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Experimental Investigation of Injectivity in Unconsolidated Formations

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Experimental Investigation of Injectivity in Unconsolidated Formations

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Abstract

A series of injection experiments were conducted in a cell rated for high pressures that was also equipped with a transparent glass sight. The device allowed for the physical simulation of radial flow in unconsolidated sand in order to better understand the factors affecting injectivity. Aqueous glycerin solutions of varying viscosities were used as the injected fluid, and various proppant mesh sizes were used to represent the unconsolidated formation. The objective of the study was to determine factors that control injectivity into granular media, and to observe any channeling or other flow patterns through the use of this physical apparatus.

The experimental findings did not reveal any channeling during the injection period. The results were limited as the pump used could not vary or increase injection rates, nor was overburden pressure effectively simulated. The study was successful in delivering a working model that allows for the visualization of fluid as it propagates through the system. Addressing some of the design issues associated with the experimental setup is suggested to further this study on injectivity into unconsolidated granular media.

1. Introduction

Oil and gas reservoirs with unconsolidated formations such as those in the Gulf of Mexico have been developed for decades. After so many years of production, these reservoirs depend on a secondary recovery technique known as waterflooding in order to recover further hydrocarbons and maintain the overall reservoir pressure. In this technique, the reservoir is flooded with water or a polymer via one or more injection wells, which not only serves to increase the reservoir pressure, but also further displaces the hydrocarbons towards the production wells. This technique maintains the production rate for a longer period and also increases the ultimate recovery of the reservoir (Chappell, 2006).

Since these deepwater developments rely on this type of enhanced recovery, it is important to understand how the injected fluids flow through the porous media in order to optimize the effectiveness of such huge economic projects. Specifically, this project is interested in exploring how the fluid flows in the near wellbore region.

A variety of experiments and models have been used to understand how injected fluid flows through unconsolidated sand formations in order to better optimize the waterflooding process. This experiment aims to study this process in the near wellbore region while being subjected to a confining pressure. The injectivity parameter (Golovin, 2011) will be measured by the injection rate (Q_{inj}), injection pressure (P_{ip}), and confining pressure ($(\sigma_y + \sigma_x + \sigma_z)/3$). The following ratio will be used to represent the sand injectivity parameter I:

$$I = Q_{inj}/P_{ip} \quad (1)$$

This project aims primarily to discover what factors affect injectivity into porous media by investigating such variables as injection rate, fluid viscosity, and grain size. This topic has been modelled extensively in the past and will continue to be an active area of research in industry as long as these types of reservoirs are being developed. Previous studies have investigated the variables mentioned, but there have been limited attempts to apply a confining pressure on the system in order to more accurately simulate in-situ reservoir conditions. The apparatus designed for this project will not only support a confining pressure, but will also allow for the propagation of the fluid to be viewed as it is injected.

2. Background

a. Literature Review

A large portion of today's oil production comes from fields that are considered 'mature', or past their primary production stage. In order to continue meeting world oil demand, secondary recovery and enhanced oil recovery (EOR) technologies are needed to recover known resources in these mature fields (Manrique, et al., 2010). Currently, gas and water-based projects dominate in offshore formations. Gas injection is increasingly popular as there are several cost effective sources for CO_2 available, making these types of projects more economically attractive. This recovery method is more common for fields with light, condensate, and volatile oil reserves. For fields with heavy and extra heavy oil reserves, thermal methods such as cyclic steam injection, steamflooding, and Steam-Assisted Gravity Drainage (SAGD) are the more widely used recovery methods (Manrique, et al., 2010).

Several large, deepwater developments such as those in the Gulf of Mexico (GOM) and offshore Western Canada rely on waterflooding to maintain a desired reservoir pressure and recovery factor (Guan, et al., 2005). Despite the extreme weather conditions that can exist in these areas, oil production is expected to continue growing into the future as demand increases. Not unlike other environments, offshore operations are continually being optimized and utilize EOR methods to extend production life and maximize oil recovery. Fields in the GOM are mostly supported by waterflooding and gas injection (Manrique, et al., 2010), and despite significant development costs, these projects have become more common as there in an increase in offshore production (Chappell, 2006).

Waterflooding refers to a technique that is used in order to improve recovery and enhance oil production in fields whose reservoir pressure has fallen below its bubble point (Guan, et al., 2005). The reservoir is flooded with water via injection wells which not only increases the reservoir pressure, but also displaces the oil and drives it towards the production wells. In this way, not only is the production rate maintained for a longer period, but the ultimate recovery of the reservoir is also improved. In offshore unconsolidated sand formations, it is important to understand how the injected fluid will flow through the porous media, especially when considering the huge economic risk associated with some of these projects. In fact, nearly 50% of the total capital expenditure for these offshore projects can be spent on the drilling and completion of wells alone, so efficiency during the planning stages of these projects is key to minimizing costs and time spent (Al-Kindi, et al., 2008).

Over the past several decades, a variety of experiments and models have been used to understand how the injected fluid flows through an unconsolidated sand formation and how to best optimize the waterflooding process. Several experiments were designed using the Hele-Shaw cell

configuration which was developed initially by Henry Selby Hele-Shaw for the purpose of studying micro-flows between two transparent parallel plates. The transparency of the plates allows the viewer to observe the fluid as it is injected and displaces the current media in place (Huang, et al., 2011). This can be either a more viscous fluid (Saffman, 1986), or even a thin layer of unconsolidated granular material (Greenkorn, et al., 1964). Other experiments utilized a different apparatus in order to investigate variables that could not be studied using the Hele-Shaw cell system, such as temperature and pressure. As such, the apparatus used tends to reflect the variables to be altered and the data that the researcher wishes to collect.

Since the development of the Hele-Shaw cell, it has been used in various applications. Its primary use is to view how a fluid injected between two parallel plates interacts with the original media in place, be it another fluid or granular material. Huang, et al. conducted fluid injection experiments in two-dimensional porous media, which were aimed to further understand the flow mechanisms when a fluid displaces granular media (Huang, et al., 2011). The apparatus was constructed using two transparent plates bolted together and sealed with tape around the perimeter of the cell. Fluid was injected with a syringe pump and high-resolution images were captured by a camera positioned atop the cell. Sand ranging in size from 100 to 200 µm was poured in between the two plates and a shake table was used to ensure heterogeneity of the compacted sand (Huang, et al., 2011). A schematic of the experimental set-up can be seen in **Figure 1**.

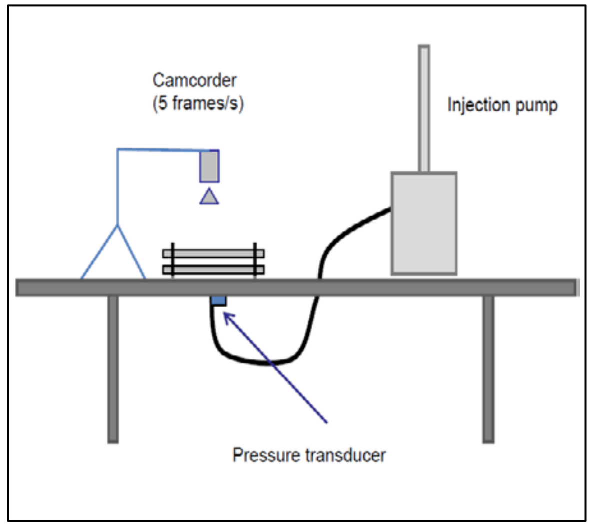

Figure 1*: Huang's experimental set-up. (Huang, et al., 2011)*

Using this setup, there were two sets of injection tests completed; one using glycerin as the injection fluid and the other using polyacrylamide. The glycerin tests studied the effect of a Newtonian fluid invading the system and are therefore most like the experiments to be conducted in this study. The effects of varying the fluid viscosity and injection rates on the flow mechanisms were examined.

One of the main conclusions from Huang's experiment was that "[given the same granular media properties] there is a transition from solid-like (fracturing) to fluid-like (fingering) behavior in the injection process" (Huang, et al., 2011). This transition can be seen in **Figure 2**, where the effects of increasing fluid viscosity and the injection rates are pictured. At the lowest injection rate and viscosity (Test A1), there is a simple radial flow pattern with little to no grain displacement. As the viscosity increases (left to right, A-C), the flow regime becomes more grain-displacement dominated, which is seen in the propagation and widening of the dark channels in the images. As the injection rate is increased (top to bottom, 1-4), the flow regime is more leak-off dominated. This is seen in the propagation of the lighter-colored radial pattern surrounding the injection point. Simultaneously increasing both the viscosities and flow rates of the injection fluid results in a transition from the creation of large fractures (such as in B2 and B3) to the initiation of viscous fingering (C4). The Hele-Shaw cell, though limited in its ability to support a confining pressure, proved in this study to be useful in further understanding the injection process and the fundamental flow regimes surrounding the injection point (Huang, et al., 2011).

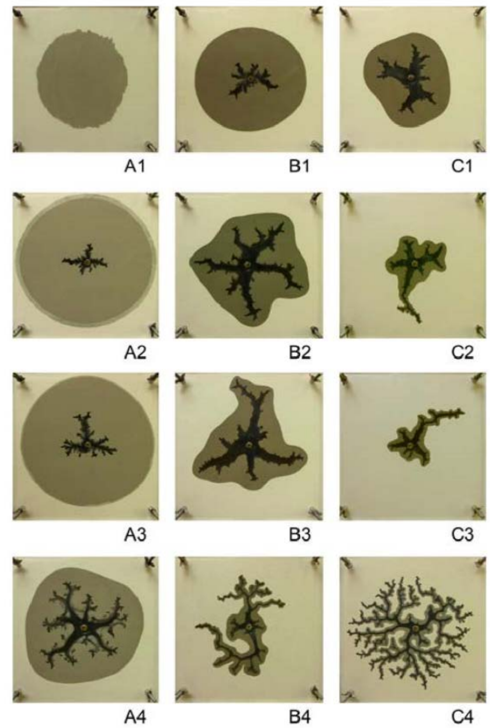

Figure 2*: Injection test results with increasing viscosity (A-C) and increasing flow rates (1-4). (Huang, et al., 2011)*

Other experiments have been done with larger samples of unconsolidated sand and consolidated cores, which required the use of either a core-holder or clear glass container (Brock, et al., 1991). The use of a steel core-holder allows for a confining pressure to be placed on the system so that the experiment may more fully model reservoir conditions (Gobran, 1987). However, due to the absence of a glass window, the effects of this pressure on the fluid as it flows through a core or a sample of unconsolidated sand is not known until after the trial is over and the core-holder can be opened. Hwang, Lehardi, and Sharma were able to develop empirical correlations for the filtration coefficient in frac-packs at high velocity flows, but required the use of a cylindrical tube with an inner diameter of 0.95 cm (Huang, et al., 2014).

A clear glass container can also be used to view fluid propagation. Brock and Orr were able to study the effects of viscous fingering in heterogeneous porous media using a 12 inch long, 3 inch wide, and 0.225 inch deep glass container (Brock, et al., 1991). Using homogenous and heterogeneous models, they tested three different flow rates and mobility ratios. In the

homogenous model, the flow channels (fingers) grew outward from the injection site, often splitting into smaller fingers or merging with larger ones. In the heterogeneous models, there was preferential flow in the higher permeability streak, no matter what the fluid viscosity was. This caused non-uniform flow and a less efficient areal sweep of the system (Brock, et al., 1991).

Physical experiments are very useful when empirical data and visible results are required, however, they can be limited if the scale of the project is too large or there are too many variables than can be accurately simulated in a lab setting. In order to most accurately describe the water flooding process, factors such as phase behavior, viscous instability, permeability heterogeneity, and various capillary, viscous, and gravity forces would have to be included (Brock, et al., 1991). Numerical models have the advantage of being able to handle large data sets and multiple combinations of variables. In 2007, Suri and Sharma from the University of Texas in Austin developed a model for water injection into frac-packed wells (Suri, et al., 2007). The model included the pressure profile that existed around the wells, and its main conclusions were that injectivity varies with time. Further empirical experimentation with the frac-packs proved that the pressure change and injectivity are also "controlled strongly by the degree of filtration in the frac-pack" and these findings were applied to Suri and Sharma's already comprehensive model (Hwang, et al., 2014). After completing their empirical research, Brock and Orr also simulated the same tests numerically, and obtained a model for finger growth in porous media that gave results "remarkably similar" to those seen in the lab (Brock, et al., 1991). As such, the empirical investigations have proven to be instrumental in developing accurate numerical models for further research.

Injectivity is a parameter represented by the following ratio (Golovin, 2011), where Q_{inj} is the injection rate and P_{ip} is the injection pressure:

$$I = Q_{inj}/P_{ip} \qquad (1)$$

This is an index used to optimize the rates and pressures to predict conditions under which favorable fluid propagation occurs. The more pressure that exists in the system, the more the injection rate has to increase in order to overcome the confining pressure and keep the injectivity index at a level optimum for the system. In the same way, as the fluid viscosity increases, the overall injection rate will decrease, thus decreasing the overall injectivity. Depending on the existing reservoir conditions, the injectivity will have to be optimized. Too high of an injection rate or fluid viscosity may fracture the formation, which can be undesirable when attempting to waterflood the system. Too low of a rate, on the other hand, may do little to improve the recovery of the reservoir.

b. Project Objectives

It appears as though while there are numerous studies using a variation of the Hele-Shaw cell, very few were set up with the exact same conditions that this project plans to use. To reiterate, this experiment hopes to investigate how the fluid flows through a porous media while applying an external pressure. The studies discussed above that used a variation of the Hele-Shaw cell were able to study the effects of pumping through a homogenous or heterogeneous grain sample while varying a combination of injection rates and fluid viscosities. However, these experiments were typically conducted under standard temperature and pressure conditions. Only with the use of a different apparatus, such as a steel core-holder, was it possible to apply an external pressure.

The importance of the transparent portion of the apparatus is to view the flow paths of the fluid as it is being pumped under various conditions. This review of previous studies has illustrated the flow patterns one might expect, and it is hoped that these results will be similar to those obtained from this project. The challenge moving forward, however, is to modify the apparatus so that there is not only a window through which to view the flow paths, but also so that it is sturdy enough to support an external pressure.

It is also important to note that this project is meant as a preliminary insight into the injection process from an experimental standpoint. Results from this study may lead to the creation of a more rigorous numerical model which will be able to better simulate real-world conditions and help evaluate the fluid properties necessary to complete a successful waterflood.

3. Experimental Setup

a. Overview of Project

As this project progressed, the design of the apparatus to be used developed in order to accommodate each component of this study. The original design was based off of the Hele-Shaw cell type experiments as referenced previously. Much like previous studies, this experiment will investigate fluid flow through unconsolidated porous media. Unlike those studies however, the system will be placed under a confining pressure as both the properties of the fluid and the unconsolidated media are varied and injectivity investigated.

Specifically, the variables to be altered include fluid viscosity, injection rate, and grain size. As a confining pressure is applied to the system, other variables such as the time for injection, fluid type, and volume of sand will all be kept constant. Qualitatively, the propagation of the fluid will be observed during the injection period, and the quantitative results such as the number of channels and their lengths and widths will be recorded for further statistical analysis.

In order to incorporate each of the above-mentioned variables, the apparatus needs to consist of more than just two parallel glass plates. It is important that the design allows for an external pressure to be applied but will also include a glass window for viewing purposes (**Figure 3**). The sample of sand will be housed in a steel cylinder complete with glass viewing window. After the sand sample is saturated with fluid, compacted into the steel housing, and the confining pressure applied, the fluid will be injected from the bottom at a certain rate. A camera will be positioned above the viewing window and will record the propagation of the fluid throughout the experiment.

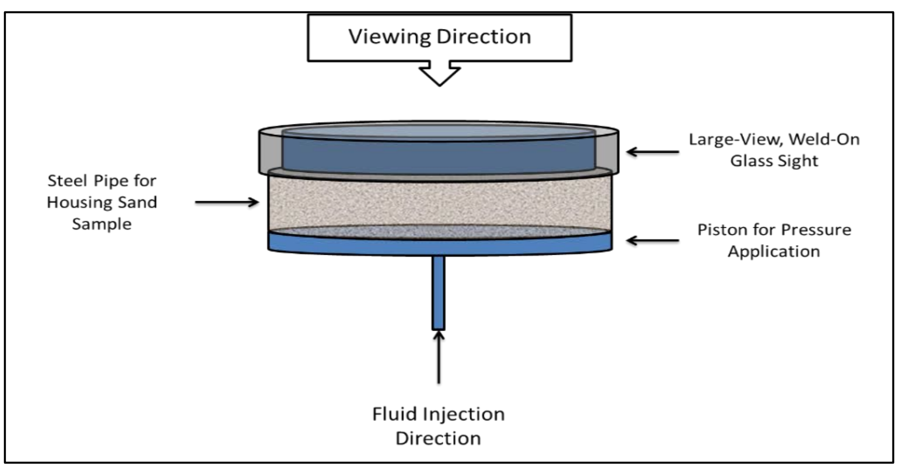

Figure 3: *Side View of the Experimental Setup*

b. Experiment Description

Following the construction of the apparatus as illustrated in **Figure 3**, a series of experiments will be conducted that will vary the injection rates, fluid viscosities, and grain sizes. **Table 1** lists the independent variables for this experiment.

Table 1: Independent Variables	
Proppant Mesh Size	(100), (40/70), (30/50), (20/40)
Fluid Viscosity (cp)	(1.0), (3.0), (12.5)
Injection Rate (cc/sec)	(0.45)

The cell will be filled with proppant of a single mesh size, and fluid will be pumped into the system at a constant flow rate. Images of the fluid propagation will be taken using a digital camera for future reference as the pressure is monitored and recorded during the injection period. Several trials will be completed as the different fluid viscosities are pumped into the differing mesh sizes and their flow patterns are compared. The fluid viscosity is increased by using mixtures of sugar and water with increasing sugar concentrations. Please see the **Experimental Results** section for images of these trials.

c. Experimental Setup

As seen in **Figure 4**, the cell is connected to a pump using steel tubing. The injection fluid is fed from the reservoir to the pump which injects it into the system at a constant rate of 0.45 cc/sec. The glass viewing window places a pressure limitation of 45 psi on the system, which is monitored using a pressure gauge on the pump. The lack of an outlet for the fluid means that the pressure will continue to build until the injection process is stopped, which, due to the pressure constraint, is usually at or before 45 psi has been reached.

Photographs of the actual experimental cell are shown in **Figures 5-6**, showing the cell after construction. See **Appendix A, Figures A-2** and **A-3** for the original AutoCAD drawings. The stainless steel sight glass was welded to a pipe of 5” ID and four inches in length. A 1” thick, 4.997” OD steel piece with an injection port drilled through the center was used for the piston piece and installed from the bottom of the cell in order to seal the sand and fluid in the system and apply a confining pressure. After welding however, the steel pipe was slightly deformed, preventing the piston from travelling further than 3” away from the bottom of the cell. The sand pack was larger than planned as a result and the injection port was too far away from the glass window to allow for the fluid propagation to be viewed. This was remedied by attaching a thin steel tube of the same diameter as the injection port to the top of the piston, effectively raising the port closer to the glass. The thin steel tubing is seen in **Figure 5**.

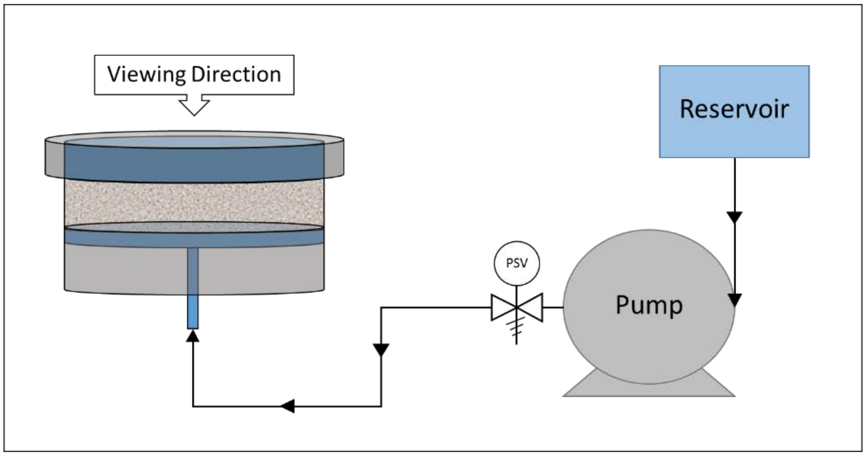

Figure 4: *Experimental Flow Diagram*

Figure 5: *Open cell displaying 30/50 mess sand and the raised injection port*

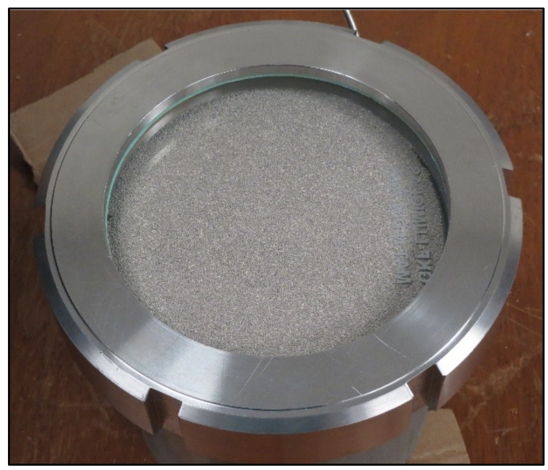

Figure 6: *Closed cell with 30/50 mesh sand covering the raised injection port prior to injection*

d. Statement of Goals and Deliverables

By varying the parameters described in previous sections, this project aims to create fluid channels of varying lengths and measure changes in injectivity. Under the right conditions, this experiment will result in an evolution of the pore geometry and the formation of flow channels. The goal is to predict a range of conditions under which channels form and the effects of various parameters on the structure and length of the channels. Our experimental outputs will be a measure of injectivity, channel lengths and widths, and overall channel geometry during each trial condition.

Due to the distribution of resistances in the porous media, a distribution of flow paths should exist and flows along certain pathways through the network will be higher than in neighboring

paths. Paths that are preferential over their neighbors may create a cascade where a channel will eventually dominate and carries virtually a majority of flow in that region. (Hoefner, 1998.) This is the basis of the channeling process that will be observed.

The main deliverable for this project is an experimental model that can be used to study injectivity. Whether or not there is a significant amount of channeling, the model still allows for visibility during the injection process which can be used as an important tool for waterflooding. Any trends observed through the use of this experimental setup have the potential to be utilized in a numerical model that can help to optimize future EOR projects.

4. Experimental Results

The results from each trial are tabulated below in **Table 2**. Two sand mesh sizes were used, the 100 and 30/50, and three different viscosities of fluid were injected in separate trials. The other grain sizes mentioned in **Table 1** were not utilized during these runs due to poor visibility during the injection period. For each run, the progression of the fluid movement through the system over time was photographed and documented in the table below. Please note that the times for each run are not equal– as the viscosity increased, the injection pressure reached the maximum limit more rapidly and resulted in shorter run times. This phenomenon and other results are discussed in the **Analysis of Results** section below.

Table 2: Experimental Results

Mesh Size	**Visc. (cp)**	**Pump Time (sec)**	**Empirical Results**
(30/50)	1	534	
(100)	1	540	

(30/50)	3	344	
(100)	3	360	
(30/50)	12.5	240	
(100)	12.5	319	

a. Analysis of Results

As each run was completed, several different phenomenon were observed. The first, as noted in the section above, is that as the fluid viscosity increased the maximum pressure of 45 psi was reached much more quickly than for the lower viscosities. This is graphically illustrated in **Figure A-1** in the appendix. While this graph does not indicate a fluid propagation trend, it does illustrate a limitation of the experiment that will need to be remedied to allow for future trials to inject higher viscosities for longer periods of time.

For the trials pictured above, no channeling was observed. This can be due to several experimental factors, but it is most likely that the current injection rate is not high enough to induce an evolution in the pore geometry. The viscosity of the fluid was increased from 1 cp (pure water) to 12.5 cp, but could be increased further once the issue with the rapidly increasing pressure is resolved. For the current pumping conditions, however, there was not any grain movement or creation of fluid channels.

The larger grain size appeared to allow for a larger areal sweep as compared to the smaller grain size. This is due to the larger permeability which allowed the fluid to travel farther in the same period of time. While the flow appeared to be mostly radial for the majority of the trials, the lower viscosity fluids exhibited less radial (and therefore more irregular) flow patterns, which was unexpected. This could be due to how the injection port is situated during experimentation, or how the sand is packed into the system.

It was also observed that the flow patterns tended to be more radial for the smaller mesh size than for the larger one. For example, the last two trials used the same fluid viscosity (12.5 cp), but the trial with the 30/50 mesh has a flow pattern that extends in a lateral direction. The flow pattern using the 100 mesh extends radially. This is mostly likely due to the heterogeneity of the larger grain size, which is a mix of diameters between the 30 and 50 mesh sizes. The 100 mesh sample, on the other hand, is made of grains that are of a single diameter corresponding to that mesh size. The heterogeneity, or mixing, of grain sizes is what allowed for the fluid to propagate in a non-radial pattern in the 30/50 mesh trials.

b. Conclusions and Recommendations

The experiment as is it designed currently does not allow for the creation of channeling during the injection period. While it does operate successfully in terms of sealing the air and water inside the system and allowing for a build-up in pressure, there is something to be desired in terms of the results generated. Other limitations of the system include: the inability to vary the injection rates due to the current pump being used, the lack of a constant confining pressure due to the flaw in the piston construction, and the rapid pressure build up as the higher viscosities are pumped which results in shorter run times and less fluid propagation.

Due to the errors during the construction of the apparatus, it was also impossible for the piston to apply a confining pressure on the system prior to injection. As such, any results gathered will only be influenced by the constant pressure build-up of the system and will not reflect any in-situ stress conditions.

Despite these limitations, the goal of delivering a model that allows for the visualization of the fluid as it propagates through the system has been achieved. Future trials will hopefully yield more concrete results that will either confirm or deny the current empirical results and determine changes in injectivity according to the fluid and grain properties of the system.

5. Further Study and Applications

The apparatus as it stands has the potential to yield further conclusions following the resolution of the limitations described in the previous section. For example, sourcing a pump that measures injection rates and pressures in real time and allows for increased injection rates will result in more accurate data that can be used to determine injectivity. Increased rates may also lead to the creation of channeling while injecting.

Changes in injectivity can be monitored using pressure versus time data, as well as injection rates versus time. It is expected that as the rates increase, so will the injectivity index. However, as the pressure on the system increases, the injectivity should decrease. Due to the flaw in the piston design that keeps it from applying any confining pressure on the system, the experiment begins at atmospheric pressure and only sees an increase as the fluid is pumped into the cell. For further studies to be able to more accurately reflect in-situ stress conditions as originally proposed, the piston will have to be modified so that it can apply a confining pressure to the sand pack prior to fluid injection.

All of these modifications will yield an experiment that can be used to visualize the fluid injection process and the propagation patterns created under various conditions. This is intended to give further insight into waterflooding and how it may be optimized depending on the grain and fluid properties of the reservoir. Determining the appropriate injectivity index for a particular field by changing the properties of the injected fluid and the rates at which it is injected will hopefully lead to more effective EOR projects in the future.

Acknowledgements

There are several groups of people that were essential to completing this Senior Design project and in writing this undergraduate thesis paper. My advisor, Dr. Dahi, was supportive in directing my team down the right path when we would get stuck, and helped me to shape this paper into one worthy of the Petroleum Engineering department and the Honors College. I'd like to thank him also for suggesting the project idea to us originally.

Dr. Dandina Rao and Bikash Sakia from the Petroleum Engineering department were instrumental in finding lab space for us to run our experiment and getting the apparatus set up. I'd also like to thank Dr. Juan Lorenzo from the Geology department and Dr. Rao for being a part of my thesis defense committee and providing their insightful feedback towards improving my paper.

Don Colvin and his ME Machine Shop team were crucial in turning our design plans and ideas into a reality. They worked to build our apparatus to our exact specifications and helped to troubleshoot any issues we had.

And finally, this project would not have been completed without the members of my Senior Design team: Forrest Hise, Jake Lucidi, and Matt Stuart. Our compatibility as a team was essential and allowed us to accomplish as much as we did.

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Appendix A

i. Graph of Trend Between Injection Time and Fluid Viscosity

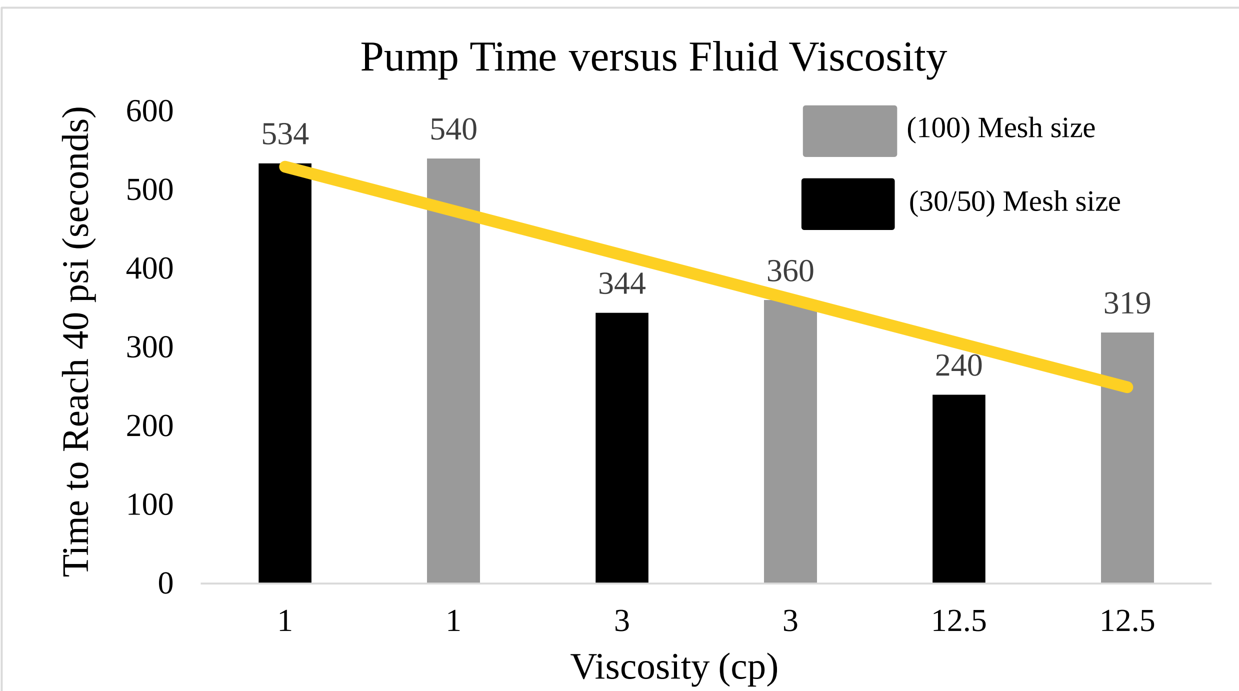

Figure A-1: Graph showing a decrease in allowed pumping time as viscosity increased

ii. Engineering Drawings of Apparatus

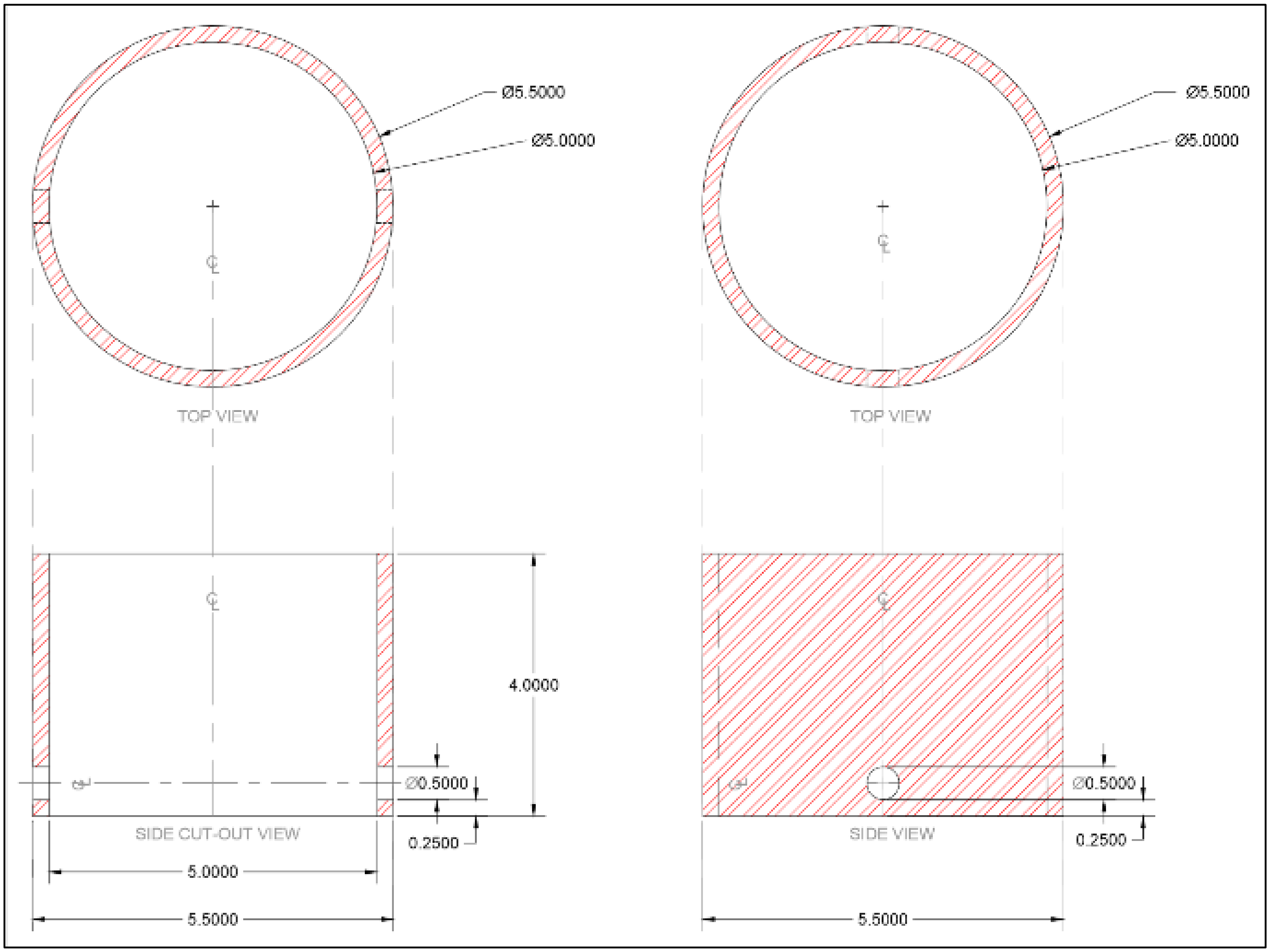

Figure A-2: *AutoCAD rendering of Stainless Steel Body Housing (lengths are in inches)*

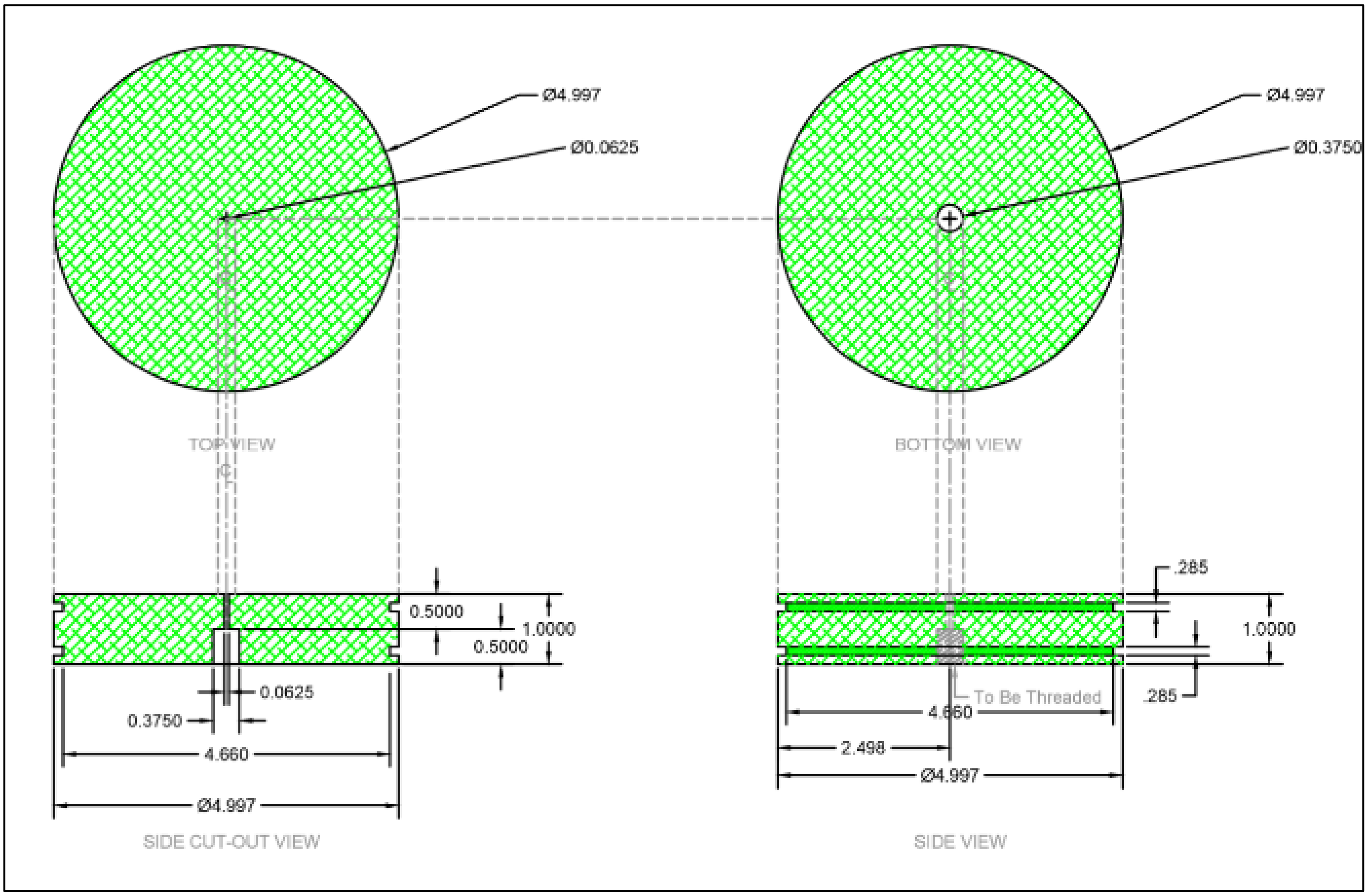

Figure A-3: *AutoCAD rendering of Steel Piston (lengths are in inches)*