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Sement-forskyvningsprofiler

En analyse av lokal turbulent strøm

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Cement Displacement Efficiency

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Abstract

Efficient cement displacement during a cement job will create better bond between cement and formation. This creates better isolation. The displacement efficiency is affected by many different factors. This may in turn lead to a better cement job.

The lab work done for this thesis looks at how four different factors will affect the cement job. These factors are roughness in pipes, flow regimes during displacement, different viscosities of the cement and amount of cement being displaced. Having a model to predict the flow of cement will make it easier to monitor and predict the cement flow during displacement. A model is created to complete this aim, but more thorough investigation of effects of how the pipe roughness affects the cement flow is needed to create an accurate model.

Both the simulations and lab tests that were conducted in this project suggest a strong dependence between flow regime and displacement efficiency. Higher displacement rate created higher displacement efficiency. This happens because a more turbulent flow will cause the displacement profile of the fluid to be more evenly distributed in the pipe. Rough walls will cause the flow to turn from laminar to turbulent at a lower Reynolds number and also give local turbulence along the walls. Displacing cement with turbulent flow in the field is not ideal since it would increase the equivalent circulating density, causing the formation to fracture more easily. Increased pipe roughness and local turbulence will contribute to the cement front moving faster and becoming more even. Thus: when local turbulence occurs during cement displacement, the cement quality improves. The displacement profile was also clearly affected by amounts of displaced volume and viscosity of displacement fluid. The more volume being displaced through the pipes, the better the displacement became. Increased viscosity improved the displacement efficiency as well.

A model for flow of cement is presented. The initial condition of zero-slip velocity at the walls during displacement proves to be inaccurate. The main factor contributing to displacement increasing along the walls in the model is roughness in pipes. While viscosity of cement, flow rate and amount of displaced volume had their own effect on displacement efficiency, the increased roughness leads to a large improvement in displaced fluid. This is also the factor that can best be tested in the field. If increased roughens in drill pipes and casings cause an improved cement job, we can get both better zonal isolation and improved cost efficiency. This understanding of local turbulence will be described through comparison of experimental results with theoretical or expected results.

Sammendrag

En effektiv forskyving av sement vil skape bedre binding mellom sement og formasjon. Dette skaper bedre isolasjon av formasjonen. Det fins flere faktorer som påvirker sementforskyvningen og som kan skape en bedre sement jobb.

Lab arbeidet som er gjort i denne oppgaven ser på hvordan fire forskjellige faktorer påvirker sement jobben. Disse faktorene er ruhet i rør, forskyvnings regime, viskositet i forskyvningsfluidet og mengde fluid som er forskjøvet. Dersom vi har en modell som nøyaktig klarer å forutsi hvordan sement forskyves, kan vi lettere overvåke og forutsi sement forskyvningen. Det skapes en modell for forskyvningen som kan brukes til dette formålet, men det trengs mye mer lab analyse av hvordan ruhet påvirker sement forskyvningen hvis vi vil ha en helt nøyaktig modell.

Både simulert data og lab data som ble funnet i dette prosjektet indikerer at det er en sterk avhengighet mellom forskyvningsrate og forskyvningseffektivitet. Høyere forskyvningsrate skaper høyere forskyvningseffektivitet. Dette skjer fordi turbulent forskyvning skaper en forskyvningsprofil som er jevnere fordelt i røret. Å forskyve sement med turbulent strøm i ekte brønner er ikke ideelt siden det vil skape et høyt trykk i fluid søylen som igjen kan skape sprekker i formasjonen. Ruhet i veggene kan føre til at strømmen går fra å være laminær til turbulent ved lavere Reynolds tall enn vanlig, og det kan også føre til økt lokal turbulens langs veggene. Å øke ruhet i rør vil altså føre til at forskyvningsprofilen til sementen beveger seg raskere og blir jevnere fordelt i røret. Med dette kan vi slå fast at når lokal turbulens under forskyvning av sement finner sted, vil sement kvaliteten forbedres. Sementforskyvningsprofilen ble også tydelig påvirket av mengder fluid som ble forskjøvet gjennom røret og viskositeten til fluidet som ble forskjøvet. Jo mer fluid som ble forskjøvet, jo bedre ble fortrengningseffektiviteten. Økt viskositet i fortrengningsfluidet førte også til økt fortrengningseffektivitet.

En modell for flyt av sement blir presentert. Den opprinnelige antagelsen om at det ikke eksisterer en hastighet i fortrengningen langs veggen viser seg å være unøyaktig. Faktoren som så ut til å øke forskyvningshastigheten mest langs veggene er ruhet i rør. Viskositet, strøm rate og mengder forskjøvet volum hadde en effekt på sementforskyvningseffektiviteten, men det som førte til størst forbedring var ruhet i rør. Dersom økt ruhet i borerør og fôringsrør fører til forbedring i sementjobben kan vi forbedre både sementens isolerende egenskaper og kostnadene knyttet til komplettering. Forståelsen av lokal turbulens beskrives gjennom sammenligning av eksperimentell og teoretisk data.

Content

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Sera Ferizi

Sera Ferizi, June 19th 2014, Oslo

1. Introduction

Optimal production depends on a good completion. A good completion in its turn depends on the primary cement job. Failure in primary cement jobs cost the oil and gas industry an estimated USD 450 million annually. The cement job also has a direct impact on the economical longevity of the well (Erik B. Nelson, 2006). Poor cement displacement efficiency is one of the reasons we get bad cement jobs. Failure to isolate hydro carbon zones will lead to abnormal casing string pressure. Gas and produced water will contaminate other subsurface zones and results in wells that are environmentally and operationally hazardous (Erik B. Nelson, 2006).

Poor cement jobs are fixed with remedial cementing operations. Remedial cement operations consist of cement squeezing and plug cementing. Each remedial cementing operation requires as much time, energy and experience as a primary cement operation (Erik B. Nelson, 2006). It is therefore important that we create an efficient cement displacement during the primary cementation of the well. Modelling the movement of cement during displacement will help us reach this goal. Understanding the cement movement during primary cementing helps us get a complete and durable zonal isolation with less cost.

Primary reasons for cement job failures are improper balancing of the pressure and movement of pipe, cement, or both in the wellbore during depletion. The challenges in achieving excellent cement displacement and zonal isolation are being met with improved hole conditioning techniques (Erik B. Nelson, 2006). Improved hole cleaning will cause the cement to flow easier and displace more evenly in the annulus. It is however noticed that even with very good hole conditioning techniques, the cement job can still be bad. The goal of the thesis work is creating an accurate model for flow of cement in the annulus. Velocity profile distribution and shape are shown to strongly affect the cement isolating factor (Silva, 1996) so there is no doubt that more research and simulations with more accurate models of the cement displacement need to be done.

To develop an accurate model for cement flow it is important to understand how cement jobs have been performed in the field. Understanding how flow occurs in the boundary layer is also important. The different flow regimes, roughness and other factors affecting the displacement of cement are studies. Real data used to develop the flow model is found through lab experiments. The model will be developed based on four measurable factors. The four factors are different roughness for each pipe, different displacement rates, displacement volumes and viscosities. It is first tried to understand how each factor will affect the displacement, and then a mathematical relationship between the displaced amount of cement and each factor is found. This is then used to develop the model for flow. The displacement model used to simulate the cement displacement is at first a simple model with zero-slip condition. This assumption is however unrealistic. A study of how roughness and near wall turbulence makes the zero slip condition in-accurate is presented. The lab analysis and theoretical investigation is use to improve the simple model. The improved model is compared to the lab data to find if it is acceptable.

In chapter 2, we will present existing knowledge about cement displacement and the boundary layer. In chapter 3 we will present actual data from wells in the North Sea, where the cement displacement will be analyzed. Simulated flow is presented together with the development of the displacement model in chapter 4, and actual flow in the pipes will be found through lab work and presented in chapter 5. Not all data presented in chapter 2 and 3 will be measured in the lab, but is presented here to create a fuller understanding of displacement of cement. Evaluation of lab results, discussion and conclusion comes towards the end of the report.

2. Existing knowledge

The displacement efficiency of cement displacing wash fluid will in this thesis be described using the velocity profile of the cement. A velocity profile moving forward at higher speed at all points of the profile displaces mud more efficiently than a profile moving forward in slower velocity closer to the wall.

In chapter 2 we will present the main parameters that influence the entire velocity profile. The theory presented here is the base of the interpretation of real data and experimental data that will be presented in chapter 3 and 5 respectively. The largest focus will be on how movement in the boundary layer occurs. Parameters affecting the velocity profile are; low displacement rates; not sufficient density differences between the mud and spacer and spacer and cement; not sufficient reciprocation of casing before and during cementing or not sufficient hole cleaning. The boundary layer is affected by roughness, different flow regimes and viscosities.

2.1 Cement failure after displacement

Before proceeding with the presentation of published material related to cement displacement efficiency, it is important to highlight that a good cement displacement efficiency is not the cure to all problems related to the cement job. Due to shrinkage, gel strength build up and fluid loss the hydrostatic pressure in the cement column can become smaller than the pore pressure. This can in turn lead to gas migration. Gas migration is believed to occur during transition state between initial and final set of cement during primary cementing. This is when pressure goes from being hydrostatic to becoming even lower due to the density of the passing water. (Lyomov, Justen & Sveen, 1997) Gas leakage in annulus after primary cementing is a problem particularly in upper, unconsolidated cavernous holes and in deep wells. Deep wells are known to have high pressure and high temperature which will more easily cause shrinkage, gel strength build up and fluid loss. Gas migration also occurs when cement slurry stays permeable or initial gas forms channels, micro annuli and fractures before cement has reached a certain strength.

In general we can say that there are three main categories of cement failure. These categories are; cracking, de bonding and shear failure. Cracking is caused by large variations in drawdown pressure. Large variations in drawdown pressure and temperature occur for example in gas wells as the gas demand changes. De bonding usually occurs when there is cement shrinkage with time or gradual pressure decrease as a well is produced. Shear failure occurs when effective-stress increases around a wellbore caused by rock subsidence and movement as the reservoir is depleted. These three cement failures cause flow paths in form of micro annuli or small fractures. Permeable cement defeats its own purpose and does no longer provide a durable zonal isolation. (Erik B. Nelson, 2006)

2.2 Flow Regime

Laminar Flow

One of the parameters affecting the displacement profile that will be analyzed in the lab is flow regime. The displacement is different for laminar and turbulent flow. Laminar flow is signified by fluid which appears to move by the sliding of laminations of infinitesimal thickness over adjacent layers. Relative motion of fluid particles occur at a molecular scale, the particles move in definite and observable. Viscosity plays a significant part in this laminar flow. (J. E. Finnemore, 2009)

Laminar or turbulent flow have very different effect on a variety of flow features, energy losses, velocity profiles and mixing and of transported materials. Turbulent flow will transport cuttings and displace cement more efficiently. However, in the field cement is displaced with laminar flow to avoid high ECD and fracturing of the formation (Carrasco-Teja, 2008). With laminar flow, there will still be local turbulence in the boundary layer due to disturbance of from pipe roughness. This relationship will be thorougly investigated in the lab.

The Reynold's number determines the flow regime. The Reynolds number is shown in equation 2.1.

$$N_{Re} = \frac{\rho\, v\, d}{\mu} \tag{2.1}$$

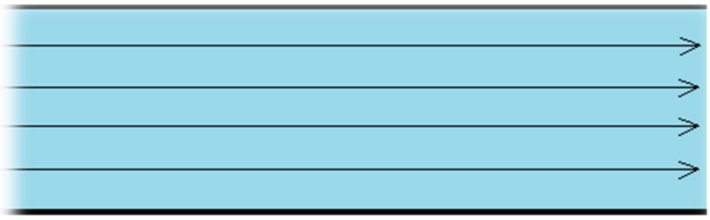
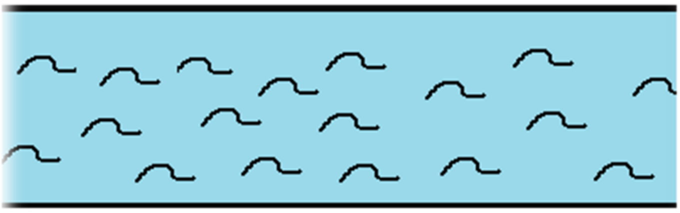


Figure 2.1: Laminar Flow with no local turbulence along the walls

Turbulent Flow

Turbulent flow is characterized through movement of infinitesimal turbulent flow lines, irregular motion of particles where there is no definite frequency and no observable pattern of flow. Flow turns from laminar into a transition flow at Reynolds number equal 1800 and fully turbulent at 2100 (Skalle, 2013).

In the field, there will be no displacement of cement with turbulent flow. Displacement of cement with turbulent flow will give us an ECD that is too high for the formation to handle, and it will fracture. The effect of displacement with turbulent flow will however be tested in the lab. This helps us see the effect increasing flow rate would have on the cement displacement profile.



2.2: Turbulent Flow is irregular motion of particles

Reynolds Number

Reynolds number describes the ratio between inertia forces and viscous forces and is shown in equation 2.

$$Re = \frac{F_I}{F_V} = \frac{L^2V^2\rho}{LV\mu} = \frac{LV\rho}{\mu} = \frac{LV}{\mu}$$

(2.2)

If flow is laminar or turbulent depends on the Reynolds number. Empirical studies have shown that laminar flow occurs at low Reynolds number. The flow becomes unstable if the Reynolds number is increased to 2200- 2300. This range marks a transition between laminar and turbulent flow. Flow at Reynolds numbers lower than 2200 are usually laminar and flows at Reynolds numbers larger than 2300 are usually turbulent.

Flow regime is also affected by pipe roughness. It turns from from laminar to turbulent at different Reynolds' numbers depending on the roughness of the pipe. (Skalle, 2013) If cement has the same density, velocity and viscosity and is sent through the same diameter-annulus with rough walls in stead of slick walls, the flow will turn from laminar to turbulent at a lower Reynold’s number. The effect of this phenomenon is part of the analysis which will be conducted in the lab and presented in chapter 5.

2.3 Rheology

Two rheological parameters affect the displacement of cement the most. They are viscosity and density. The effect each of these parameters will be discussed in section 2.3.

Viscosity

As we see from equation 2.1; a decrease in viscosity will increase the Reynolds’ number. How low the viscosity of the cement can be is however limited by the viscosity of the wash fluid it is displacing. The cement viscosity cannot be lower to or close to the mud viscosity as this would create an uneven displacement and could lead to cement fingering into the wash fluid. This is poor cement displacement efficiency and would not create a fully isolating cement column. In the lab, we will displace oil with water and more viscous fluid to understand the effect increased viscosity will have on the displacement efficiency.

Density

A displacement model like the one which is going to be suggested in this thesis assumes a symmetrical displacement on both sides of a centralized axis in the center of the annulus. A simple displacement profile created by the model is shown in figure 2.3.

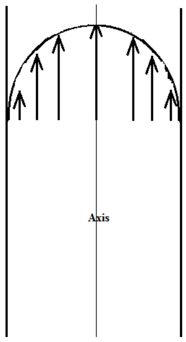


Figure 2.3: The displacement model developed in this thesis describes movement of cement symmetrically across and axis in the center of the annulus.

Understanding how density affects the displacement profile in horizontal wells can be of great use when creating a displacement model that can be used in both horizontal and vertical wells. Cement displacement in horizontal wells is more challenging to model than cement displacement in vertical wells due to gravitational effects.

Increasing density will affect the displacement profile and hence the cement quality. Heavy fluid will fall further down than the light fluid during the displacement like shown in figure 2.4. Increased density differences will change the flow pattern and may cause the cement job to fail completely. Real data is analyzed in chapter 3 where the effect of cementing horizontal wells with low eccentricity also will be discussed.

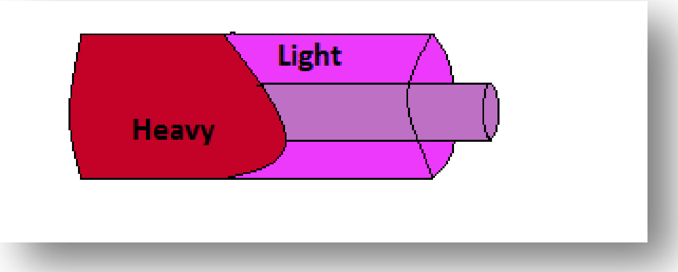


Figure 2.4: Heavy fluid displacing lighter fluid will lead to the heavy fluid falling down in the horizontal well.

Lighter displacement fluid will og further up than the fluid being displaced like shown in figure 2.5 (Carrasco-Teja, 2008).

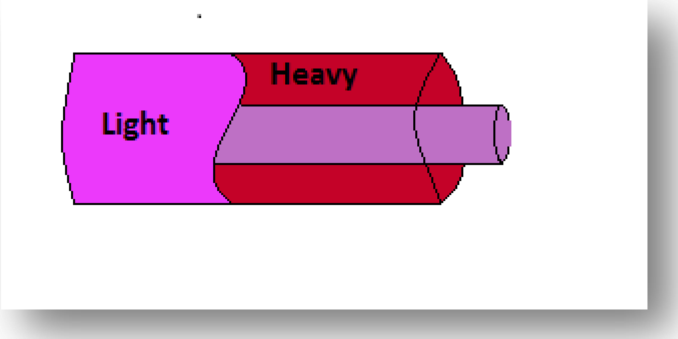


Figure 2.5: Lighter fluid displacing heavy fluid will lead to the lighter fluid moving along the upper part of the well

Even with high density differences between the fluids being displaced, the displacement of cement can be steady as long as there is sufficiecnt eccentricity in the well. Eccentricity, e, is a measure of how close to the center of the hole the center of the casing is. Carrasco-Teja did simulations on how the displacemenet profile of cement is affected by the densities and ecentricity of the well. If density differences between the two fluids being displaced is not high enough to overcome the increased eccentricity and the displaced fluid yield stress, there is a tendency of the fluid to elongate along the wide side of the annulus. This means that cement will be displaced along the upper side of the hole, since the casing has fallen down, making the lower side narrower.

Rotation of casing during cement displacement will stir up the cement and create a more even distribution of cement during displacement. Rotation of casing is however not easy in long horizontal wells. Displacement will be possible even with non-rotation of casing. The displacement profile does however elongate a bit further than if the casing is rotated.

For high density fluids displacing low density fluids Carrasco-Teja finds three conclusions. Firstly, we see that when the density differences are incereased, the steady stable interface profile is elongated. Secondly, we see that there is a competition between eccentricitu and buoyancy, each factor favours unsteady fingering in the different parts of the annulus. Lastly and thirdly, we see that the critical paramaters exist in the ranges at which the behavuour changes from steady to unsteady.

Elongation of the displacement profile occurs when the interface is not steady to begin with or when the difference between the densities of the fluids is too high. Low density differences between the displacing fluid and the fluid being displaced will – according to this information and for the parameters we are using - not affect the results of the lab experiments.

Lab experiments will be conducted through a pipe at an angle of 20 degrees on the table. Gravity does not affect the flow pattern when the conduit is completely filled and there is an angle on the pipe during displacement. The lab analysis will therefore be done will a completely filled pipe during displacement and the pipe will be on an angle on the table. A completely filled conduit also eliminates effects of capillary pressure (E. J. Finnemore, 2009). Neither gravity nor capillary pressure need not be a part of the modelling of displacement.

Eliminating Effect of Viscosity and Density Differences in the Field

To create a steady displacement when turbulence cannot be achievable during the displacement, three criteria should be met (Carrasco-Teja, 2008):

1. Each displacing fluid should be heavier than the fluid it is displacing
2. Each displacing fluid should be more viscous than the fluid it is displacing
3. Pressuregradient should be high enough so that fluid on the narrow side of the annuli is also mobilized

These three criterias are met during the lab experiment and are part of the assumptions for the model so that it can be used in all horizontal wells.

Both viscosity and density of the cement is significantly higher than the viscosity and density of the mud. To avoid an abrupt change in these parameters and to avoid mixing chemically incompatible fluids, it is common to use a spacer between the mud and cement during displacement. The high density and viscosity differences between cement and mud get evened out with a spacer having a density and viscosity somewhere between the mud and the cement. The model for displacement created in this thesis takes into account that cement is displacing a lighter fluid. The density and viscosity differences between cement and the fluid being displaced are important, but not reflected in the model.

Transmitting data to the field

Lab analysis will be done using water and a mix of water and HEC to displace oil. Obviously, these fluids don't have the same viscosities and densities as cement slurry and wash fluid. We want to create an understanding of how accurate it is to transmit the data that will be found in the lab to the field.

If two different systems are dynamically equivalent when it comes to inertia and viscous forces, they must have the same value of the Reynolds number. (E. J. Finnemore, 2009). If Reynolds numbers for the model and the prototype are in the same range according to equation 2.5, the data can be transmitted to the field.

$$(\frac{LV}{\mu})_m = R_m = R_p = \left(\frac{LV}{\mu}\right)_p \tag{2.5}$$

This means that as long as length of the pipe and the velocity of the displacement are chosen so that they give the same value of R in the model and prototype; the fluid used in the model does not have to be the same as the fluid used in the prototype (E. J. Finnemore, 2009). We can use water and water and HEC to displace oil and compare this to cement displacing heavy mud.

Yield point

Fluid should not have a high yield point because it makes it removal of the cement slurry difficult. Lower yield point of cement helps the cement move behind highly decentralized casing, but it is important to keep the yield point in slurry higher than in wash fluid. (Silva, 1996)

Analysis from the Campos Basin Offshore Brazil found that yield point of wash fluid should be at least less than 10Ibf/100ft2 the cement slurry yield point. It should be as low as possible without losing its ability to carry cuttings. (Silva, 1996) For substitution of one fluid to be complete, it is important that the displacement profile becomes as homogeneous as possible. It is also important that it overcomes the yield point of the drilling fluid which is in the annulus. (Silva, 1996)

Lower yield point of cement helps the cement move behind highly decentralized casing, but it is important to keep the yield point differences slurry and drilling fluid positive. (Silva, 1996)

2.4 Hole Conditioning time

Hole conditioning is a process that describes circulation of the well. It is usually set to one full circulation of the well and aims to clean out remaining cuttings and caving in the well. When what we have pumped down the well from the mud pumps comes back up to the pit we have had one full circulation of the well. This is described in figure 2.6.

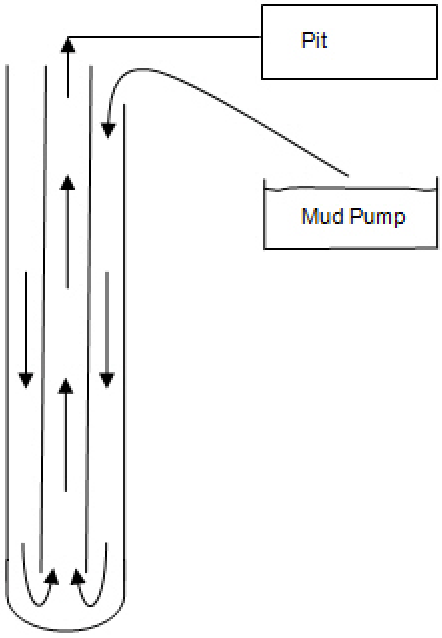


Figure 2.6: Circulation of a Well. When what we have pumped from the mud pumps returns to the pit, we have had one full circulation of the well. Hole conditioning continues until the well is sufficiently clean of cuttings.

Amount of cuttings in the well is monitored throughout the conditioning time and hole conditioning time is increased in the field until amount of cuttings have decreased sufficiently. If the well has not been cleaned sufficiently, it will have a large effect on the cement displacement and the cement quality. As we will see with one of the cement jobs that will be analyzed in chapter 3, hole conditioning time might have an impact on poor cement jobs.

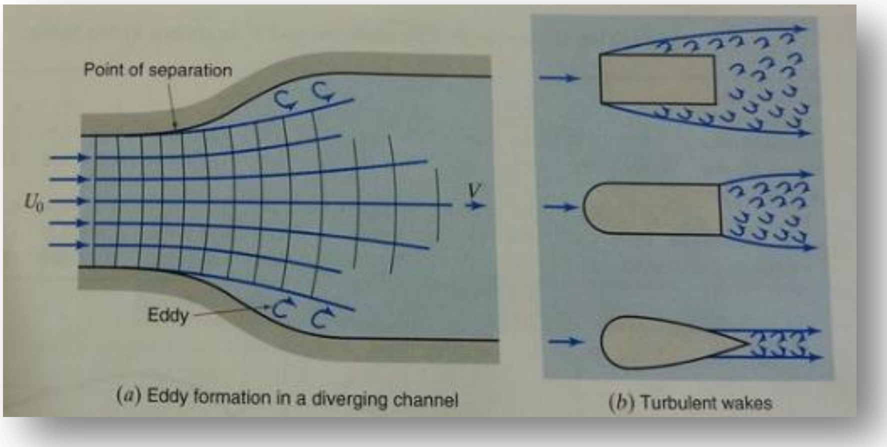
The model that will be created will assume that there has been sufficient hole conditioning, and that there are no cuttings to disrupt the flow path. Less interference from cuttings on the displacement profile will make the proposed model more accurate.

2.5 The Boundary Layer

The heart of this thesis is understanding displacement in the boundary layer and how movement in the boundary layers affects the cement displacement profile. In addition to theory presented here, there will be lab experiments conducted in chapter 5 that will help us further understand the effects movement in the boundary layer has on the cement displacement profiles. The rest of the displacement can be described mathematically.

When the flow regime is turbulent, increasing roughness in pipes will create a laminar sub layer. Looking at the Reynolds's Number from equation 2.1, we see that if density, viscosity and diameter of the pipe remain the same, pipe roughness will have the same effect on the Reynolds' Number as an increase in velocity. Roughness is defined as average height of random protuberances. Protuberances are bulges, knob, or swellings. Roughness of a pipe depends on the type of material the pipe is made from and how long it has been in use (E.J. Shaughnessy, 2005).

Roughness in the pipe has the opposite effect when there is laminar flow going through the pipe. Figure 2.7 is taken from Finnemore and Franzini's "Fluid Mechanics" and shows how eddy currents develop at a point of separation. When the flow is laminar, roughness has the same effect on the flow as a point of separation. It will create disturbance in the flow, creating local turbulence along the wall.



(a) Eddy formation in a diverging channel
(b) Turbulent wakes

Figure 2.7: The forming of eddy currents happens when laminar flow loses contact with surface at a point of separation in a pipe (E. J. Finnemore, 2009). This theory can be transmitted to the disturbance pipe roughness has on the flow lines. Small constant upheavals of the flow occurs constantly along the wall due to the pipe roughness.

Eddy currents appear in the boundary layer in laminar flow when there is some change along the wall at which the laminar flow is moving. In a sharply diverging flow such as the one showed in figure 2.7, there is a separation of the boundary layer from the wall resulting in eddy currents. When the boundary layer and the solid wall suddenly loose contact, there may be created eddy currents at this change. How large the effect of increased roughens is on creating local turbulence will be tested in lab experiments presented in chapter 5. Theoretically, the roughness creates a boundary layer in the flow which is never free of eddy currents and will improve the displacement efficiency. Local turbulence will occur when there is a change in angle higher than 26^o. The roughness of a pipe can represent several small changes of 26^o so the displacement profile of the cement where local turbulence is taken into account is more realistic than the displacement profile where it is not taken into account.

Even very laminar flow will according to this theory have some local turbulence along the walls if the pipes are not entirely slick. The theory also claims that if pipe-roughness increases, the local turbulence will increase. This will be tested in the lab, and results will be presented in chapter 3.

2.6 Pressure Loss due to Friction

Roughness affects flow and friction loss. Since the lab experiments will be conducted with pipes of 6 meters length, friction loss will never be large. It will be difficult to measure how friction effects flow when there is close to nothing of it in the lab. Friction loss is however an important factor in the field, and this section is needed to understand how increased roughness in pipes affects friction loss.

Loss of pressure due to friction is very dependent on the geometry, shape and dimension of what the fluid is flowing in. (Skaugen, 1997) In a slick pipe, fully turbulent flow will develop when the Reynolds’s number is above 3000. If the pipe however has a certain roughness, turbulent flow develops at a much lower Reynolds number (Skalle, 2013). Turbulent flow in cement will displace mud more efficiently. Since pipes with roughness create turbulent flow at lower Reynolds numbers, an accurate model of the cement displacement should include a factor suggesting if pipes are rough.

There is no scientific way of measuring the roughness of a pipe. Friction measurements of fluid flow through pipes with different artificially made roughness have showed that friction is not only dependent on the size and shape of the projections, but also on their distribution and spacing. (E. J. Finnemore, 2009)

Let us look at this through understanding of the sub layer. It is claimed by investigators that if the thickness of the viscous sub layer, δ_v, is larger than the diameter of the grains creating the roughness, the effect of roughness is completely submerged. In this case the friction factor becomes like for smooth pipe flow.

For steady, fully developed laminar flow in a round pipe, the friction factor is given by equation 2.3

$$f = \frac{64}{Re} \tag{2.3}$$

There are no analytical solutions to finding a friction factor for turbulent flow, it is found based on a large number of empirical observations. Expression 2.4 is found by Colebrook who correlated the data:

$$\frac{1}{\sqrt{f}} = -2.0\log\left(\frac{\frac{e}{D}}{3.7} + \frac{2.51}{\sqrt{f}Re}\right) \tag{2.4}$$

This is a transcendental equation and requires iterations to determine the friction factor for known values. According to this reasoning it will not be important to include friction in the analysis in the lab.

2.7 Cavings and percentage

Unpredicted hole cavings can create problems in the cement job. They remove our ability to estimate the exact quantity of cement needed to fill up the well bore. Cavings and be detected with a multiarm caliper log run over the total borehole with the casing in place to determine the total hole volume.

They can also be detected by putting a marker in the casing, and determine the volume pumped until the marker is in the mud return line. This test determines percentage of fluid in the wellbore that is active or can be circulated. Cement will only displace drilling fluid that can be circulated, so this caliper test gives a good indication of the displacement efficiency that will be achieved during the cementing operation. Figure 2.8 shows a cross section of displacement in a well where there is unmovable fluids.

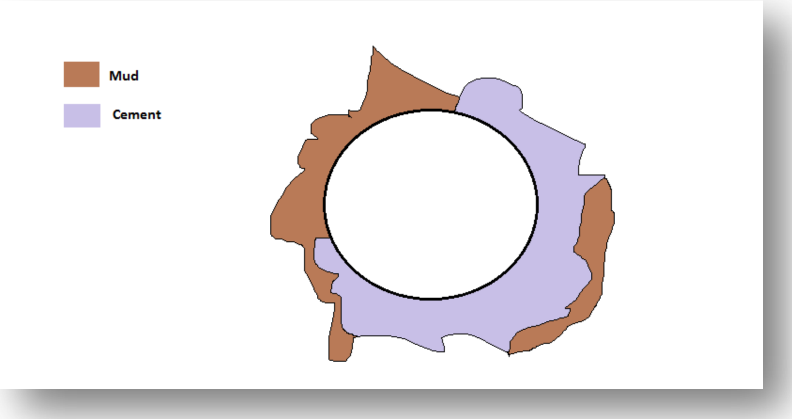


Figure 2.8: Cemented area in an annulus when there is not enough cement to fill up the entire annulus.

3. Field Data

This section is an analysis of two cement jobs in wells completed by Statoil. The aim is to create a better understanding of cement displacement in the field, even if all information from the wells cannot be directly implemented in the displacement model. Well logs from a 7” liner and a 13 3/8” casing are used. Together with information on how cement jobs on the two different wells have been performed, we can create an understanding of what created a poor or efficient cement displacement. Statoil has requested that the data used in this thesis is anonymized. Neither well names nor fields they are drilled in can be named. The two wells will only be called well A and well B.

3.1 Data acquisition

Daily Boring Reports are collected in Statoil’s DBR-database. The information on how the cement jobs were performed is collected from this database. The DBR-database contains detailed information about how the section was drilled, how the hole cleaning was performed and how the cement job was executed.

Cement Bond Logs and Ultra Sonic Imaging Logs were acquired by running tool in the hole after cementing. They give a clear image of how the cement job has gone. The logs were interpreted by geophysicists and interpretations of the logs are used to analyze the cement jobs.

3.2 Data needed to understand the cement displacement

Analysis of cement bond creates a better understanding of the bond between cement and formation. This is used together with the Ultra Sonic Imaging Tool-log to create a full understanding of the cement displacement efficiency.

Running a caliper log prior to executing the cement job will give us an image of how the geometry of the bore hole looks. Like described in chapter 2; the geometry of the hole affects the cement job. Uneven geometry can create problems when pumping the cement because we don’t know the exact volume of the hole.

We need to know the cement displacement parameters. This is monitored throughout the cement job and the information can easily be accessed through DBR. If displacement velocity created a high velocity, equivalent circulating density can become too large and create a fracture in the formation. If then, there are pressure losses during displacement; we have an indication of cement being lost to the formation.

Inclination of the logged interval helps us get a better understanding of which conditions the cement was displaced through. The higher the inclination of the well, the more difficult it becomes to get an even distribution of the cement in the hole. Like shown in chapter two, using the simulations provided by Carrasco-Teja, cement will elongate along the wider side of the annulus. Cement has a tendency to choose the easiest path to flow. The large the inclination of the well becomes, the higher the probability of getting a well where the upper side of the liner, but not the lower side, has been cemented.

Information on how the cemented section was drilled, how the hole cleaning process went and which problems were encountered during drilling should be taken into account. Some well engineers have indicated that when a section is drilled with oil based mud, it can be easier to cement. Equipment works better when using oil based mud to the lubricating effect oil based mud can have. This improves hole cleaning.

Interpretation of logs depends on how the logs were run. Information on what happened prior to and during logging should be included to create a full understanding of the results of the logs.

Figure 3.1 shows the log labels used in the logging process. Figures 3.2 and 3.3 show examples of a good and bad cement job, respectively.

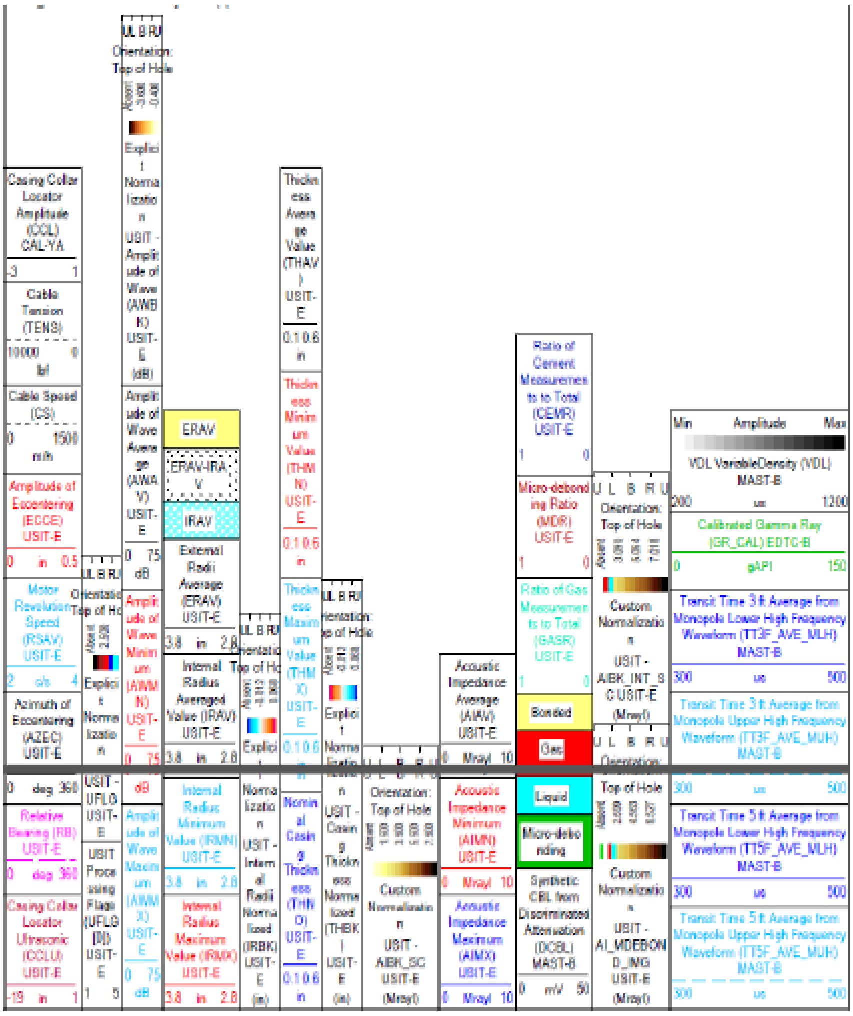


Figure 3.1: Log labels used in the cement bond log interpretations.

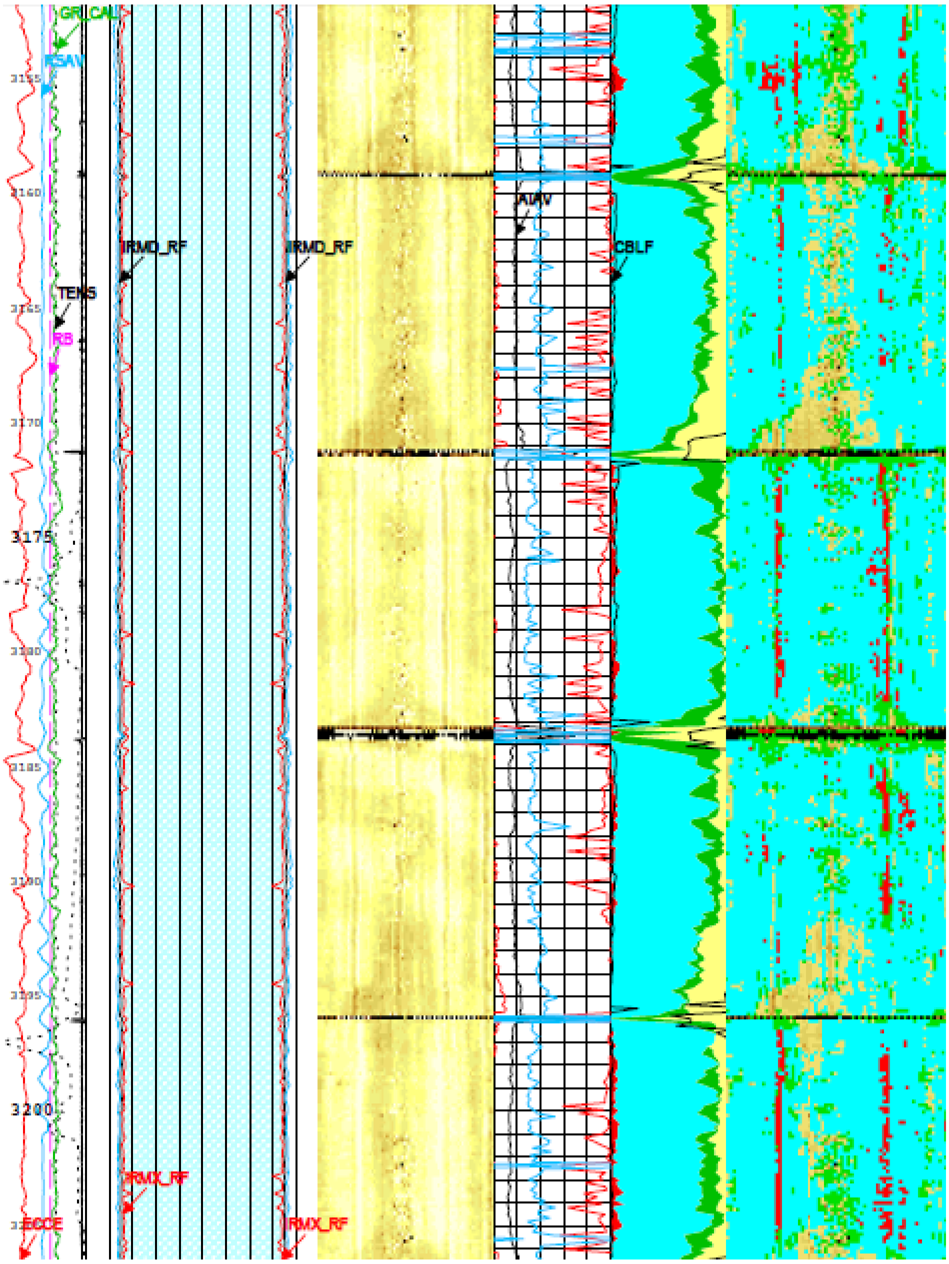


Figure 3.2: Example of log of a good cement job. Logged interval is from 3140mMD to 3210mMD. Including all the logged material would take up too much space in the thesis.

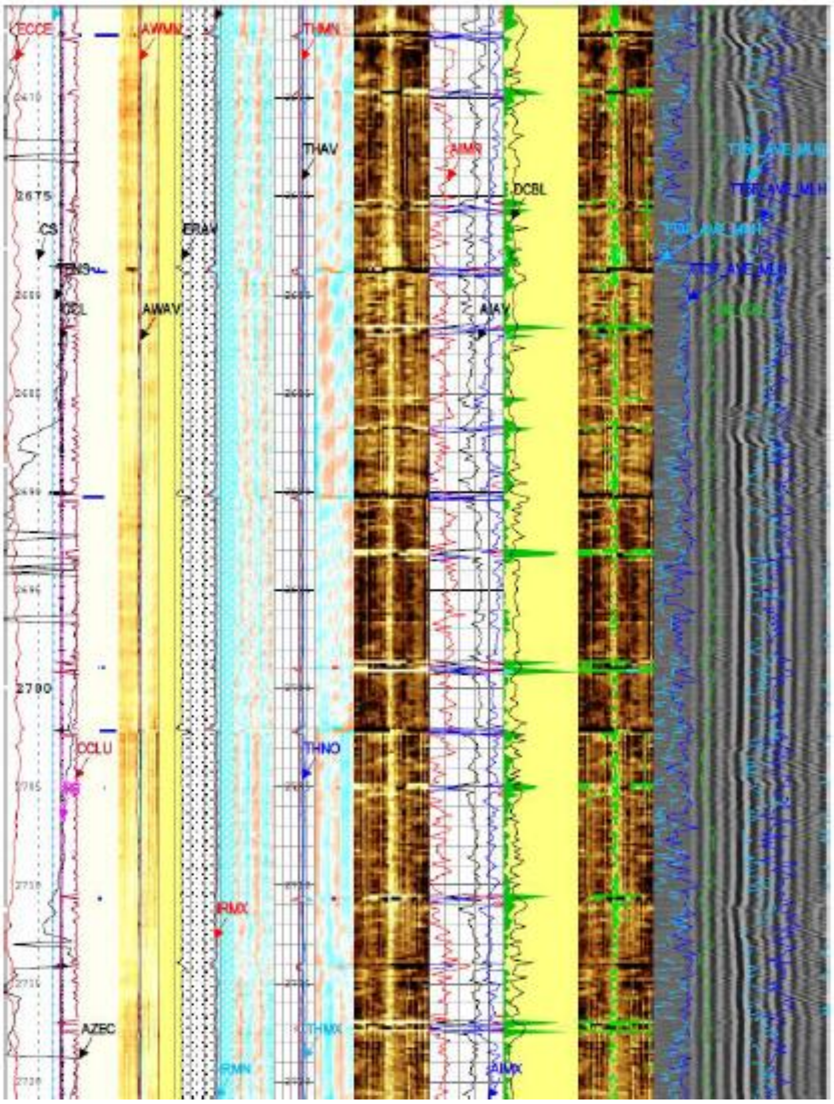
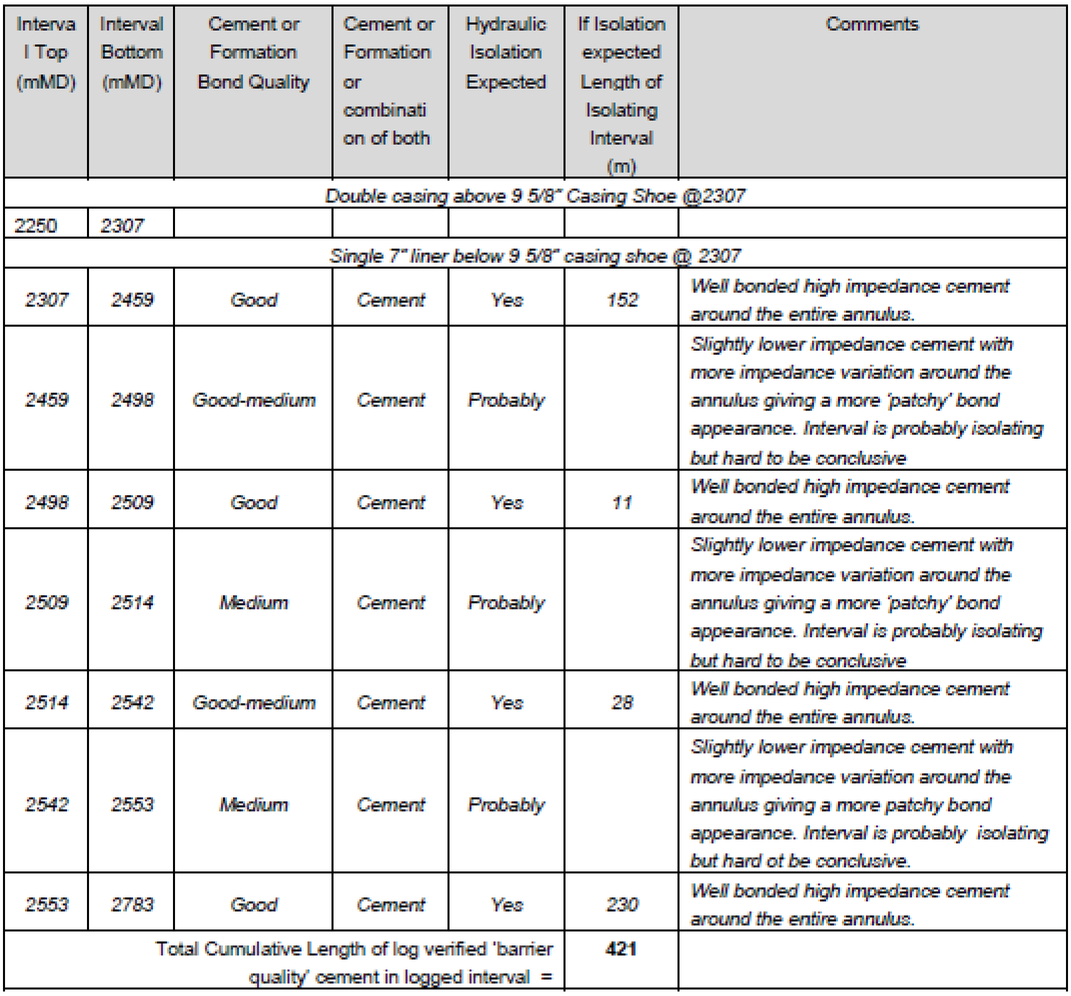


Figure 3.3: Example of a bad cement job. Logged interval is from 3140mMD to 3240mMD. Including all the logged material in this thesis would take up too much space.

3.3 Well A – an example of a successful cement job

In well A, a 7” liner was logged and analyzed. Log data showed that the cement was fully sealing. The cement job was classified as successful and there was no remedial cementing operations done one the section. The interpretation of the CBL and USIT-log is shown in table 3.1.



Interval Top (mMD)	Interval Bottom (mMD)	Cement or Formation Bond Quality	Cement or Formation or combination of both	Hydraulic Isolation Expected	If Isolation expected Length of Isolating Interval (m)	Comments
Double casing above 9 5/8" Casing Shoe @2307						
2250	*2307*					
Single 7" liner below 9 5/8" casing shoe @ 2307						
2307	*2459*	*Good*	*Cement*	*Yes*	*152*	*Well bonded high impedance cement around the entire annulus.*
2459	*2498*	*Good-medium*	*Cement*	*Probably*		*Slightly lower impedance cement with more impedance variation around the annulus giving a more 'patchy' bond appearance. Interval is probably isolating but hard to be conclusive*
2498	*2509*	*Good*	*Cement*	*Yes*	*11*	*Well bonded high impedance cement around the entire annulus.*
2509	*2514*	*Medium*	*Cement*	*Probably*		*Slightly lower impedance cement with more impedance variation around the annulus giving a more 'patchy' bond appearance. Interval is probably isolating but hard to be conclusive*
2514	*2542*	*Good-medium*	*Cement*	*Yes*	*28*	*Well bonded high impedance cement around the entire annulus.*
2542	*2553*	*Medium*	*Cement*	*Probably*		*Slightly lower impedance cement with more impedance variation around the annulus giving a more patchy bond appearance. Interval is probably isolating but hard ot be conclusive.*
2553	*2783*	*Good*	*Cement*	*Yes*	*230*	*Well bonded high impedance cement around the entire annulus.*
Total Cumulative Length of log verified 'barrier quality' cement in logged interval =					**421**	

Table 3.1: Interpretation of the Cement Bond Log and the Ultra Sonic Imaging Tool-log. The cemented section of the well was logged and showed medium to good cement quality throughout the section. The cement is assumed to be hydraulic isolating throughout the well.

The well was logged from 2245m MD to 2784 m MD. The theoretical top of cement, TOC is at 2243m. Understanding of what is meant with theoretical top of cement is described in figure 3.4.

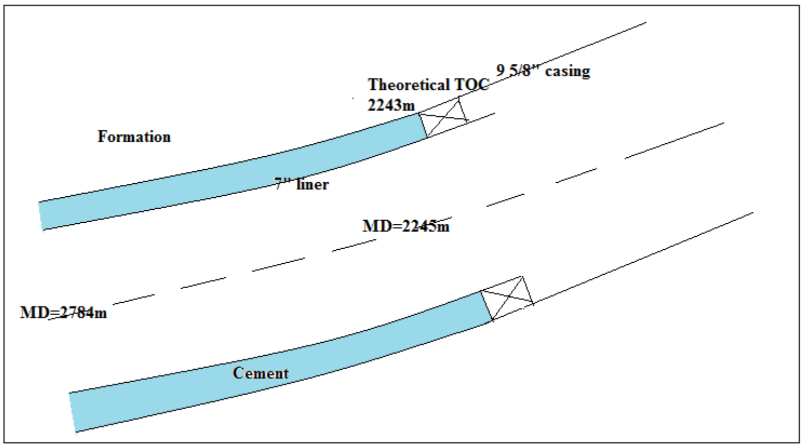


Figure 3.4: Logged interval was from 2245 to 2784 meters measured depth. The theoretical top of cement is assumed to be 2 meters closer to the surface than the top of the 7" liner. This is assumed based the fact that there was no recorded loss of cement during displacement. The CBL and USIT log showing good and isolating cement bond in the logged interval.

CBL and USIT-log showed that there was medium to good cement bond throughout the logged section. There was also an indication that the cement was fully hydraulically sealing throughout the logged interval.

No Caliper Log was run prior to cementing the 7" liner section. There were no cavings in the mud suggesting that there would be need for a caliper log. The good cement quality found through the logs later suggests that estimated volume of pumped cement had been accurate.

According to the information we were able to retrieve from DBR, there were no problems with the displacement process. There were no fractures to the formation and no record of lost circulation. There was a full return to mud tanks during displacement. This is a strong indication that the cement job is going well.

Logging of well A showed that max derivation in the logged interval was 57 degrees. This is a high inclination, but didn't seem to create problems during cementing. The wells that have been the most difficult to cement are wells with inclinations above 60 degrees. Usually, when there is a high inclination in the well, the liner will fall to the lower side of the well, making it difficult to cement the lower part of the well. The effect of having a high deviation in the well is partly eliminated with centralizers surrounding the liner. The centralizers keep the liner in the center for the hole, making it easier for cement to float freely around the liner and cement the entire section. Inclination of the well is shown in figure 3.5.

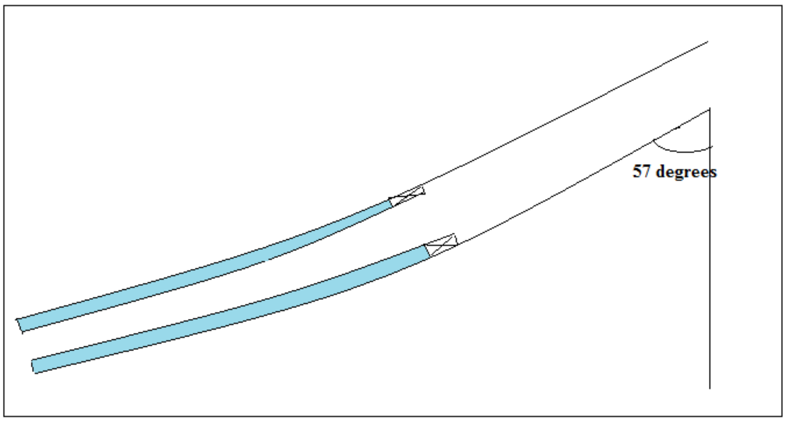


Figure 3.5: The inclination of well A was 57 degrees, making is more difficult to cement than a horizontal well. The high deviation did, however, not seem to have a large impact on the cement displacement. The effect of a liner falling down on the lower side of the formation is partly eliminated with centralizers. Centralizers surround the liner and keep it centralized in the hole. This makes it easier for cement to flow freely aroun the liner and cement the entire section.

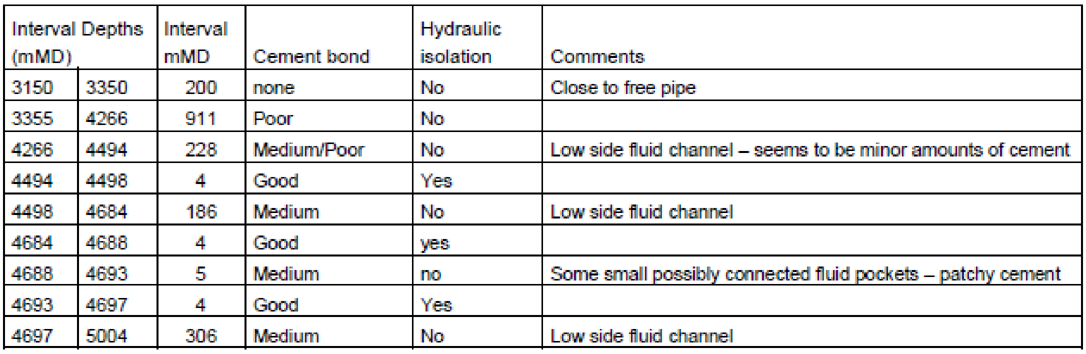
The cemented section was drilled with oil based mud with a density of 1,3 s.g. Drilling with oil based mud will lubricate the cleaning and drilling equipment and make it easier to drill the section. Usual indications of problems with hole cleaning during drilling is that the drilling is not continuous, but stops at times. There were no records of problems during drilling in DBR. We can assume that there was sufficient hole cleaning during the drilling of this section. This is also a large contributing factor to creating a good cement job.

The well was scraped before logging, making it easier to get good images from the imaging tool. There was a 48 hours’ time lap between cementing and logging, which is sufficient time for the cement to set and give us an accurate interpretation of the cement job. Logging occurred in 1.3 s.g. mud, which means that we were logging in slight underbalance. The tool was medium centralized. Analysis of the well has shown good bond and cement sufficiently isolating.

The factors contributing the most to a successful cement job are usually good hole cleaning, no losses during cement displacement and sufficient centralization of the liner or casing in the hole. All these factors are fulfilled with well A, giving us a good cement displacement efficiency and creating a good cement job.

3.4 Well B – an example of an unsuccessful cement job

In well B, a 9 5/8” casing has been logged. The logged interval was from 3150mMD to 5004mMD. The interpretation of the CBL and Ultra Sonic Imaging Tool log is shown in table 3.2.



Interval Depths (mMD)		Interval mMD	Cement bond	Hydraulic isolation	Comments
3150	3350	200	none	No	Close to free pipe
3355	4266	911	Poor	No	
4266	4494	228	Medium/Poor	No	Low side fluid channel – seems to be minor amounts of cement
4494	4498	4	Good	Yes	
4498	4684	186	Medium	No	Low side fluid channel
4684	4688	4	Good	yes	
4688	4693	5	Medium	no	Some small possibly connected fluid pockets – patchy cement
4693	4697	4	Good	Yes	
4697	5004	306	Medium	No	Low side fluid channel

Table 3.2: Interpretation of CBL and Ultra Sonic Imaging Tool log. All interpretation of the logs showed that there was a fluid channel on the lower side of the hole. This is what that caused the cement to not be fully hydraulically isolating.

From table 3.2 we can read the conclusive interpretation of the CBL and USIT-log suggesting that there was a fluid channel on the lower side of the casing. This is most probably what caused the poor hydraulic isolation. The cement job of the 9 5/8” casing in well B is - due to the poor hydraulic isolation- classified as unsuccessful.

No caliper log was run before the cement job was executed in this section. Had a caliper log been run, we might have detected what was would later cause the poor cement job.

There were no problems related to the displacement process in terms of pressure loss. No records of lost circulation during cementing were recorded. There was a full return of mud to the surface. So the problem with a low side fluid channel was not related to fractures in the formation.

The logging showed an inclination of the well of 83 degrees. This might have contributed to the low side fluid channel being created since gravitational pull along on the casing will increase with increased inclination.

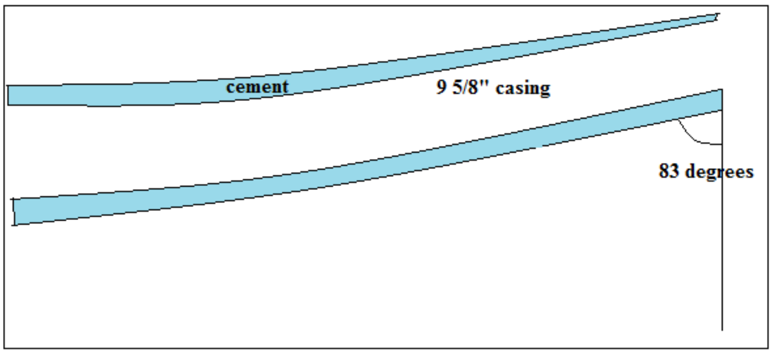


Figure 5.6: 9 5/8" casing had a high inclination mounting to 83 degrees at its highest.

Comparisons of figures 5.6 and 5.5 show a large difference in how horizontal wells A and B have become. Increased inclination will, due to increased gravitational force on the casing, lead to lessening of the effect of centralizers around the casing. This will most likely contribute to worsening the cement job.

Even though hole cleaning was thought to be sufficient before the commencement of the cement job, we can see in hindsight that it probably was not. It is likely that poor hole cleaning disrupting the displacement profile is what created fluid channels on the lower side of the annulus. The situation is displayed in figure 5.7.

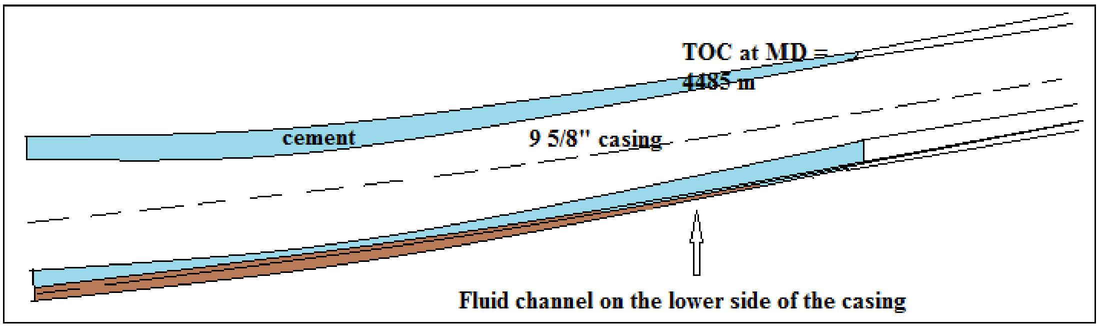


Figure 5.7: Cementation of the 9 5/8" section in well B created a fluid channel on the lower side of the casing.

The TOC was found to be at 4485mMD. Log information found for this well does not suggest that there were errors in logging that gave us the information about fluid channels on the lower side of the casing.

Another factor which may well have contributed to creating a poor cement displacement efficiency is that the casing was not rotated during displacement. Casing rotation does, like shown in chapter 2, stir up the cement as it is being displaced, an even and efficient displacement profile.

4. Modell of the Displacement Process

This section will develop a simple model of the displacement process. A mathematical derivation of the displacement front with no-slip condition is derived first. Later on, lab data is used to verify if the no-slip condition is valid in all types of pipes. Based on the lab data, a more accurate model is described in chapter 6.

4.1 Creating the model

A model for the displacement-profile of cement based on no-slip conditions at the walls and incompressible flow after 1 and 10 seconds is shown in figures 4.1 and 4.2.

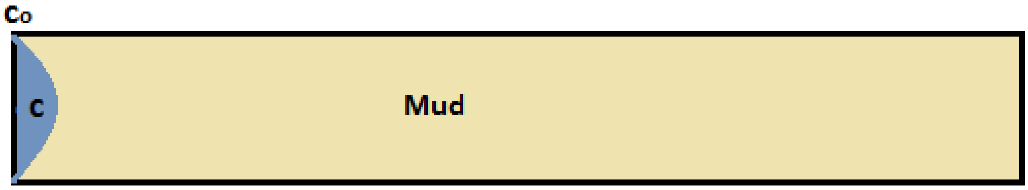


Figure 4.1: Displacement of cement after 1 second. There is no slip of cement at the walls

Figure 4.1 shows a displacement profile of the cement. The center of the displacement profile has velocity 1m/s, and the displacement profiles at the walls have velocity 0m/s – fulfilling the criteria of no-slip condition.

A simple understanding of the movement of the front is described through formula 4.1.

$$x = V_{max} * t \tag{4.1}$$

After time t=1s, the center of the displacement profile has moved 1 meter, while the cement at the walls remains at the starting point.

We need to find the position of the front everywhere on the profile. The position of the front is a function of the velocity of a point r in the profile and time after equation 4.2:

$$L_{front} = v(r) * t \tag{4.2}$$

Velocity in a point r on the velocity profile is a function of the radius and the initial velocity after equation 4.3:

$$v(r) = v_o * (1 - r^2) \tag{4.3}$$

At a time t = t_x seconds, the cross-section of the velocity profile will be like depicted in Figure 4.2. There is decreasing velocity along the velocity profile from the center of the profile to the walls.

Figure 4.2: Velocity Profile of the Cement after x seconds. There is still no slip of cement at the walls.

At time t=t_x, the velocity in the center of the displacement profile has moved, while the cement along the walls, remain where it was. This type of behavior creates a very poor cement job as the annulus will never be fully cemented.

Development of simulations and simulations that follow in chapters 4.3, 4.4 and 4.5 will be a study of how the cement displacement profile varies with velocity. The displacement profile will be different if it is based on a no-slip condition or if the effect of turbulence along the wall is taken into account. Both these scenarios are simulated and the cement quality for both scenarios is calculated. The factor determining how quickly cement moves along the walls is guessed and used in the simulations to show the difference in cement quality between two scenarios; one scenario where local turbulence is taken into account and one where it isn't.

The near wall turbulence happens in the sub layer of laminar flow and the effect of turbulence along the walls is that the velocity profile advances quicker than if local turbulence is not present. A discussion of how the model should be improved further is done after the presentation of simulation results.

4.2 Validity of the Model

Based on the research done for this project, there are a few points that have come to my attention. The model is not valid in all cases, but only if a few requirements are met. The model is only valid for:

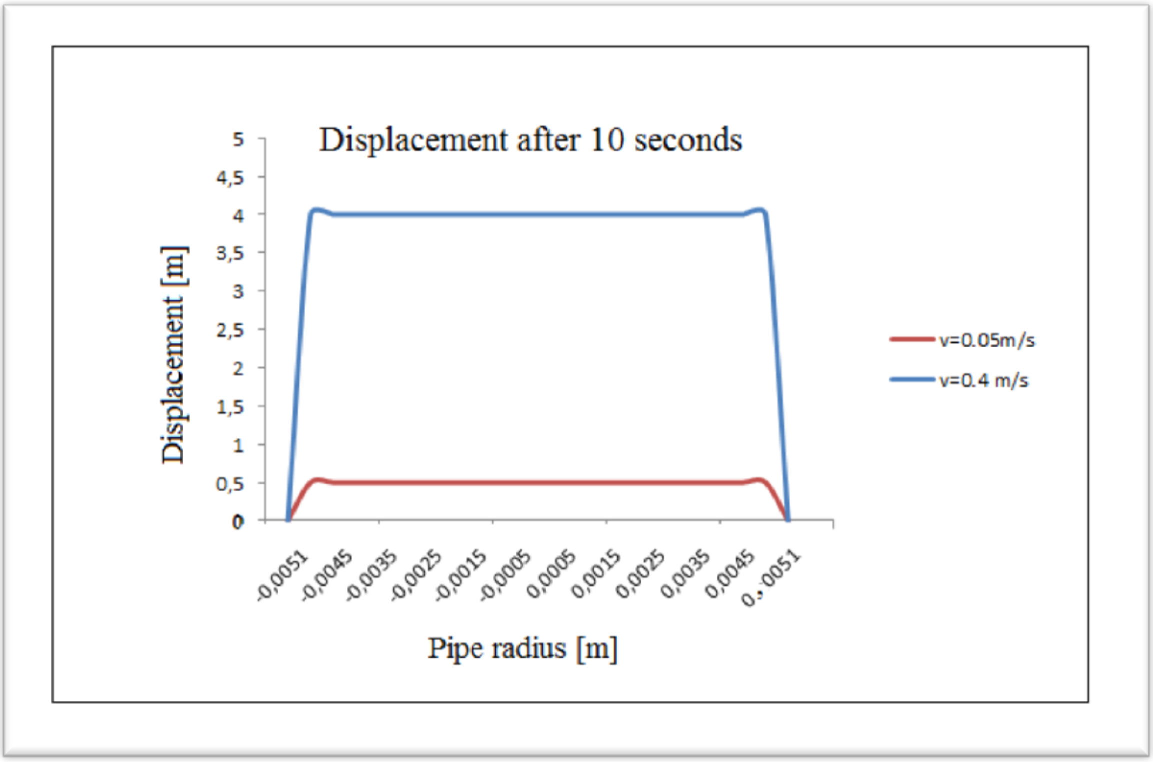
- Wells with low standoff.
- Wells with high enough viscosity to overcome eccentricity
- High density fluids displacing low density fluids and low density fluids displacing high density fluids
- Holes that have had sufficient hole conditioning time
- There is no loss of cement to formation, i.e. the formations fracture pressure cannot be exceeded during cement displacement.

4.3 Simulations

The simulations of displacement efficiency are done for a pipes with internal diameter d_i = 0,01m and length 6 m. This is the same as the pipes that will be used in the lab. Simplifying simulations to what we would see in the field makes it easier to compare lab data to simulated data. It also makes it easier to verify if the improved model that takes into account wall roughness, viscosity and displacement rates is in alignment with the test results that will be done.

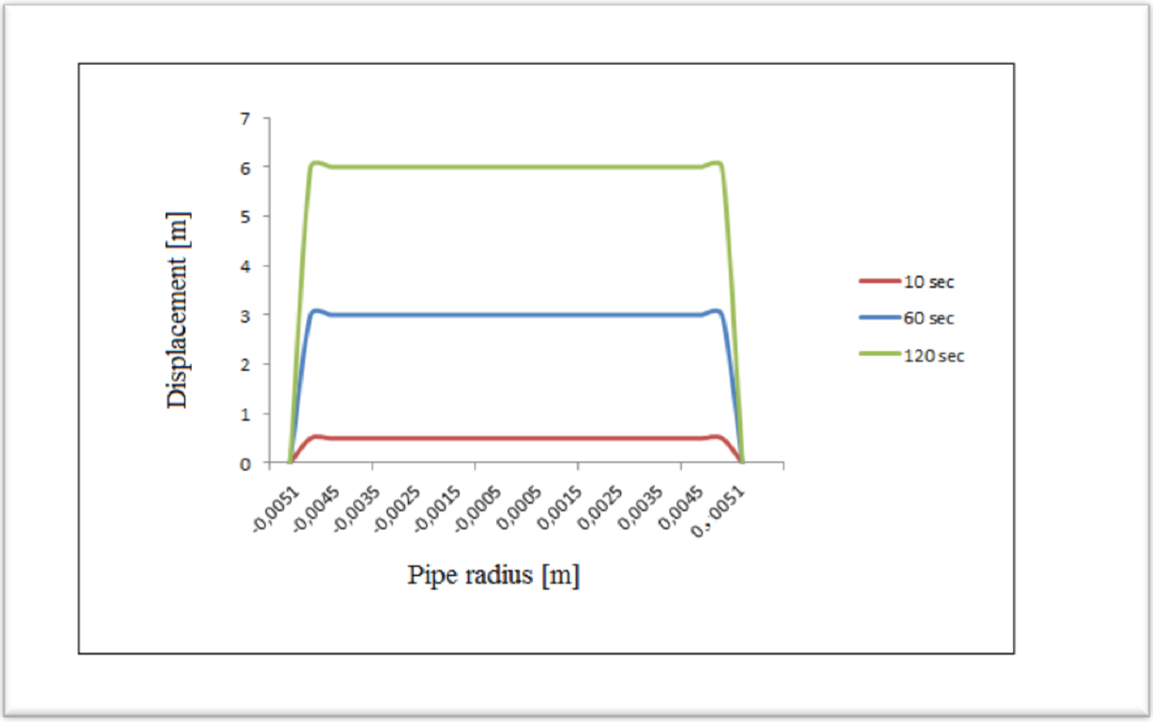
Simulations will be done for displacement velocities of 0,05m/s to 0,4 m/s. This range of displacement velocities will give Reynolds numbers from approximately 500 to 4500, showing us displacement efficiencies from very laminar to fully developed turbulent flow. The displacement profile of the cement will also vary with time. Simulations on displacement using both the no-slip displacement model and the displacement model including movement at the walls are shown in chapter 4.4

4.4 Simulations of displacement profile



Simulation 1: Frame image of displacement after 10 seconds for displacements with simulated with velocities of 0.05 m/s and 0.4 m/s. The two displacement profiles how the transgression of cement with time. Displacement of 0.05 m/s gives laminar flow while displacement of 0.4m/s gives fully turbulent flow.

Simulation 1 shows a frame image of the displacement front for two displacements with 0.05m/s and 0.4m/s at a time t=10seconds. The no-slip condition is valid for both displacements, giving an elongated form of cement within the pipe. A displacement like the one showed in the simulation would not give a fully sealing cement.



Simulation 2: Frame image of displacement fronts at times t = 10 seconds, t=60 seconds and t=120 seconds. Displacement velocity is 0.05m/s for all three simulations. No-slip condition is valid for all three simulations.

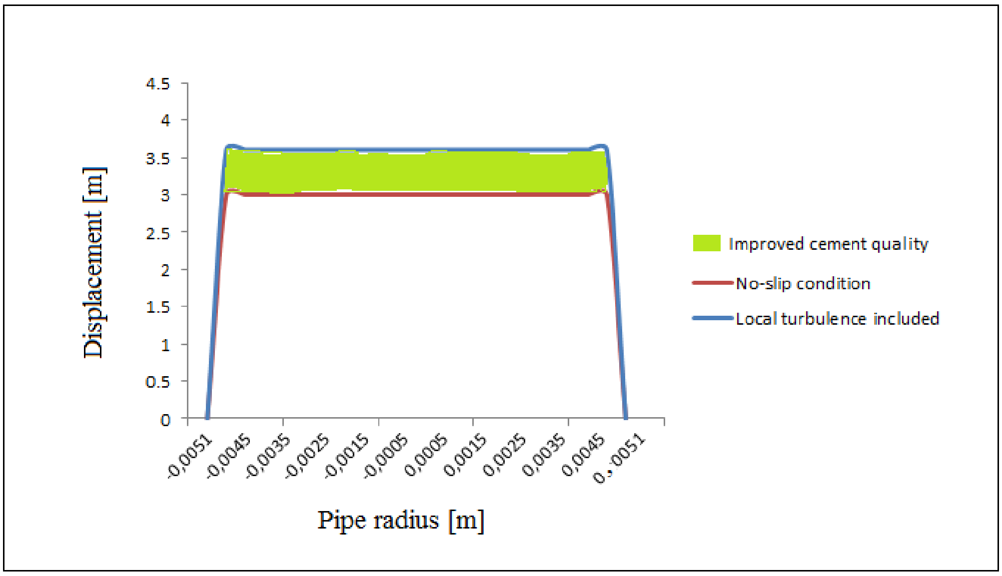
The above simulation shows the advancement of the displacement front at different times through frame images of the displacement after 10, 60 and 120 seconds. No-slip condition is valid for all three simulations. Cement displacement improves with time and fills up a larger part of the pipes.

4.5 Local turbulence improves the displacement efficiency

When local turbulence is taken into account in the simulations, the displacement profile will change and improve. The equation used to describe the advancement of the displacement front is no longer equation 4.3, but contains an extra part which includes the local turbulence. The equation which would take into account local turbulence is given in equation 4.4 and includes v_{local} which gives the local displacement.

$$v(r) = v_o * (1 - r^2) * t + v_{local} * t \tag{4.4}$$

Simulation 3 shows displacement of cement in the pipe after 60 seconds. One simulation shows displacement when there is no local turbulence, and the other shows displacement where there is local turbulence giving a velocity of 0.01m/s. both profiles are advancing with a velocity of 0.05m/s, but when local turbulence is taken into account, the simulated profile will advance quicker. The improved cement quality is highlighted in green.



Simulation 3: Two frame images of the displacement fronts at time t=60 seconds. Both displacement fronts are moving forward with a velocity v=0.05m/s, but the more advanced displacement front takes into account local turbulence. Local turbulence here is taken to give a velocity advancement of 0.01m/s. The local turbulence will be quantified with lab experiments to give an exact and real value.

We can see from the displacement profiles in simulation 3 that when local turbulence along the walls is taken into account, the displacement of cement becomes much more efficient. At the same displacement velocity, the front has moved further to the front than when local turbulence is not taken into account. This creates a more accurate simulation of how the displacement of cement actually takes place. The theory that is being proposed in this thesis claims that local turbulence is not a fixed value, but varies with wall roughness, viscosity and velocity. If local turbulence has anything to say on the displacement, and what the value of the velocity might be, will be proposed after the lab experiments have been done.

Cement quality can be found through formula

$$q_c = \frac{Vc}{V} \tag{4.5}$$

where Vc if the volume fluid pumped through the pipes, and V is the volume of the pipe.

$$V_{pipe} = A_{pipe} * l_{pipe} \tag{4.6}$$

Where Apipe is the crossection of the pipe and l_{pipe} is the length of the pipe. Crossection is found through equation 4.7

$$A_{pipe} = \frac{\pi}{4} * d^2 \tag{4.7}$$

After 60 seconds of displacing cement with 0.5m/s and not taking local turbulence into account, we get a cement quality of 67%. When local turbulence is taken into account and assumed to give a velocity of 0.1m/s along the walls, the cement quality becomes 82%. So for this simple simulation, there is an improvement of 15% on the cement quality when local turbulence is taken into account.

5. Lab Experiments

In chapter 5, lab tests will be planned and executed. The results are used to describe how local turbulence affects the displacement profile. The displacement model is then improved based on how local turbulence affects the displacement. The lab set up will be planned in detail before the experiments commence. Some equipment might not be ready and needs to be created after the lab work has been planned. Four different factors will be investigated in the lab experiments. These factors are; pipe roughness, viscosity, flow rate and displacement volumes. The whole lab process will be described in the following sub chapters and finally the results will be discussed.

5.1 Test Matrix

The aim of the experiment was to find out how displacement efficiency will be affected by pipe roughness, viscosity, flow rate and displacement volumes. Table 5.1 shows the test matrix that will be used when conducting the lab experiments. Displacement efficiency will be tested at different displacement volumes from 1 to 10 times each. Pipes, fluid and flow rate will also be varied in addition to varying the volumes of displacement fluid. 600 lab measurements is the goal, and will be tried to achieve.

Variable	**Variation**	**Comment**
Roughness	3	Completely Smooth Rough Very Rough
Fluid	2	Water Water and polymer HEC 0,4
Flow rate	4	Laminar Flow (Re= Less Laminar Flow (Re= Less, less Laminar Flow (Re= Turbulent Flow (Re= Find out Reynolds number for each measurement as well
Time. Displacement of Oil in number of volumes in pipe, V	25	1 V – 10 times 3 V – 5 times 10 V – 3 times 16 V – 1 time 20V – 1 time
Total: 4 variations	**Total:** 34	**Grand Total:** 600 tests

Table 5.1: Test matrix with the variables and number of variations of each tests. 25 different measurements for 4 different flow rates, 2 different fluid types and 3 different variations of roughness of the pipes will give us a grand total of 600 lab measurements.

5.2 Planning and designing the lab

In chapter 5.2 I will describe the execution of the lab measurements. Everything from how the planning to lab setup to creating of equipment will be described. How the test procedure was followed will also be described stepwise. Calibration of test method was conducted before the experiments were done, and the calibration method will be described before the results are presented and analyzed.

5.2.1 Schedule for labwork

Task	**Respon-sible**	**Week 6**	7	8	9	10	11	12	13	14	15	16	17
Create a scetch for lab setup	Sera	🟥											
Create a test matrix. Height of mud tanks. Find location for tests	Sera, Pål, Håkon	🟥											
Order Pipes. Find measurements indstuments	Sera, Håkon, Jarle, Åge		🟥										
Chemical additives + rheological measurement training	Sera Ferizi & Roger Øverå		🟥										
Make tanks. Find elevation solutions. Find transition between pipes and tanks. Create table to keep pipes on	Sera & Håkon			🟥									
Create Internal Roughness Pipes	Håkon, Sera, Jarle				🟥								
Run pilot Tests with Water in both tanks	Sera & Håkon					🟥							
Order Oil, Install pressure measurement& Flowmeter equipment	Sera, Roger, Håkon, Åge					🟥	🟥						
Run Pilot Tests with Oil & Water. Find a way to calculate cement quality + run test	Sera Ferizi							🟥	x	x	x	x	

Table 5.2. Execution plan for lab work. Red indicates in which week the task will be done.

5.2.2 The Lab Setup

The design criterias are explained in the following. The experiment will consist of a pipe filled with oil. The oil is displaced with water or a more viscous fluid. How much oil is being displaced during every experiment will be measured in a measurement cylinder. The displacement rate is found through dividing the displaced volume on the time it took for the volume to be displaced. Time of displacement will be measured with a simple stop watch. Oil will be filled in the pipe through a tank placed above the measurement equipment. The height difference between the oil container and pipe is set to be high enough to give a pressure that will fill the pipe with oil without disconnecting it from the valves. The pipe has a 20 degree tilt so that the whole pipe can be filled with oil, and there is no unfilled void at the top of the pipe. Pressure from the oil tank should also overcome the 20 degrees tilt that the pipe will have. A 3 meter height difference between the pipe and the oil-container will suffices. The water and viscous fluid will be displaced with pressure received through a pressure tank. The pressure tank is connected to an air hose that will provide the pressure to the tank. Figure 5.2 shows the lab setup.

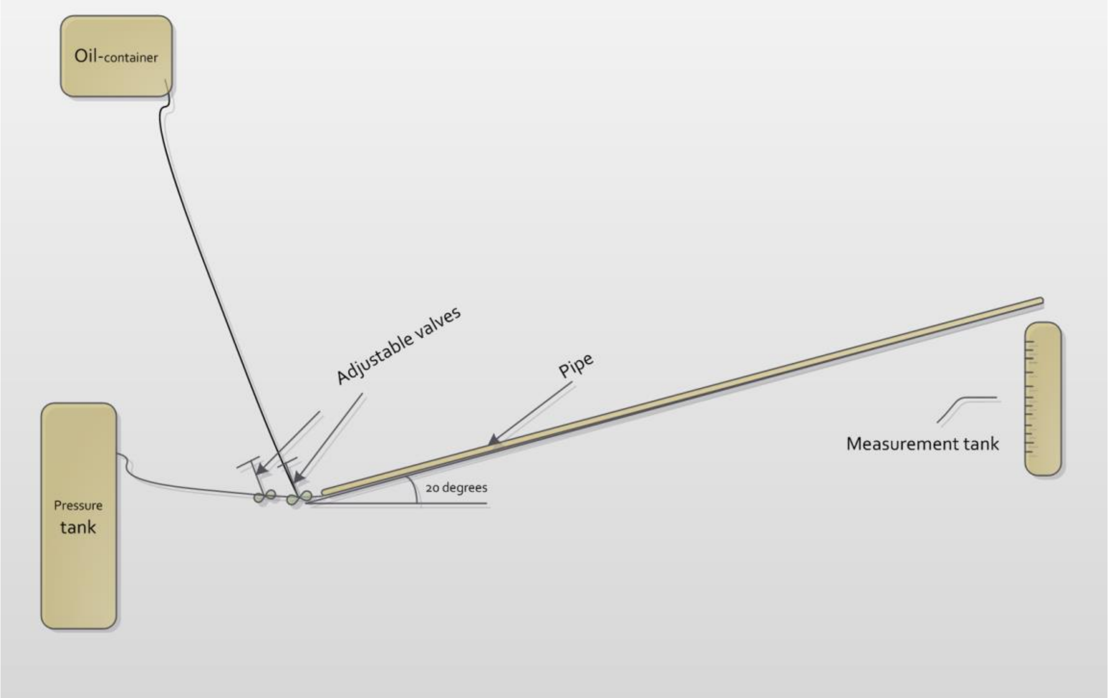


Figure 5.1: Lab setup. A pressure tank is providing pressure to the displacement. The oil container is used to re-fill the pipes with oil after every test. The measurement tank is used to measure how much oil and water is being displaced in each test.

The pressure tank was not originally a part of the lab setup. Both the oil tank and the tank containing the displacing fluids were going to be regular tanks. Both tanks were going to be placed above the pipe to provide pressure for the displacement. It was important that the tank containing the displacing fluid be so high above the pipe that we would get very turbulent flow even when using a very viscous displacing fluid. The following calculations were used to find which height of the tank would give Reynolds number 5000.

Reynolds number is found from formula 5.1

$$\mathrm{Re} = \frac{\rho \mathbf{v} D_H}{\mu}$$

(5.1)

Dynamic viscosity of water at 20 ^{o}C is 0,89* 10^{-3} Pas.

How much pressure is needed to give the desired Reynolds numbers is found through Bernoulli’s equation (5.2). This is used to set the pressure-tank to desired level.

$$p + \frac{1}{2}\rho V^{2} + \rho g h = p + \frac{1}{2}\rho V^{2} + \rho g h$$

(5.2)

Equation 5.1 and 5.2 were together used to find that to displace viscous fluid with a 10cP viscosity, the height difference between pipe and fluid tank should be up to 6 meters. There was no practical and safe way to fulfill this requirement in the lab. We tried to hoist up the pressure tank. This made it unsafe to come near it as it was hanging loose in the air. We had to look for another solution. A pressure tank and pressure meter was found to provide the accurate pressures needed for each measurement. 10 meters increase in height gives an increase in 1 bar in pressure, and the pressure gauge was gave measurements down to 0,05 bars, which I evaluated to be accurate enough.

Mixing displacement fluid: The experiments where more viscous water displaces oil will be done with a 5 cP viscosity, HEC / water mix. Increasing the viscosity in the displacing fluid will, according to the theory that have been explained in chapter 2 from Silvia et al, increase the displacement efficiency.

Pipes: 5 meter long pipes with an internal diameter of 1cm will be used in the experiments. The pipes will have three different types of internal roughness. The analysis of the displacement will help to understand how roughness contributes to the displacement process.

Mud Tanks: Mud tanks will be used to contain the oil. The pipe will be refilled with oil before each experiment.

Table: The table has to have an angle of approximately 20degrees so that the pipe would be fully filled with oil before the displacement process starts.

Measurement Cylinder: To measure how much oil and displacement fluid is being displaced in each experiment, I had to use a plastic measurement cylinder. The measurement cylinder also had to be able to contain at least 20 times the volume of the pipe, i.e. 8 liters.

Valves: The pipes were filled with oil through valves. In addition to controlling the displacement through the pressure valves on the tank, there is a valve close to the pipe.

5.2.3 Building the Lab

Production of pipes: Slick pipes of length 5 meters and internal diameter of 1cm each were ordered, and the process of creating different roughness was started.

Figure 5.2 meter long pipes with internal diameter 0.01m

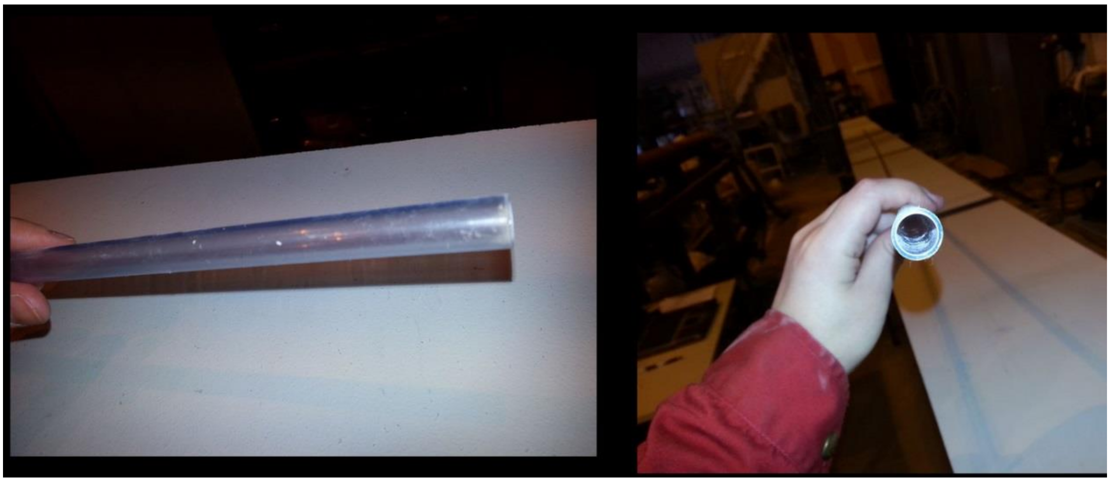


Figure 5.3 The pipes were initially slick internally and we needed a way to create internal roughness

We tried to create internal roughness in the pipes by attaching different parts to a wireline or pole and running them through the pipe with a drill. One of the first attempts made to create internal roughness in the pipes were done with sandpaper. The result was however unsatisfying as this barely created any roughness in the pipes.

Figure 5.4 Trying to create internal roughness with sandpaper. This did not create enough internal roughness in the pipes.

We then tried to create internal roughness with a semi-hard brush and wireline that was run through parts of the pipe. The result here was also unsatisfying as we could not feel any internal roughness in the pipe.

Figure 5.5 A semi-hard brush and wireline is run through the pipes. This did not create enough internal roughness in the pipes.

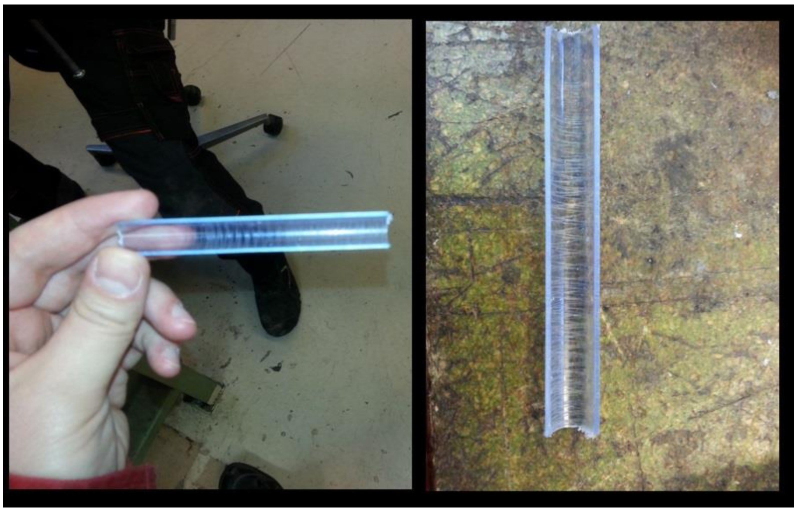


Figure 5.6 Internal roughness created after use of a semi-hard brush and wireline was neither very visible nor could be felt by running your fingers through it.

The next attempt done on creating internal roughness was with a hard piece of nail attached to a pole. The results were successful creating the "roughest" internal roughness we used in the experiment.

Figure 5.7 A nail attached to a pole was run through the pipes and created desired internal roughness

Another successful attempt to create internal roughness was done with a piece of hard wire nailed through wireline and run through the pipe. This created the "medium" internal roughens used in the experiments.

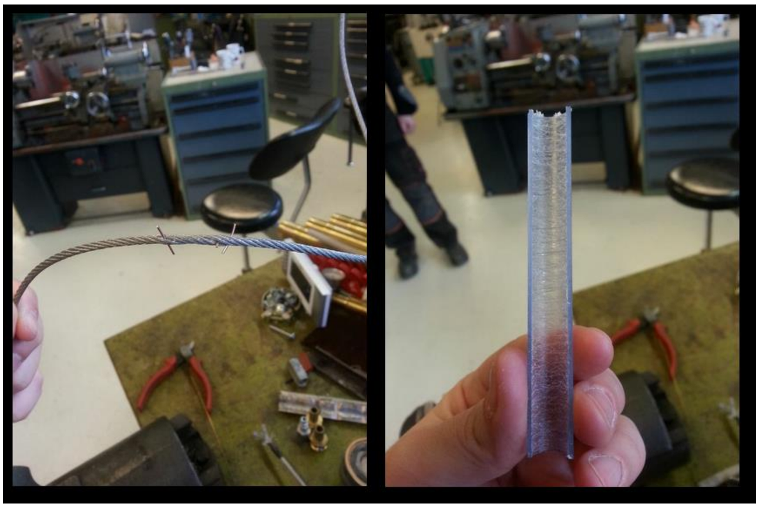


Figure 5.8 A piece of hard wire was nailed through wireline and run through the pipes with a drill

Mud Tanks: There was originally a need for a tank to contain oil and one for the mud and water used to displace the oil. We decided to try and use large tanks and raise them with a crane to desired height. Holes were drilled in the tanks and 10 long tubes were added to the tanks.

Figure 5.9 Two tanks intended for containing the oil and displacement fluid were drilled and we attached tubes to them. Pressure from the tanks was going to be provided through a height difference created when the tanks were lifted up. This was not safe, so the tank containing displacement fluid was switched to a pressure tank. The tank containing oil was placed in fixed place at 3 meters above the pipe.

Pressure tank: Using mud tanks to displace fluid from the elevated pallet showed to be a little more difficult than we assumed. It made it difficult to control the flow and the pressure. We chose instead to use a pressure-tank to contain the water and drilling fluid and displace the oil. The level of fluid in the tank will decrease as water and mud is used from the pressure tank. It is necessary to see the accurate level of fluid in the pressure tank to know how much pressure to subtract and have an idea of how quickly the fluid was going. A tube was attached to the pressure tank so the level of fluid could be read in the tank.

Figure 5.10 Pressure tank used to displace mud. To the right a tube has been installed to see the fluid level inside the tank. To the right we also see a blue hose filling the tank up with air used to increase pressure in the tank.

Table: The angle of the table was easily adjusted by placing metal under two of the outer legs. This gave us a upwards dipping angle of 20 degrees, allowing the pipe to be completely filled with oil each time, and not having an upper side where there was no oil.

Production of measurement cylinder: To measure the displaced fluid there was a need for a cylinder. The cylinder we made has an internal diameter of 15,5 cm and height of 95 cm. There is a valve at the end of the cylinder. Oil is lighter than both water and the viscous fluid used to displace the oil. This density difference causes the two fluids to separate, and the valve will be used to pour out the water and viscous fluid. The oil is returned to the oil tank and reused in the experiments. This lowers the oil costs for the experiment. Total displaced volume was divided with the time of displacement to find exact displacement.

5.11: A Measurement Cylinder was used to measure how much oil and displacement fluid was displaced after each test.

Valves: Valves were needed to create a transition between the oil tank and pipe and between the pressure tank and pipe. The pressure supply from the pressure tank was not completely even during one displacement and there was a need for a valve that would make it possible to adjust create an even flow. The valves used in the experiment consisted of an adjustable valve and an on/off valve. This allowed me to adjust the flow first then turn the on/off valve around and allow flow through the pipe. Figure 5.12 shows on / off valves allowing flow from the oil tank and the pressure tank.

5.12: Valves creating transition between pressure tank and pipe and between oil tank and pipe. The flow can be completely turned off with the valves shown in the picture. There was another adjustable valve used to maintain a defined flow from another valve. The adjustable valve allowed a precisely adjusted flow even when the pressure supply from the tank was not completely even.

5.2.4 Test procedure

Each test was conducted in a specific order. The following procedure shows how the tests were performed:

1. Flow valve between oil tank and pipes were open, and oil was allowed to flow through. Due to the height difference between the oil tank and the pipes, the flow was high enough to displace any residual water or viscous fluid.
2. Pressure in the tank was adjusted to give a desired flow rate.
3. Valve adjusting flow from pressure tank to pipes was adjusted to a set flow.
4. On/off valve on adjusting flow to pipe was turned on.
5. Stop watch was turned on at the same time as the on/off valve was turned on.
6. When the cylinder was filled up to desired amounts of pipe volumes, the on/off valve from the pressure tank to the pipe was turned off and stop watch was stopped
7. Exact amount of displaced volume was measured

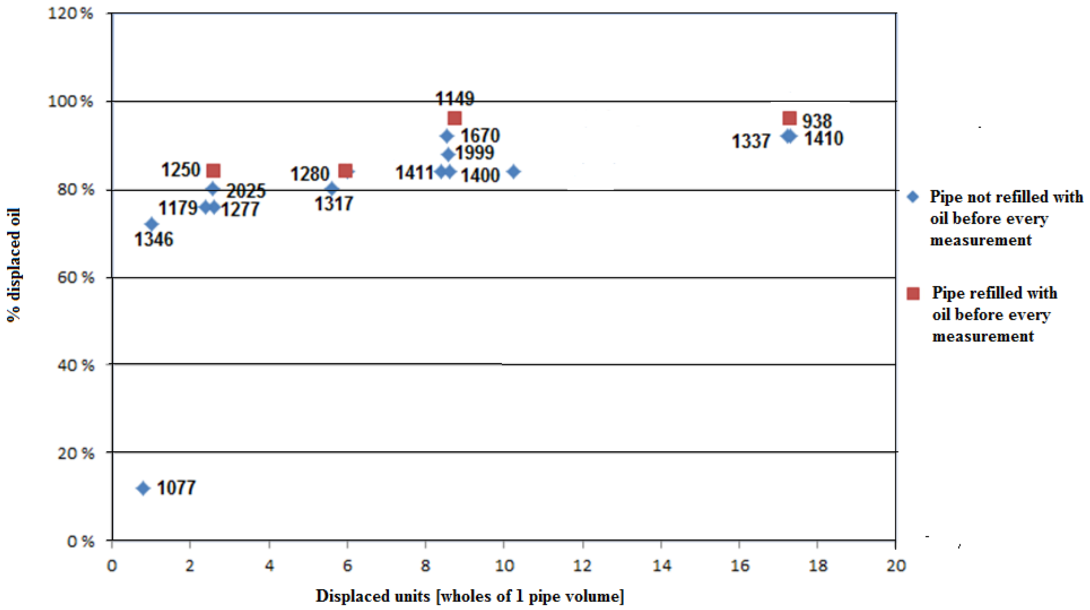
8. When the oil and water or the oil and viscous fluid has separated, amount of displaced oil is also measured. Measurement of displaced volume was accurate down to 0, 05 deciliters.
9. Total displaced volume is divided by the time the displacement took, and flow rate was found. Flow rate was used to find the Reynolds number inside the pipe for each measurement, allowing us to know if the flow was turbulent, laminar or transient.

5.2.5 Calibration

Calibration of measurement method: As described in section 5.2.4, there are two parts of each measurement. One part is when the oil is refilled in the pipe, and the second part is displacing the displacement fluid. This section describes measurements done to see if it was possible to do the first part of each experiment only once for five different measurements.

Volume of displacement fluid being displaced in every measurement is 1 to 20 times the volume of the pipe. I wanted to see if it was possible to do five measurements at 1, 3, 10, 16 and 20 volumes units without refilling oil in the pipe between each measurement. This was to make it a little easier to do the planned 600 measurements.

Graph 5.1 describe the measurements that were done. Blue points show measurements of displaced oil- volume when the pipe was not re-filled with oil before every measurement. The red points show measurements of displaced oil where the pipe was refilled with oil before every displacement measurement. The numbers standing close to each point indicate the Reynolds number that the water was being displaced with at each test. All the tests were conducted with laminar flow to eliminate effects of turbulence on the displacement.



Graph 5.1: Shows measurement of displacement efficiency when oil was being displaced with water in a slick pipe. Blue points indicate measurements done where the pipe was not re filled with oil before every single measurement. Red points indicate measurements where oil was re-filled in the pipe before every measurement. Numbers close to each point is the Reynolds number of each displacement. Only Reynolds numbers giving laminar displacement are included in the plot to eliminate the effects of turbulence on displacement and to give us comparable points. 1 pipe- volume is 0,47 liters, and 20 pipe-volumes is 9,4 liters. Measurements show a higher displacement efficiency when the pipe was re filled with oil before every measurement.

Filling the pipe with oil only once before five measurements gave a lower displacement efficiency than if the pipe was re-filled with oil before every single measurement. It is assumed that parts of the oil settles in the pipes when the displacement process is stopped, and creates inaccurate displacement compared to real life data. The displacement efficiencies are shown in Graph 5.1 with percent oil displaced on the y-axis and amounts of total volumes of water displaced in the x-axis. Volume of the pipe is 0, 47 liters, while 20 volume units of displaced water is 9,4 liters.

Only measured points with Reynolds numbers giving laminar displacement are included. This eliminates the effects of turbulence on displacement. It also made the graph more readable when fewer points were included. All measurements are presented in the Appendix, chapter 11. Displacement was more efficient when displacement occurred continuously up to the measured point. When the flow was stopped to measure displacement at different points, the displacement became lower.

This occurred even though the flow regime was the same for both methods. In real life, cement is displaced continuously until it has reached its theoretical destination. Data which would give the best comparison to real life displacement should be used. It was decided to refill the pipe for every single measurement.

Calibration of pressure tank equipment: Discontinuity between what the gauge meter on the tank showed and how much pressure the tank provided was observed. This happened even with fluid inside the pressure tank being at the same level and the gauge showing the same pressure for different measurements. The error in pressure supply was however greatly adjusted by the flow valves on the pipe. The valves adjusted the flow and helped make it continuous throughout each measurement.

But even with the valves adjusting the flow, the errors in pressure supply were still not completely eliminated. The flow could go from laminar to very turbulent back to laminar within a few seconds for some measurement. Measurements with great fluctuation in flow are eliminated from results shown in the Appendix as well as in the graphs which will be presented soon. Including these unrealistic measurements would have made comparisons between measurements un-reliable.

5.2.6 Preparation of viscous fluid

In addition to oil being displaced by water, there was a need to conduct experiments with viscous fluid displacing oil. This was to see the effects of increased viscosity and density in the measurements. 50 liters of water will be mixed with 100 grams (2 grams/liter) HEC to create a viscosity of 5 cP. The water will be mixed with HEC in a small mixer first. The mixer contains up to 1 liter of water and is shown in figure 5.13. The total amount of water will then be thoroughly mixed in large tank - like the one shown in figure 5.14- before being poured into the pressure tank.

Figure 5.13: The viscous fluid was mixed in small volumes at a time. Total amount of HEC was divided between small volume units and later poured into a large tank.

5.14: HEC is a viscous fluid. Mixed with water, it will give us the needed viscosity and density to analyze effects of viscosity and density of the displacing fluid has on displacement.

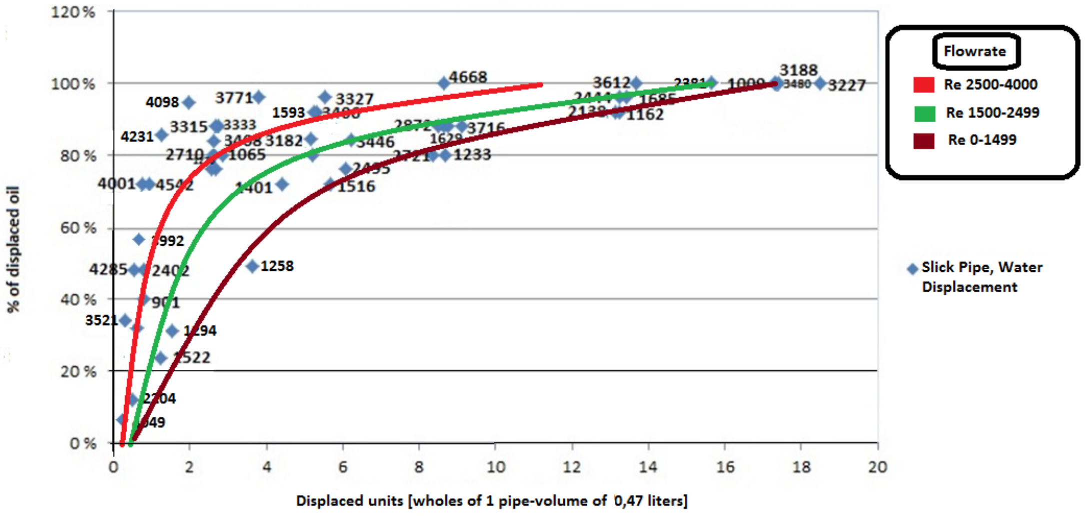
The viscous fluid will be tested for correct viscosity in a viscometer like the one shown in figure 5.15.

Figure 5.15: Viscosity meter used to take correct measurements of the viscosity in the viscous fluids used to displace oil.

5.2.7 Results

The results of the tests showed that roughness in pipes had a large effect on displacement efficiency. In slick pipes; displacement efficiency was also affected by the flow regime of the displacement fluid. Displacement rate had little to no effect on displacement efficiency in medium to course roughness in pipes. Amounts of displaced volumes needed to create full displacement also varied for the different pipe roughnesses. In the medium and rough roughness pipes, there was a displacement of up to 100 % with only 3 times the volume of the pipes being displaced. Analysis and presentation of results follows underneath.

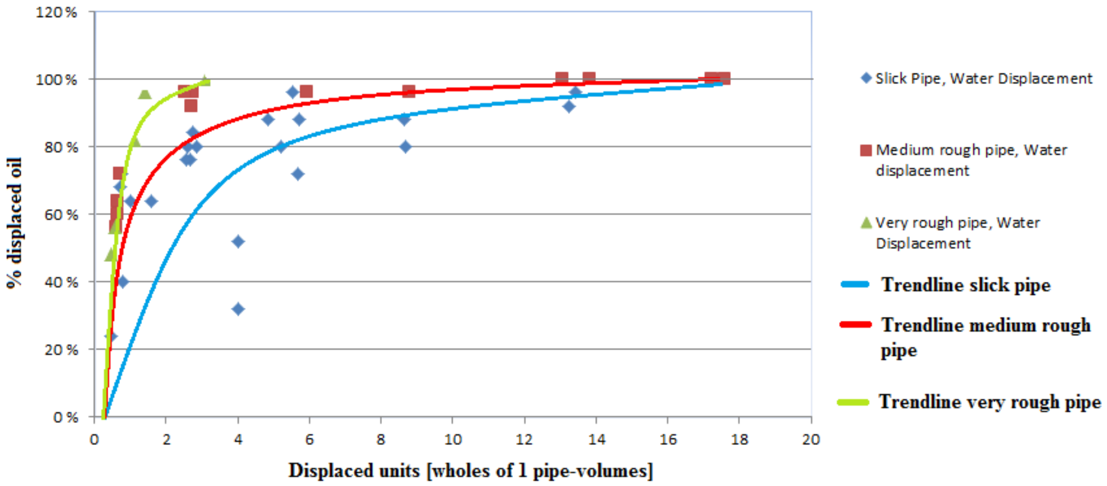
Displacement Rate: We know from the theory presented in chapter 2 that increasing the displacement rate would increase displacement efficiency. As displacement rate increases, so does the turbulence in the flow. With increased turbulence, the sweep efficiency on the fluid being displaced will increase. There was a need to understand the mathematical relationship between changing flow regimes and increased displacement. I tried to find this relationship empirically through the lab tests. The results of how displacement rate affects displacement are shown in graph 5.2. Trend lines marked in Graph 5.2 indicate how displacement efficiency increases with increased turbulence.



Graph 5.2: Displacement efficiency when water is displacing oil in a slick pipe. The vertical axis indicates how much of the oil in the pipes was displaced by water. The horizontal axis indicates how many pipe-volumes of water have been displaced. Numbers next to each point indicates the Reynolds number each displacement had. The three different graphs highlight a trend for the displacement efficiency for different Reynolds numbers. Tests showed higher displacement efficiency when the displacement occurred at turbulent compared to transient flow. Displacement efficiency became even lower when the flow rate decreased further. For detailed presentation of the measurements, or if anything is not visible on the graph, please see the appendix.

Graph 5.2 shows measurements of displacement efficiency through a slick pipe and with water displacement. We see a clear trend indicating that displacement efficiency increases with increased turbulence. Looking at the line of 100% displacement, we see Reynolds numbers indicating when full displacement was reached. When the Reynolds number was high, full displacement of oil occurred at fewer displaced volume units.

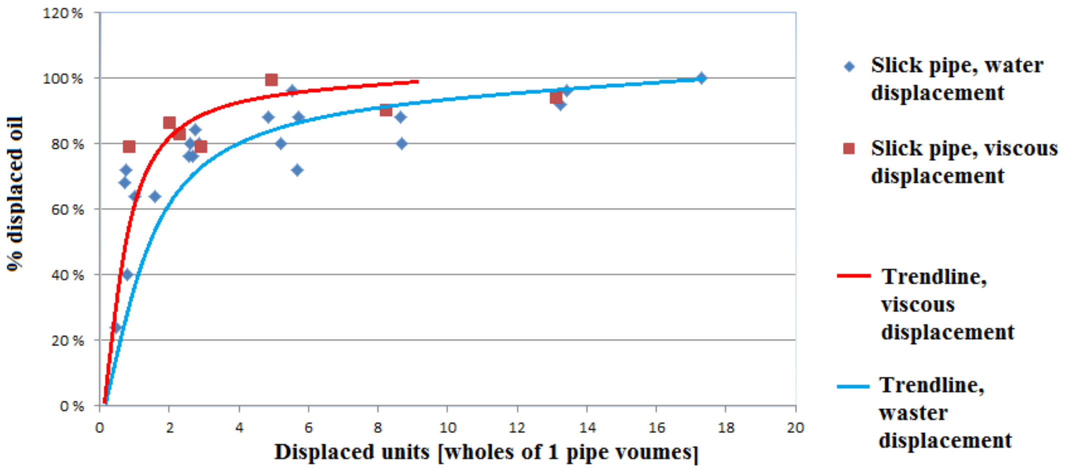
Roughness: Next, the effect of displacing fluids through pipes with different roughness was measured. There was a clear effect of increasing roughness in the pipes. The results are shown in graph 5.3.



Graph 5.3: Measurements of displacement efficiency for three pipes with three different levels of roughness. The x-axis shows how many volume units of the pipe were displaced. And the y-axis shows how much of the oil in the pipes was displaced. All displayed points are for laminar displacement to make comparison of data possible. The effect of roughness on the displacement was very visible. When roughness of pipe increased, so did the displacement efficiency. Local turbulence seems to be created widely when the pipe roughness increases. Only representable data with no calibration mistakes from the pressure tank are included.

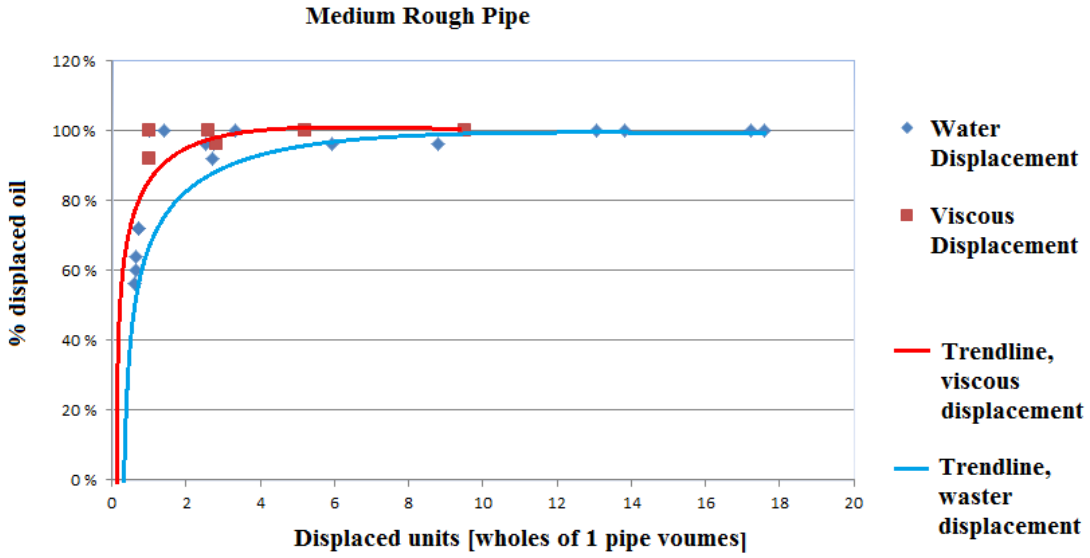
We see from graph 5.3 that roughness also has an effect on the displacement efficiency. Increased roughness creates local turbulence along the walls, and a more evenly distributed displacement profile of the displacing fluid.

Viscosity: Two fluids with two different viscocities were tested for dispalcement efficicency. The results are shown in graph 5.4.



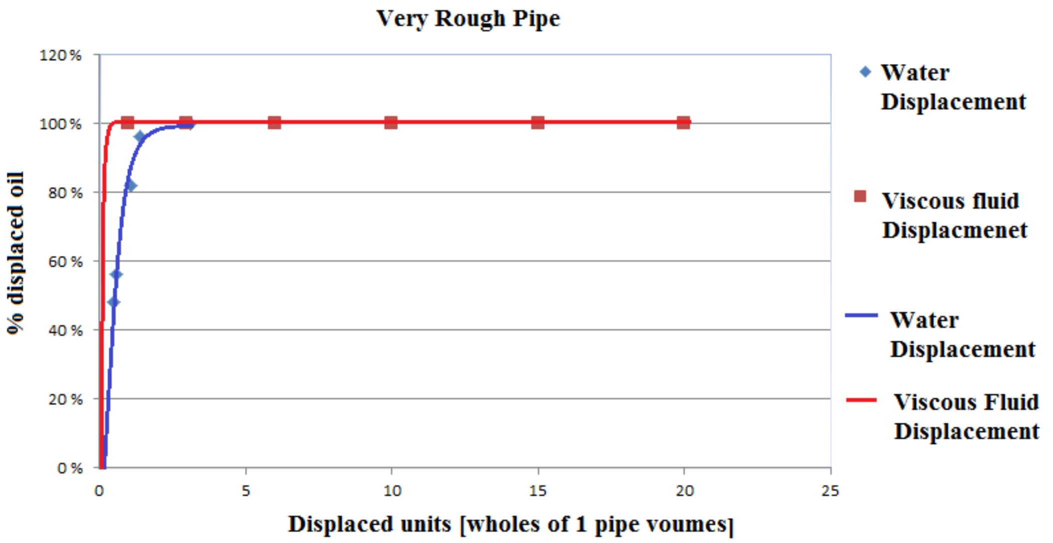
Graph 5.4. Effect of viscosity on displacement rate. Comparison of values for displacement efficiency in a slick pipe. Displacement efficiencies of fluid with high viscosity and fluid with low viscosity are compared. Displacement efficiency increases when the displacement fluid has higher viscosity. The displacement profile changes when viscosity is increased and becomes flatter. This will increase the displacement efficiency. Only measurements with laminar displacement rate are included to make data comparable.

We see in graph 5.4 that there is an effect of viscosity on the displacement efficiency. Increased viscosity increases displacement efficiency. This leads us to assume that the displacement profile of the water and HEC mix becomes flatter and displaces oil more evenly in the pipe. Even though all the measured points shown in graph 5.4 are of laminar flow, there is a difference in Reynolds number. This did to some degree affect the displacement. And we see points of lower displacement efficiency at a higher number of displaced units. This happens because the Reynolds number is slightly lower.



Graph 5.5: Effect of viscosity on displacement rate. Water and 5cP fluid is displacing oil in medium rough pipe. This data is measured and presented to see if there is a difference between displacement efficiencies with different fluids when we are displacing in pipes with different roughness. Only measurements with laminar displacement rate are included to make data comparable. Comparing Graph 5.4 to 5.5, we see that there is an increase in displacement efficiency for both water and viscous fluid displacement when displacing in medium roughness pipes. Increasing both the viscosity of the displacement fluid that creates as well as the pipe roughness that creates local turbulence, we get much higher displacement efficiency.

Measurements were done to see how both increased viscosity and pipe roughness would create greater efficiency in displacement. Displacement efficiency increased for both water displacement and viscous fluid displacement when compared to displacement in slick pipes. During these measurements, displacement was close to 100% with very small amounts of displaced units of fluid. A volume in the pipe compared to real life annulus volume in wells will also affect the displacement efficiency and create a greater sweep in the pipe. If roughness of the pipe is increased further, we get the results shown in Graph 5.6.



Graph 5.6. Water and 5 cP viscous water displacing oil shows 100% displacement efficiency for viscous fluid even with very low displacement volumes. Only values with laminar flow are included to make results comparable. As pipe roughness increases so does displacement efficiency. When the pipe is very rough, and we are displacing with a viscous fluid, the displacement efficiency becomes close to 100% at displacement volumes lower than 1 V. Several measurements done with low displacement rates and only a few displaced units, showed 100% displacement for viscous fluid.

We can see a clear effect from changing the four tested parameters. Increase in displacement rate, displaced volumes, viscosity or roughness all created a higher displacement efficiency.

6. Evaluation of the Results

The model for displacement developed in this project previously assumes no-slip conditions close to the wall. This condition is however not completely valid as local turbulence in the flow along the walls takes place. Tests in the lab supports that there is movement along the walls resulting in increasing displacement efficiency. We have seen that for displacements with the same type of fluid, and the at the same theoretical flow regime, there is higher displacement when the pipe walls become rougher. These findings call for an adjustment of the displacement model.

Adjusting the model

The velocity describing the displacement of cement at the wall has previously been set to 0 m/s. As we can see from the lab analysis, there was a clear improvement in displacement when the walls of the pipes increased in roughness. This happened because local turbulence was being induced. Increased roughness also made the flow switch from laminar to turbulent at a lower Reynolds number than if the wall had been slick. It is now clear that movement along the walls can no longer be described as 0 m/s.

We need to find a factor describing the improvement of movement when all the four analyzed factors are included. The improvement is based on the average improvement when each factor is taken into consideration. The averages are found based on comparisons between the slopes of the trend lines between different factors given by Excel.

Going through each of the analyzed factors:

Higher displacement efficiency caused by displacement rate:

- Compared to laminar flow, transient flow had 14% higher displacement efficiency of oil
- Compared to transient flow, there was on average a 11% higher displacement efficiency with turbulent flow in the displacement.

Higher displacement efficiency caused by increased roughness:

- 15% improvement in displacement when the roughness went from slick to medium rough
- 8% improvement in displacmenet when roughness went from medium rough to very rough

Higher displacement efficiency caused by increased viscosity:

- 10% improvement in displacement for viscous fluid displacing oil compared to water displacing oil in slick pipe
- 6% improvement in displacement for viscous fluid displacing oil compared to water displacing oil in medium rough pipe
- 4% improvement in displacement for viscous fluid displacing oil compared to water displacing oil in rough pipe
-

Higher displacement efficiency caused by increased amounts of displaced volume units:

Displacement at the walls can be described with the three following factors:

- Roughness and non-roughness
- Displacement rate
- Displacement volumes

Including the three factors that affect the displacement profile will iprove the model.

The assumptions made in the formula used in this project are simple but still seem to show a somewhat accurate picture of the displacement process. If the model considers local turbulence and roughness, we get a more accurate displacement efficiency model.

Both the model and data acquisition can stand to be improved. The model can be made more accurate with both reciprocation of casing and local turbulence and roughness of pipes being taken into account. It can be improved to take into account the rheological qualities of the cement and the displaced mud. The assumptions are at the moment quite simple, but not unrealistic. The also seem to be valid for all ranges of casing-formation distance.

If the model includes consideration of casing reciprocation the displacement would be more efficient

The equation used for displacement is normally used in pipe flow, but is here assumed to be valid for flow in the annulus gap. It is fine to use this assumption in simple calculations and for comparative reasons, but in a more advanced model, the equations for pipe flow should be improved to be used for flow in the annulus.

The slightly improved model described through formula 6.1:

$$L_{front} = \left(V_o + V(r)\right) * t \qquad (6.1)$$

telling us that the length of the displacement front, L_d varies with both radius r, and time t and are a function of both the radial velocity V, as well as the velocity, V_o, created along the walls by local turbulence. The model also does not take into account reciprocation or rotation of casing occurs. The formula does not take into account the effect of viscosity on Reynolds number when the flow shifts from laminar to turbulent.

Rotation and reciprocation of casing has something to say on the movement of the front, and should be included by for example stating that turbulent flow is reached at a lower Reynolds' number. Including the factors describing the displacement along the walls will improve the displacement by making the displacement profile more evenly distributed in the pipe. This is shown in figure 6.1.

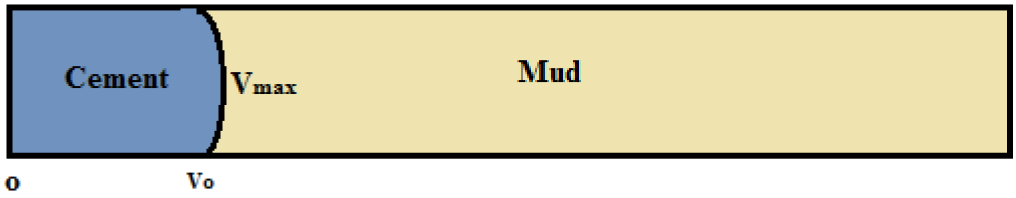


Figure 6.1: Model of displacement when the local turbulence is taken into account. Cement quality will improve since there is movement along the walls of the pipe making the displacement profile move evenly distributed in the pipe.

When local turbulence creates movement along the pipe walls, the entire velocity profile becomes more evenly distributed in the pipe. The displacement profile becomes flatter when local turbulence is included.

Improvement in the lab:

- More presise pressure tank; there were to high fluctuations in the pressure at times
- Larger diameter pipes for displacement of fluids to create a

7. Discussion

Lab analysis showed a presence of local turbulence in the displacement process. There was an improvement in displacement efficiency when local turbulence was induced through in each test through wall roughness. A discussion on the reliability of the simulated data, lab data and the model follows.

Quality of simulated data and lab data

Simulated data gave an accurate picture of displacement shown through lab analysis. They showed the displacement of water inside the pipe both when local turbulence was taken into account and when it was not. The local turbulence used in the simulations was an assumed value. We thought that through lab analysis, it would be easy to find the exact value for local turbulence at different displacement velocities. This did however show to be more complex than first assumed. Local turbulence varied with roughness, displacement velocities and viscosity of the displacement fluid. And all these three factors differ for different displacements.

Quality of the model

This thesis has shown a clear effect of local turbulence on the displacement profile. Describing the movement along the walls was difficult to describe with an exact number. There need to be conducted an even larger number of tests to help us empirically determine the exact profile of the displacement and how this is affected by the local turbulence. If the three factors roughness, displacement velocity and viscosity of the displacement fluid can be determined accurately before every displacement, the model can be developed for a specific displacement process.

Potential in improvement

There are more than four factors which could be analyzed when trying to find what induces the most local turbulence. In the Campos Basin in Brazil, 155 wells have been drilled and evaluated. (Silva, 1996) 33 parameters were investigated and it was found that among other things well geometry, drilling fluid and cement properties, contact time, displacement energies and centralizer positioning which will contribute to the effect on the cement jobs. These also contribute to the displacement of the cement profile, but have however not been included in this thesis. What had the most effect on the final result of the cementing operation were the inclination and caliper of the well, the centralizer positioning, rheological properties and gel strengths of fluids used in the drilling and conditioning of the well, rheological properties of the slurry and volumes and contact times of the fluids displaced, annular velocity and displacement regime (Silva, 1996). This suggests that we need caliper logs and precise inclination of the wells to indicate how well the cement job is done. There are numerous other examples of factors which could be investigated to improve the model, but here we have tried and create a simple understanding of how the boundary layer affects the flow of cement.

8. Conclusion

Both the simulations and lab tests that were conducted in this project suggest a strong dependence between flow regime and displacement efficiency. Higher displacement rate created higher displacement efficiency, as presented in chapter 5. This happens because a more turbulent flow will cause the displacement profile of the fluid to be more evenly distributed in the pipe. Rough walls will cause the flow to turn from laminar to turbulent at a lower Reynolds number and also give local turbulence along the walls. Increased pipe roughness and local turbulence will contribute to the cement front moving faster and becoming more even. When local turbulence occurs, the cement quality improves.

The displacement profile was also clearly affected by amounts of displaced volume, viscosity of displacement fluid and wall roughness in the pipes. The more volume being displaced through the pipes, the better the displacement became. Increased viscosity improved the displacement efficiency as well. And increasing roughness increased the displacement greatly.

Understanding of the local turbulence along the wall needs to be further investigated to understand the eddy currents that occur here and how they improve the displacement velocity. It is not practical in the field to displace large amounts of cement to get good displacement efficiency. In further research, there should be a focus on how wall roughness affects the displacement profile. Using casings and drill pipes with increased roughens in the field can help us see if it has the same effect on displacement like the one we have seen in the lab. If the effect in the field shows improved cement displacement efficiency with a more evenly distributed displacement profile of cement, it would make the zonal isolation better. The costs of the cementation of wells would be greatly reduced.

9. Nomenclature

Define symbols + abbreviations alphabetically. Do not repeat symbols in the text at every equation

ρ, density, $\frac{kg}{m^3}$

v, velocity , $\frac{m}{s}$

d, diameter, m

viscosity, μ, cP

yield stress, τ

R_o outer radii of the annulus

R_i inner radii of the annulus

δ_v viscous sublayer

e diameter of the grains creating the roughness

L Length m

F_I Forces from inertia

F_v Forces from viscosity

x: position of the center of the front [m]

V_{max}: Velocity at the center of the displacement profile [m/s]

t: time [s]

L_{front}: position of the front [m]

r: point on the displacement front away from the walls [m]

10. Abbreviations

ECD- Equivalent Circulating Density

USIT: Ultra Sonic Imaging Tool

CBL: Cement Bond Log

DBR: Daily Boring Report

MD: Measured Depth

TOC: Top Of Cement

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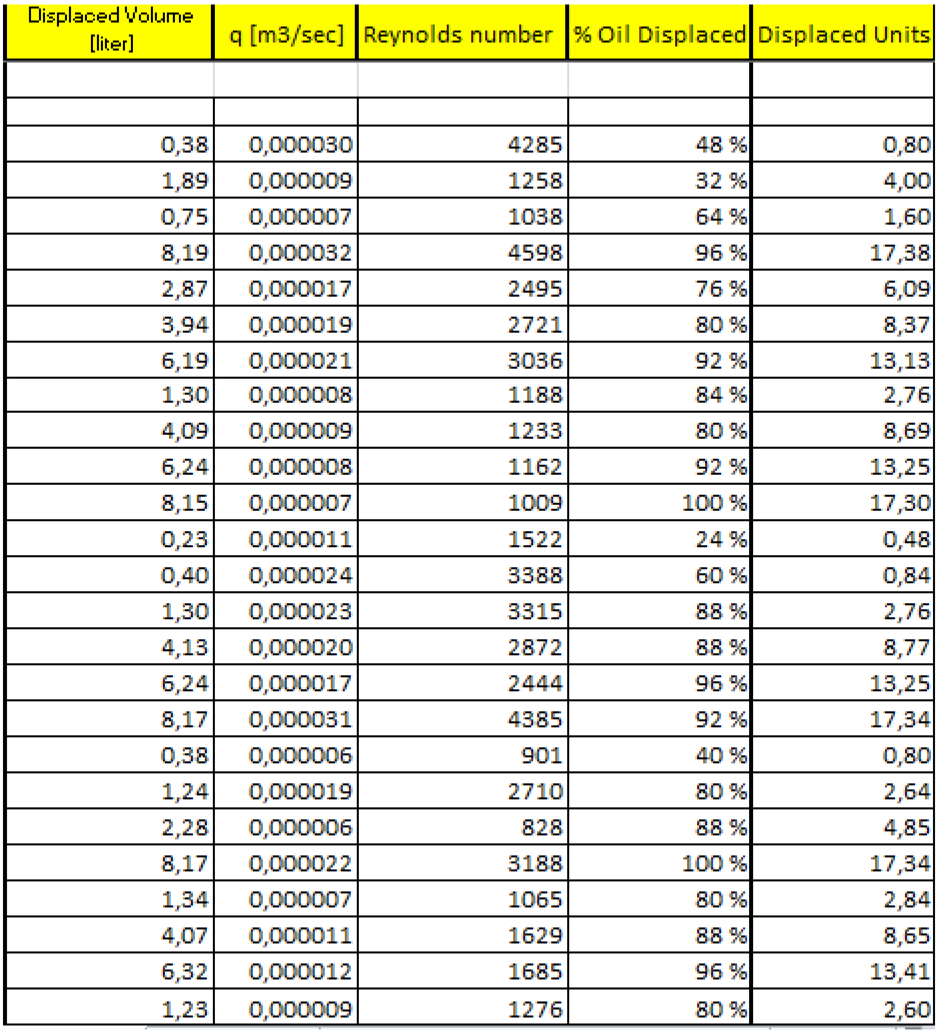
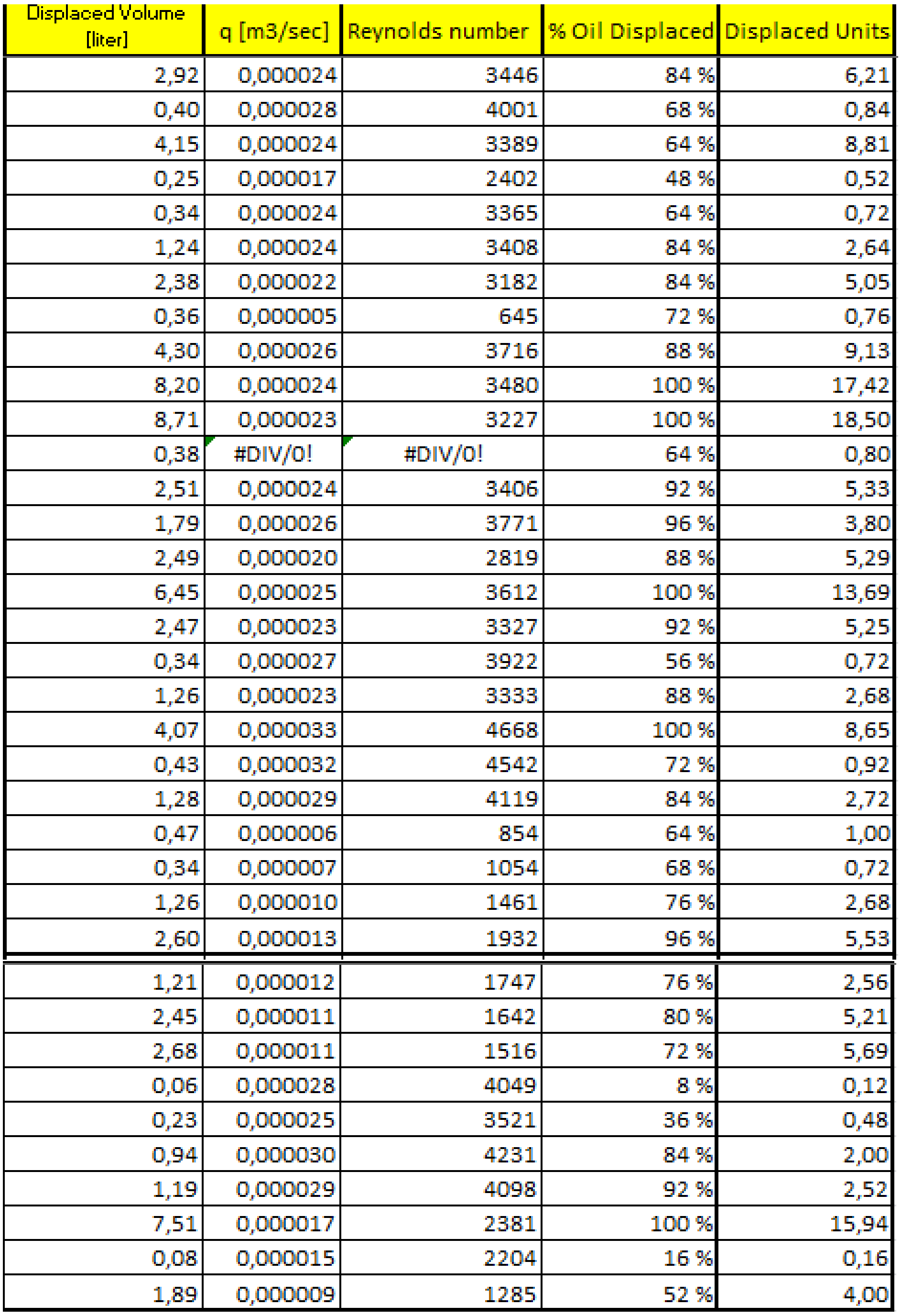
12. Appendix

1. Two tables showing Lab Measurements of Water displacing Oil in Slick Pipe

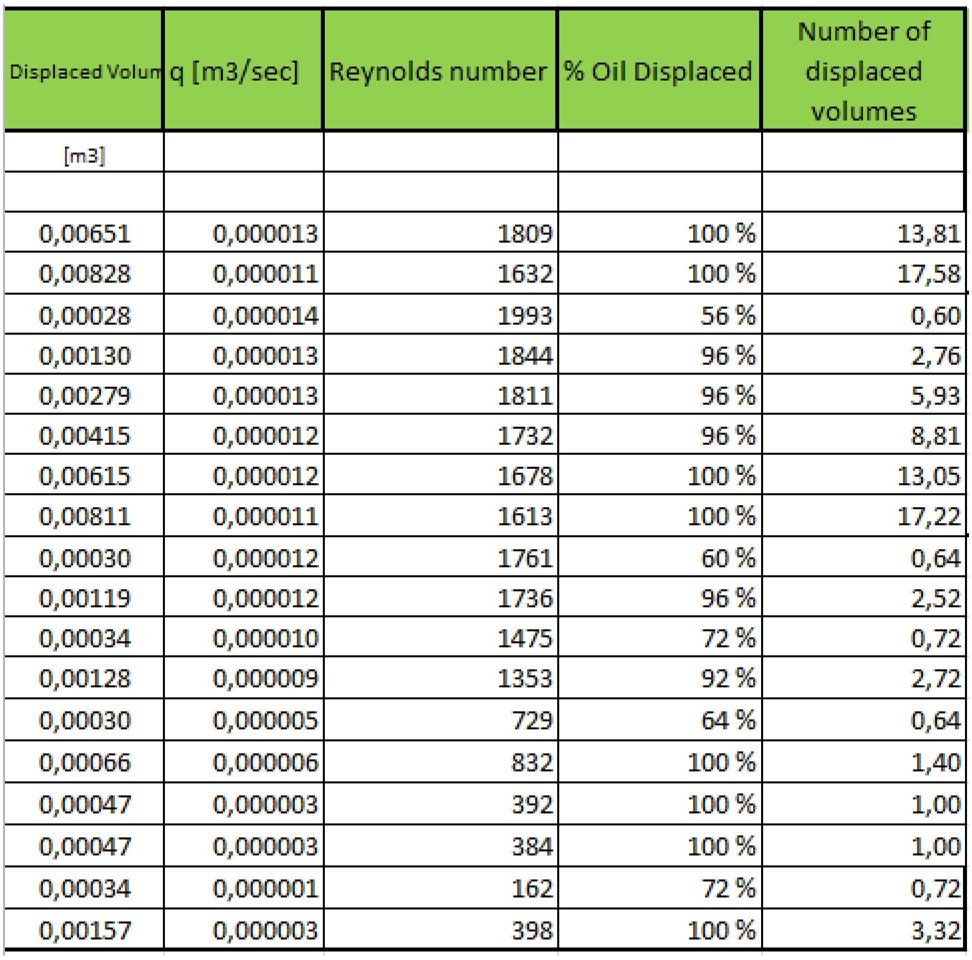


Displaced Volume [liter]	q [m3/sec]	Reynolds number	% Oil Displaced	Displaced Units
0,38	0,000030	4285	48 %	0,80
1,89	0,000009	1258	32 %	4,00
0,75	0,000007	1038	64 %	1,60
8,19	0,000032	4598	96 %	17,38
2,87	0,000017	2495	76 %	6,09
3,94	0,000019	2721	80 %	8,37
6,19	0,000021	3036	92 %	13,13
1,30	0,000008	1188	84 %	2,76
4,09	0,000009	1233	80 %	8,69
6,24	0,000008	1162	92 %	13,25
8,15	0,000007	1009	100 %	17,30
0,23	0,000011	1522	24 %	0,48
0,40	0,000024	3388	60 %	0,84
1,30	0,000023	3315	88 %	2,76
4,13	0,000020	2872	88 %	8,77
6,24	0,000017	2444	96 %	13,25
8,17	0,000031	4385	92 %	17,34
0,38	0,000006	901	40 %	0,80
1,24	0,000019	2710	80 %	2,64
2,28	0,000006	828	88 %	4,85
8,17	0,000022	3188	100 %	17,34
1,34	0,000007	1065	80 %	2,84
4,07	0,000011	1629	88 %	8,65
6,32	0,000012	1685	96 %	13,41
1,23	0,000009	1276	80 %	2,60



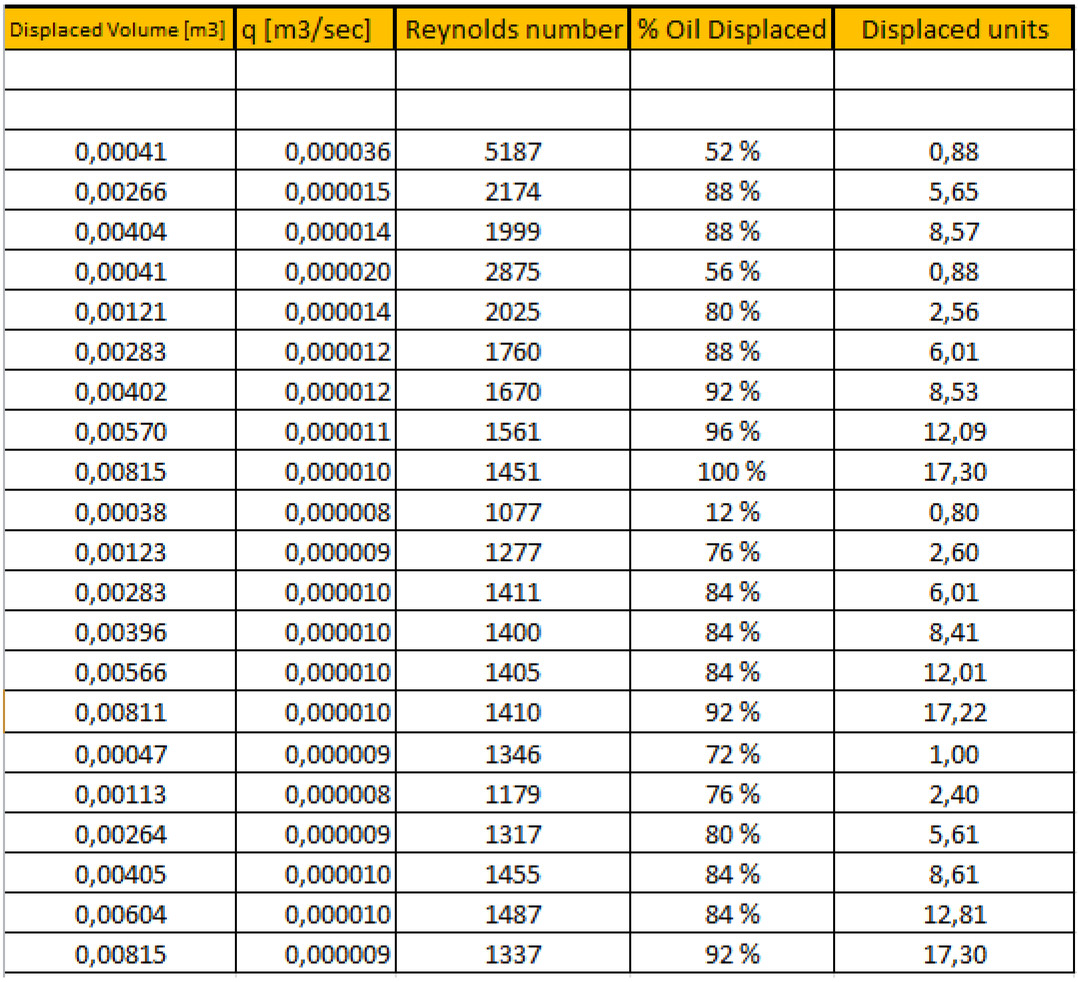
Displaced Volume [liter]	q [m3/sec]	Reynolds number	% Oil Displaced	Displaced Units
2,92	0,000024	3446	84 %	6,21
0,40	0,000028	4001	68 %	0,84
4,15	0,000024	3389	64 %	8,81
0,25	0,000017	2402	48 %	0,52
0,34	0,000024	3365	64 %	0,72
1,24	0,000024	3408	84 %	2,64
2,38	0,000022	3182	84 %	5,05
0,36	0,000005	645	72 %	0,76
4,30	0,000026	3716	88 %	9,13
8,20	0,000024	3480	100 %	17,42
8,71	0,000023	3227	100 %	18,50
0,38	#DIV/0!	#DIV/0!	64 %	0,80
2,51	0,000024	3406	92 %	5,33
1,79	0,000026	3771	96 %	3,80
2,49	0,000020	2819	88 %	5,29
6,45	0,000025	3612	100 %	13,69
2,47	0,000023	3327	92 %	5,25
0,34	0,000027	3922	56 %	0,72
1,26	0,000023	3333	88 %	2,68
4,07	0,000033	4668	100 %	8,65
0,43	0,000032	4542	72 %	0,92
1,28	0,000029	4119	84 %	2,72
0,47	0,000006	854	64 %	1,00
0,34	0,000007	1054	68 %	0,72
1,26	0,000010	1461	76 %	2,68
2,60	0,000013	1932	96 %	5,53
1,21	0,000012	1747	76 %	2,56
2,45	0,000011	1642	80 %	5,21
2,68	0,000011	1516	72 %	5,69
0,06	0,000028	4049	8 %	0,12
0,23	0,000025	3521	36 %	0,48
0,94	0,000030	4231	84 %	2,00
1,19	0,000029	4098	92 %	2,52
7,51	0,000017	2381	100 %	15,94
0,08	0,000015	2204	16 %	0,16
1,89	0,000009	1285	52 %	4,00

2. Medium rough pipe, Water displacement



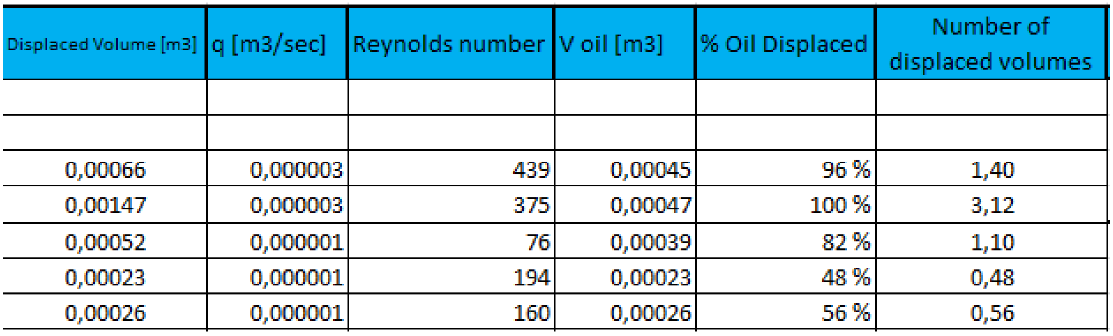
Displaced Volum	q [m3/sec]	Reynolds number	% Oil Displaced	Number of displaced volumes
[m3]				
0,00651	0,000013	1809	100 %	13,81
0,00828	0,000011	1632	100 %	17,58
0,00028	0,000014	1993	56 %	0,60
0,00130	0,000013	1844	96 %	2,76
0,00279	0,000013	1811	96 %	5,93
0,00415	0,000012	1732	96 %	8,81
0,00615	0,000012	1678	100 %	13,05
0,00811	0,000011	1613	100 %	17,22
0,00030	0,000012	1761	60 %	0,64
0,00119	0,000012	1736	96 %	2,52
0,00034	0,000010	1475	72 %	0,72
0,00128	0,000009	1353	92 %	2,72
0,00030	0,000005	729	64 %	0,64
0,00066	0,000006	832	100 %	1,40
0,00047	0,000003	392	100 %	1,00
0,00047	0,000003	384	100 %	1,00
0,00034	0,000001	162	72 %	0,72
0,00157	0,000003	398	100 %	3,32

3. Tests when the pipe was not re-filled after every attempt



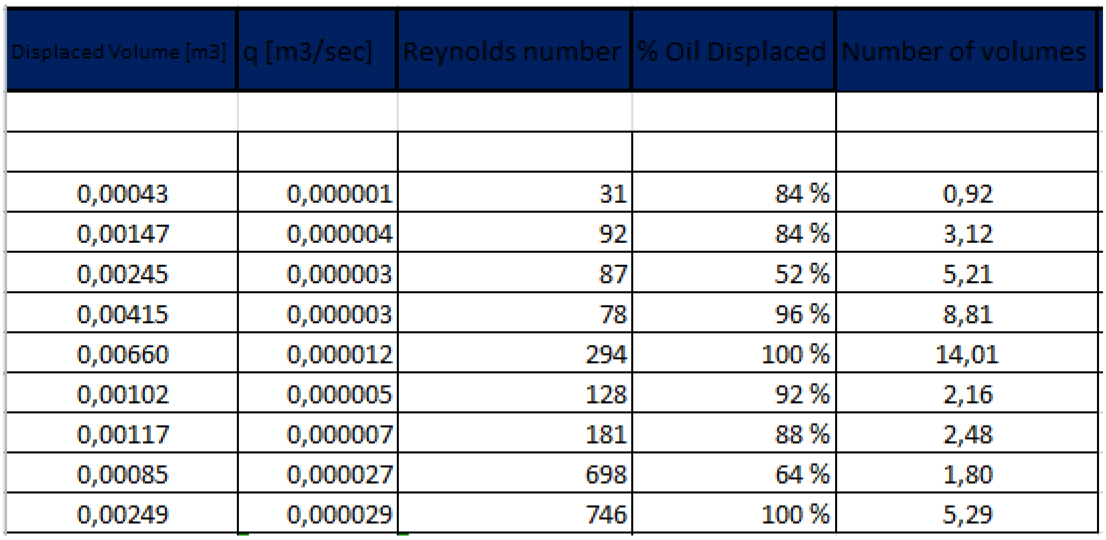
Displaced Volume [m3]	q [m3/sec]	Reynolds number	% Oil Displaced	Displaced units
0,00041	0,000036	5187	52 %	0,88
0,00266	0,000015	2174	88 %	5,65
0,00404	0,000014	1999	88 %	8,57
0,00041	0,000020	2875	56 %	0,88
0,00121	0,000014	2025	80 %	2,56
0,00283	0,000012	1760	88 %	6,01
0,00402	0,000012	1670	92 %	8,53
0,00570	0,000011	1561	96 %	12,09
0,00815	0,000010	1451	100 %	17,30
0,00038	0,000008	1077	12 %	0,80
0,00123	0,000009	1277	76 %	2,60
0,00283	0,000010	1411	84 %	6,01
0,00396	0,000010	1400	84 %	8,41
0,00566	0,000010	1405	84 %	12,01
0,00811	0,000010	1410	92 %	17,22
0,00047	0,000009	1346	72 %	1,00
0,00113	0,000008	1179	76 %	2,40
0,00264	0,000009	1317	80 %	5,61
0,00405	0,000010	1455	84 %	8,61
0,00604	0,000010	1487	84 %	12,81
0,00815	0,000009	1337	92 %	17,30

4. Very Rough pipe, water displacement (the analysis included in the graphs)



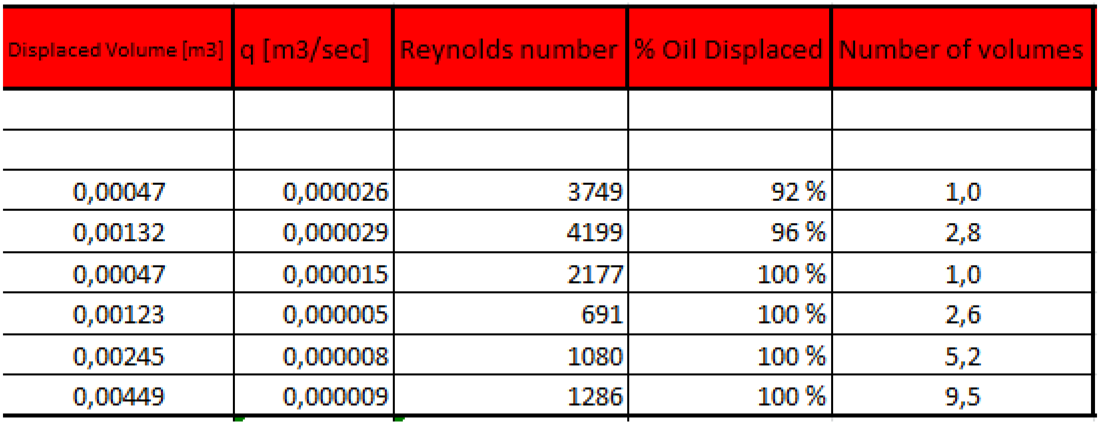
Displaced Volume [m3]	q [m3/sec]	Reynolds number	V oil [m3]	% Oil Displaced	Number of displaced volumes
0,00066	0,000003	439	0,00045	96 %	1,40
0,00147	0,000003	375	0,00047	100 %	3,12
0,00052	0,000001	76	0,00039	82 %	1,10
0,00023	0,000001	194	0,00023	48 %	0,48
0,00026	0,000001	160	0,00026	56 %	0,56

5. Slick pipe, Viscous displacement (the analysis included in the graphs)



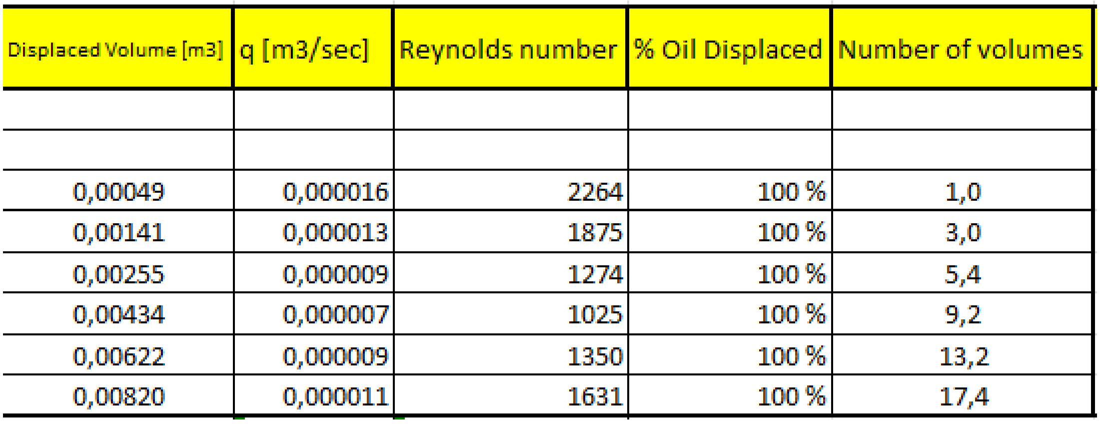
Displaced Volume [m3]	q [m3/sec]	Reynolds number	% Oil Displaced	Number of volumes
0,00043	0,000001	31	84 %	0,92
0,00147	0,000004	92	84 %	3,12
0,00245	0,000003	87	52 %	5,21
0,00415	0,000003	78	96 %	8,81
0,00660	0,000012	294	100 %	14,01
0,00102	0,000005	128	92 %	2,16
0,00117	0,000007	181	88 %	2,48
0,00085	0,000027	698	64 %	1,80
0,00249	0,000029	746	100 %	5,29

6. Medium rough pipe, viscous displacement (the analysis included in the graphs)



Displaced Volume [m3]	q [m3/sec]	Reynolds number	% Oil Displaced	Number of volumes
0,00047	0,000026	3749	92 %	1,0
0,00132	0,000029	4199	96 %	2,8
0,00047	0,000015	2177	100 %	1,0
0,00123	0,000005	691	100 %	2,6
0,00245	0,000008	1080	100 %	5,2
0,00449	0,000009	1286	100 %	9,5

7. Very Rough pipe, viscous displacement (the analysis included in the graphs)



Displaced Volume [m3]	q [m3/sec]	Reynolds number	% Oil Displaced	Number of volumes
0,00049	0,000016	2264	100 %	1,0
0,00141	0,000013	1875	100 %	3,0
0,00255	0,000009	1274	100 %	5,4
0,00434	0,000007	1025	100 %	9,2
0,00622	0,000009	1350	100 %	13,2
0,00820	0,000011	1631	100 %	17,4