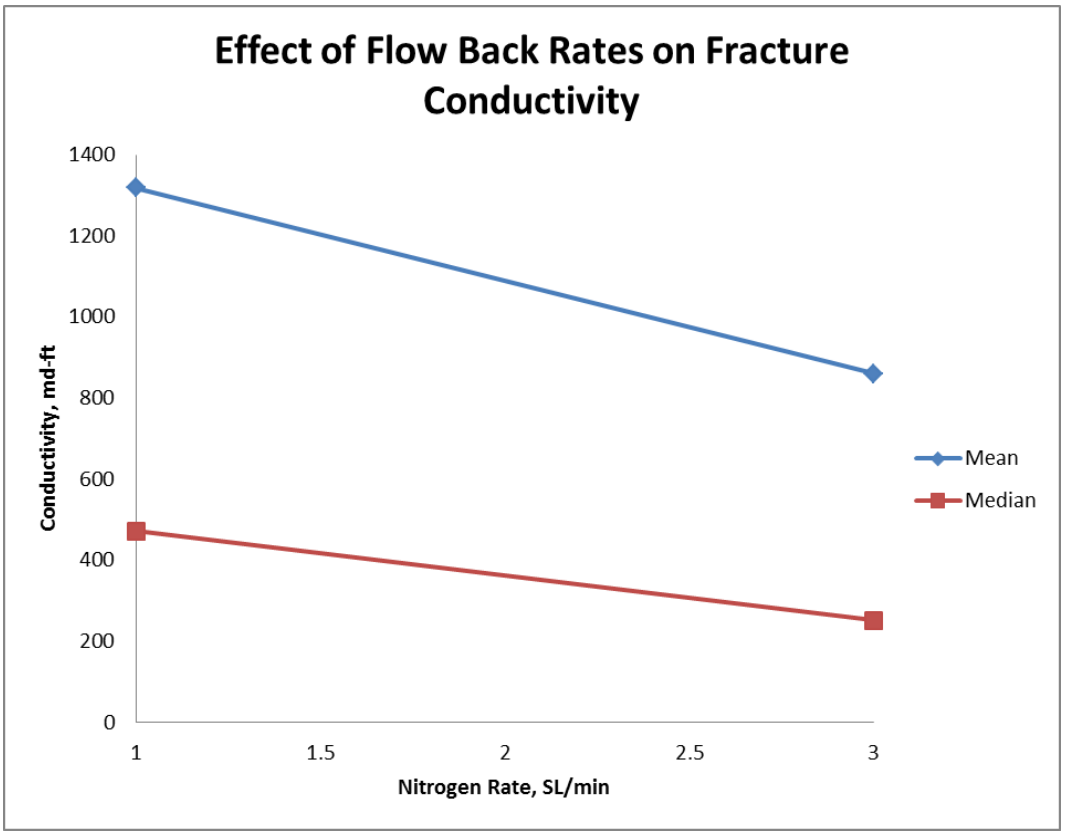


Fig B.2: Effect of Flow Back Rate on Conductivity

B.3 Effect of Proppant Concentration on Fracture Conductivity

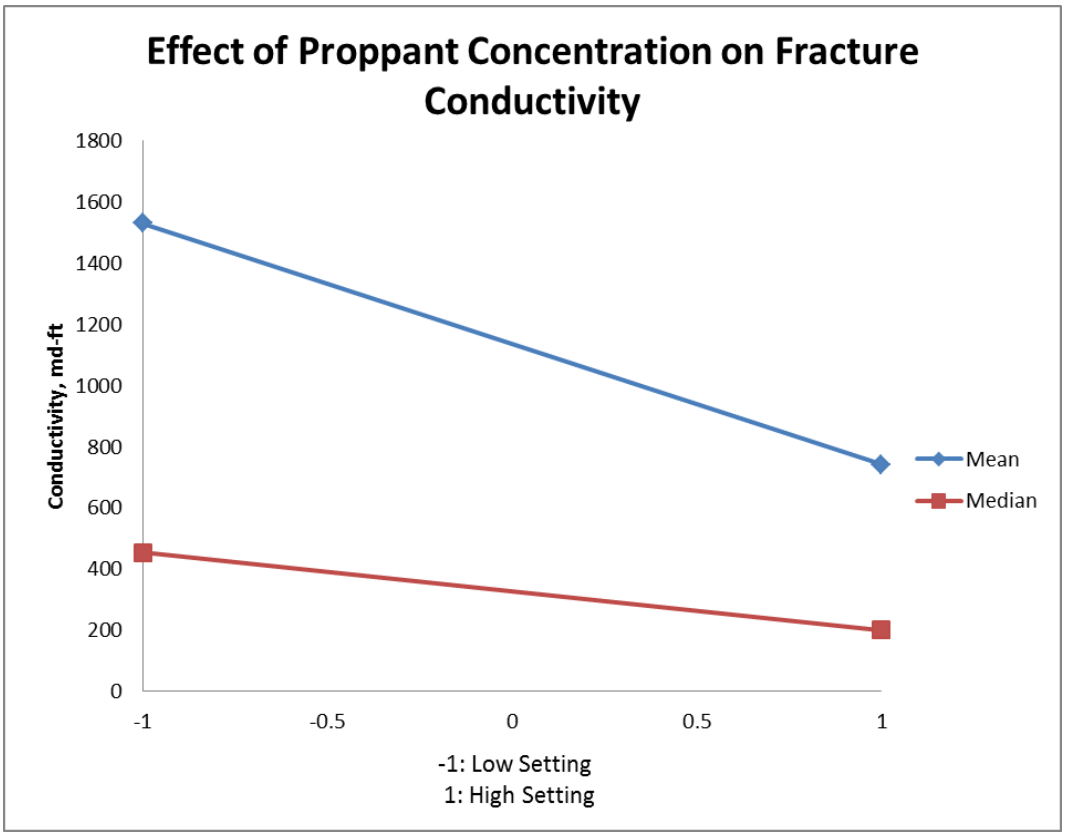
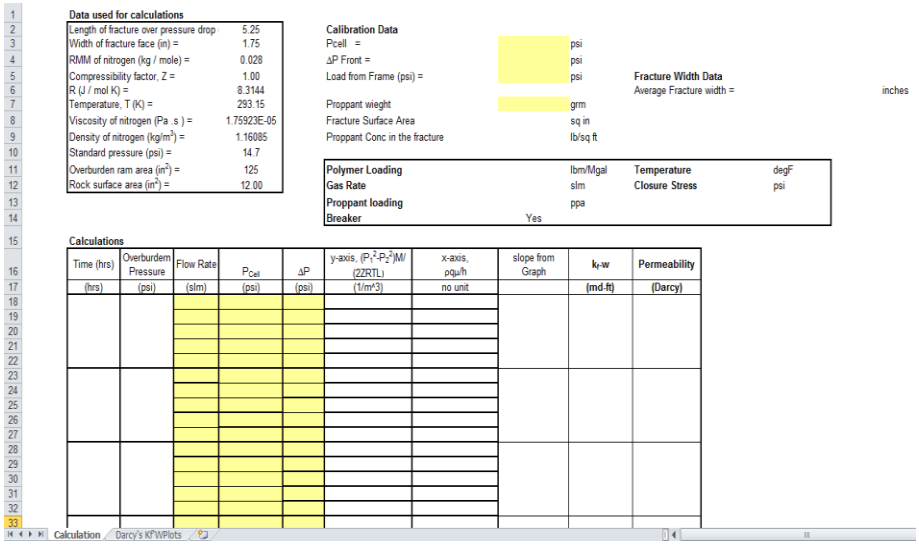


Fig B.3: Proppant Concentration on Conductivity

B.4 Darcy's Conductivity Calculation Sheet



Data used for calculations

Length of fracture over pressure drop	5.25
Width of fracture face (in) =	1.75
RMM of nitrogen (kg / mole) =	0.028
Compressibility factor, Z =	1.00
R (J / mol K) =	8.3144
Temperature, T (K) =	293.15
Viscosity of nitrogen (Pa .s) =	1.75923E-05
Density of nitrogen (kg/m^3) =	1.16085
Standard pressure (psi) =	14.7
Overburden ram area (in^2) =	125
Rock surface area (in^2) =	12.00

Calibration Data

Pcell =		psi
ΔP Front =		psi
Load from Frame (psi) =		psi
Proppant wieght		grm
Fracture Surface Area		sq in
Proppant Conc in the fracture		lb/sq ft

Fracture Width Data

Average Fracture width = inches

Polymer Loading	lbm/Mgal	**Temperature**	degF
Gas Rate	slm	**Closure Stress**	psi
Proppant loading	ppa		
Breaker	Yes		

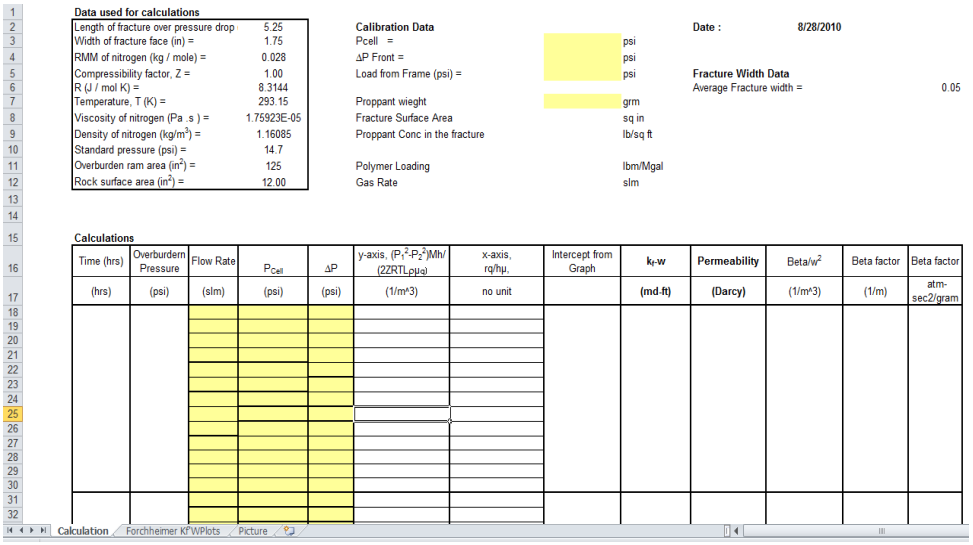
Calculations

Time (hrs)	Overburden Pressure	Flow Rate	P_{Cell}	ΔP	y-axis, $(P_i^2-P_2^2)M/(2ZRTL)$	x-axis, $pq\mu/h$	slope from Graph	k_f-w	Permeability
(hrs)	(psi)	(slm)	(psi)	(psi)	(1/m^3)	no unit		(md-ft)	(Darcy)

Calculation | Darcy's KFWPlots

Fig B.4: Darcy's Conductivity Calculation Sheet

B.5 Forchheimer's Conductivity Calculation Sheet



Data used for calculations

Length of fracture over pressure drop	5.25
Width of fracture face (in) =	1.75
RMM of nitrogen (kg / mole) =	0.028
Compressibility factor, Z =	1.00
R (J / mol K) =	8.3144
Temperature, T (K) =	293.15
Viscosity of nitrogen (Pa .s) =	1.75923E-05
Density of nitrogen (kg/m^3) =	1.16085
Standard pressure (psi) =	14.7
Overburden ram area (in^2) =	125
Rock surface area (in^2) =	12.00

Calibration Data

Pcell =		psi
ΔP Front =		psi
Load from Frame (psi) =		psi
Proppant wieght		grm
Fracture Surface Area		sq in
Proppant Conc in the fracture		lb/sq ft
Polymer Loading		lbm/Mgal
Gas Rate		slm

Date : 8/28/2010

Fracture Width Data

Average Fracture width = 0.05

Calculations

Time (hrs)	Overburden Pressure	Flow Rate	P_{Cell}	ΔP	y-axis, $(P_i^2-P_2^2)Mh/(2ZRTL_{p\mu q})$	x-axis, $rq/h\mu$,	Intercept from Graph	k_f-w	Permeability	Beta/w^2	Beta factor	Beta factor
(hrs)	(psi)	(slm)	(psi)	(psi)	(1/m^3)	no unit		(md-ft)	(Darcy)	(1/m^3)	(1/m)	atm-sec2/gram

Calculation | Forchheimer KFWPlots | Picture

Fig B.5: Forchheimer's Conductivity Calculation Sheet

B.6 Darcy's Chart Conductivity Calculation Example

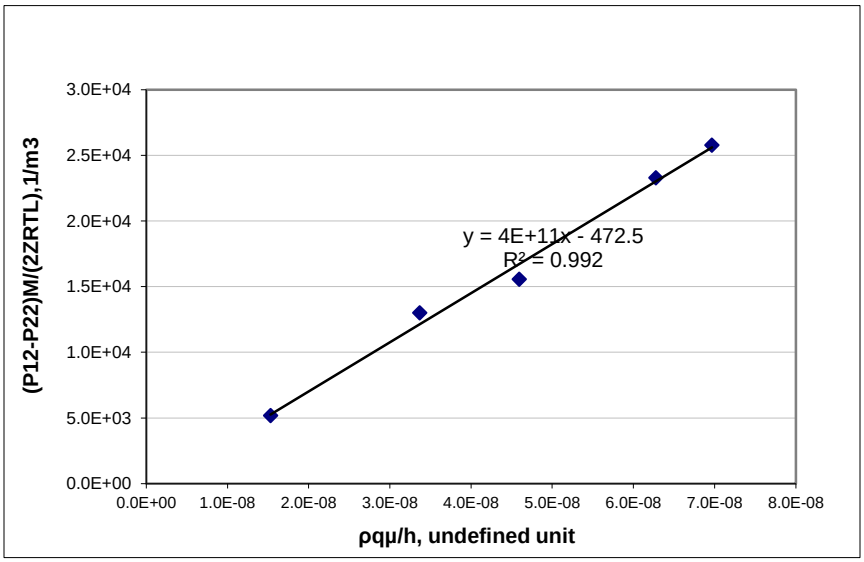


Fig B.6: Darcy's Chart Conductivity Calculation Example