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An Experimental Investigation of Density-Unstable Displacement in a Vertical Annulus with Relevance to “Reverse Heavy Over Light” Cementing Technology

by

Camilla Natalié Bjørnsen

Thesis submitted in fulfillment of the requirements for the degree of Master

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Abstract

Primary cementing of casing is considered a critical and complex well operation. During the operating, the drilling fluid is displaced by pumping a fluid train of washer, spacer, and cement slurry into the well. The aim is to fully displace the drilling fluid without contaminating the cement slurry or leaving residual drilling fluid behind. The hardened cement acts as a well barrier and should provide structural support for the casing, meaning that an effective and complete displacement is crucial for the whole life of the well. Studies show that reverse circulation method used for cementing has some advantages. The method is for example used when cementing over weak formation where a lower circulation pressure is needed. When using reverse circulation method, the fluid train is pumped directly into annulus placing the heavy fluid over the lighter drilling fluid. No experimental research of such density-unstable displacement in annulus has been executed so far. The effect of density differences, flow and eccentricity on the displacement process is yet unknown. This knowledge gap needs to be addressed in order to enable more reliable primary reverse cementing operations, especially in offshore wells.

We present an experimental study of density-unstable displacement of Newtonian fluid in an annular space. The focus is on the effect of density difference and flow rate. In an experimental setup, heavy displacement fluid is placed above a lighter displaced fluid inside a pipe using a valve separating the two fluids. The density difference is achieved by using NaCl as weighting agent in the heavy fluid, and the flow rate is adjusted by opening an outlet valve. In several runs, At of 0.0035 and 0.01, and velocities of 0, 10, and 20 mm/s are combined. For all experimental runs, mixing of fluid, transverse and backflow is seen. The level of such instabilities and counter-current flow is found to be dependent on both density difference and flow velocity. For the displacement of zero velocity, an increase of At seems to results in a more effective displacement with less mixing of the two fluids. This effect is also seen in displacement with velocity = 10 mm/s, but the effect is less prominent. For velocity = 20 mm/s, the change in density difference has no or little effect and the flow velocity becomes dominant. With an increase in velocity, the level of transverse flow and backflow seems to decrease. As the velocity increases the downward flow becomes more dominant and interrupts the rising of light fluid. This results in a more efficient displacement where more of the displaced fluid is pushed downwards in the pipe.
Acknowledgement

This thesis is a result of collaboration and contributions of many people. With this I would like to show my gratitude to all involved persons for all help, support and ideas received during the work on this Master Thesis.

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Abbreviations

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<th>Description</th>
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<tr>
<td>ECD</td>
<td>Effective circulation density</td>
</tr>
<tr>
<td>HOL</td>
<td>Heavy over light</td>
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<td>R-T</td>
<td>Rayleigh-Taylor</td>
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Nomenclature

A  Correctional areal  \( \beta \)  Inclination relative to vertical  
At  Atwood number  \( \varepsilon_H \)  Volume fraction of heavy fluid  
D  Diameter of pipe  \( \varepsilon_L \)  Volume fraction of light fluid  
Di  Diffusion coefficient  \( \vec{t}_y \)  Directional vector  
f_1, f_2  Correction term  \( \rho \)  Density of fluid  
Fr  Froude number  \( \rho_H \)  Density of heavy fluid  
g  Gravitational constant  \( \rho_L \)  Density of light fluid  
h  Height of fluid column  \( \tau \)  Shear stress  
ID  Inner diameter  \( \mu \)  Viscosity of fluid  
KA, KB  Density meter apparatus constants  \( \gamma \)  Shear rate  
L  Length  \( \nabla \)  Vector operator  
m  Mass  
OD  Outer diameter  
P, p  Pressure  
Pe  Péclet number  
Q  Flow rate  
Q_d  Quotient used in density meter  
Re  Reynolds number  
T, t  Time  
U  Velocity of fluid  
v  Velocity of fluid  
V  Volume of mass  
w  Weight
Chapter 1

1 Introduction

1.1 Background

In the oil and gas industry, primary cementing of casing is considered a critical and complex well operation where the annular space between the casing and wellbore is filled with cement slurry. The objective of the operation is to ensure zonal isolation preventing leakage to the surface, to seal the well, and to provide structural support for the casing.

During the cementing operation, a sequence of spacer and cement slurry are pumped into the well either through the casing or directly into the annulus. The aim is to place the cement slurry in the annular space without contaminating the cement slurry while avoiding residual drilling fluid. Effective and complete displacement of drilling fluid prior to cementing is considered essential to ensure a successful cementing operation. Incomplete displacement or highly mixed fluids can result in channelling and degradation of the cement. Different drilling fluids have different rheology, densities, and viscosities, and will therefore behave differently when displaced. Consequently, the properties of the displacement fluid as well as the flow rate used, need to be carefully designed during the operational planning. For the cementing operation, a steady displacement is desirable as it ensures continuous and complete displacement around the entire annulus (Pelipenko & Frigaard, 2004). A steady displacement reduces mixing of the two fluids, and avoids residual drilling fluid in the annulus and prevents mud channelling in the hardened cement.

In addition to be governed by fluid rheology, the fluid displacement is influenced by the well geometry. The annular eccentricity and irregularities such as casing collars, casing centralizers and borehole washouts can influence the displacement both locally and over a greater distance (Smith, 1987). The effect of such irregularities in the annular space is poorly understood and needs to be studied further.

Likewise, the cementing method used (conventional or reverse circulation) and the fluid arrangement will affect the cementing operation. Previous research has shown that reverse cementing has some advantages compared to conventional circulation cementing. A lower
circulation pressure allows for a denser cement slurry across weak and depleted formations, a higher flowrate used, and a larger cement height (Kuru & Seatter, 2005). Additionally, reverse cementing is needed when cementing a week zone in several steps. Here the annulus height up to the week zone is first cemented by conventional circulation. After the cement is hardened, reverse circulation is used to cement off the week loss zones. Furthermore, due to less time required for reverse circulation cementing, the use of less retarders will result in an improved compressible strength of the hardened cement. On the other hand, the reverse circulation method results in a density-unstable heavy over light (HOL) fluid arrangement, where the heavier spacer and cement slurry are placed on top of the lighter drilling fluid. In such fluid interfaces fluid instabilities and fluid mixing can be observed.

Up till now there has been several investigations, both theoretically and experimentally, of the conventional circulating displacement where the denser fluid displaces the lighter fluid in a density stable arrangement (see for example Etrati & Frigaard, 2019; Jakobsen et al., 1991; Malekmohammadi, Carasco-Teja, Storey, Frigaard, & Martinez, 2010; Skadsem & Kragset, 2019; Taghavi, Alba, & Frigaard, 2012; Taghavi, Alba, Moyers-Gonzalez, & Frigaard, 2012). However, there is a lack of knowledge of reverse circulation displacements where the fluid arrangement is HOL (density-unstable), especially in annular geometries. Only a few researchers has addressed this topic, but then in pipe geometries (see Alba, Taghavi, & Frigaard, 2013). In order to enable more reliable primary reverse circulation cementing operation, especially in offshore wells, this knowledge gap needs to be addressed. Some areas that needs to be investigated are the effects of annulus eccentricity, density and viscosity ratio, and induced flow velocity. The focus in this thesis is to experimentally study the effect of density ratio and flow velocity.

### 1.2 Statement of Problem

A better understanding of the unstable heavy over light (HOL) fluid arrangement is needed to ensure a reliable and widely used reverse circulation cementing method for primary cementing. The knowledge gap that currently exists around this technology is a barrier to the method becoming an optimized cementing process. Ultimately, this thesis aims to continue bridging this gap by further investigation and to help improving the design of reverse circulation primary cementing.
1.3 Objectives
The main purpose of this thesis is to investigate the effect of fluid properties and flow rate and in reverse cementing where the fluid arrangement is density-unstable. The objectives for the investigation are listed below:

- Study the effect of density difference and flow rate on the annular displacement.
- Show what type of instabilities can be observed when reverse cementing.
- If there under any conditions exists a steadier displacement pattern.
- Whether a heavy over light (unstable) fluid arrangement results in issues with settlement of the heavier fluid and viscous fingering resulting in an unsteady displacement.

1.4 Limitation
This study is limited to density-unstable displacements of Newtonian fluids. The fluids are miscible and has constant low viscosity. The flow regime studied are laminar and the flow is induced by gravity. Secondary cementing, displacement involving immiscible fluids such as oil and water, non-Newtonian fluids, high viscosity fluids or turbulent flow regimes are not included in this study.

1.5 Approach
For this thesis, both literature and experimental studies was performed to investigate different aspects of fluid displacement in the annulus space. Comparison and discussion of findings are based on earlier research and experimental results obtained during the work with this thesis.

1.6 Structure of Thesis
Chapter 1 gives an introduction to this thesis, its background, objectives, limitations, approach and structure. Chapter 2 is the theoretical result of the literature review, which identifies well geometry, cementing technique, fluid rheology, displacement processes, as well as governing equation and dimensionless numbers. Chapter 3 presents the results from earlier studies of unstable heavy over light fluid displacement. Chapter 4, is a detailed methodology of the experiments performed and will show the method used and the experimental setup. The result of the experimental work and a discussion of these is presented in Chapter 5. Chapter 6 provides a conclusion of the results and findings and includes a recommendation of further work. References and the previous work that this thesis builds on, follows in chapter 7.
2 Theory

The problem of insufficient primary cementing of casing to isolate production zones and prevent leakage is still one of the most critical problems in the industry (Etrati & Frigaard, 2019). There are problems with insufficient displacement, channelling and degradation of cement. Drilling fluid contains additives and materials that can contaminate the cement slurry leading to a reduction in cement strength. A thick filter cake can result in cement channelling and insufficient displacement can lead to improper cement jobs. Consequently, the degradation of cement can result in remedial action, abandonment and environmental leakage. Although such remedial action is available, they add risk and cost to the planned operation. Hence, the need for effective mud removal and steady fluid displacement from the annular space prior to cementing is important. Also, a wider and better understanding of the fluid mechanism in both conventional and reverse displacement prior to cementing is needed.

2.1 Well Design

Primary cementing is a big part of the well design. After each hole section is drilled, a casing is run and cemented in place. As drilling occurs deeper into the well, the hole- and casing sizes decrease and the casing is cemented in place inside the previous hole section. This leaves a space of \( \approx 2 \) cm between the outside of the casing and the inside of the wellbore, as shown in Figure 2.1. This area between the liner and casing, casing and casing, or casing and formation is called annulus. During drilling the annulus is used for circulation of drilling fluid and to accessing the well. Prior to drilling the next open hole section, the annular space should be cemented to provide structure support and to seal off the well. This process can be done either through the casing or the annulus. The two techniques are called conventional and reverse cementing and will be further discussed in the next section.
2.1.1 Cementing Techniques

Primary cementing of the casing or liner involves displacing the drilling fluid from the annular space and replacing it with cement slurry. This is done for several reasons; provide support for the well, seal off the formation and isolate production zones (Dowell, 1984). Flow between formations should be restricted and the cement will act as a well barrier element providing integrity to the lower part of the well. It is important that the cementing operation is done properly and that the hardened cement is of sufficient strength, holding no flow potential.

Two cementing techniques are used today; conventional circulating cementing and reverse circulation cementing (Smith, 1987). The most commonly used method is conventional circulation cementing where a train of washes, spacer, and cement slurry are pumped down the well inside the casing and then returned up the annulus (shown in Figure 2.2a). Normally, the spacer fluid is designed to be denser than the drilling fluid, and the cement slurry is denser than the spacer fluid. Wiper plugs are normally used to physically separate the fluids on the way down inside the casing, as otherwise we would have a heavy-over-light situation inside the casing. A more complex cementing technique is the reverse circulation cementing. Here, the cement train is pumped directly down the annulus displacing the mud up inside the casing (Figure 2.2b). This order of fluid train being pumped down the annulus will result in a negative density ratio with the heavy fluid above the light fluid inside the annulus.
Several studies discuss the benefits and disadvantages of reverse cementing. Kuru and Seatter (2005) and Moore, Bour, Reed, and Hernandez (2003) state that the method allows for a wider use of cement slurry due to a lower equivalent circulation density (ECD) seen at the casing shoe. Thus, the reverse circulation can be used when it is impossible to pump the cement slurry in sufficient flow rate down the casing without breaking the weak formation zones above the shoe. The lower ECD again allows for a heavier and more retarded cement to be used resulting in a higher strength of the hardened cement. Griffith, Nix, and Boe (1993) found that reverse circulation has the same mud displacement efficiency as conventional. Bogaerts, Gubanov, Dooply, Pringuey, and Sulama (2014) state that reverse cementing could take advantage of the reverse density and viscosity hierarchies, compared to conventional circulation, to minimize the cement contamination. On the other hand, there are challenges regarding detecting the end of the displacement period until required volume is placed. Also, challenges are seen when optimizing the design and placement because no mechanical placement control is available.

2.1.2 Wellbore Eccentricity

When a casing is cemented in place it is usually not placed perfectly in the centre of the wellbore. When the casing is placed closer to one side of the hole than the other, the annular space is called eccentric. The offset between the centre of the hole and the casing is often characterized by eccentricity or standoff. The percentage of standoff can vary; a 100% standoff means a perfectly centred pipe, while a standoff of 0% means that the casing is in contact with the wellbore. Different situations are illustrated in Figure 2.3.
When evaluating the displacement of fluids in a wellbore, the eccentricity needs to be considered. Flow in an eccentric annulus will not be uniform and the displacement fluid will follow the path of least resistance (Smith, 1987). Meaning that when the standoff is such that there is a considerable difference in the annulus space, the fluid will follow the widest part. The mud in the narrower part can then be bypassed leaving the displacement profile as shown in Figure 2.4 (Skadsem, Kragset, & Sørbo, 2019). Also, the percentage of standoff will affect the critical flowrate needed to ensure sufficient flow in the narrow part of the annulus.
2.2 Fluid Properties

2.2.1 Density
Density ($\rho$) is a measure of mass (m) per unit of volume (V) and can be used to compare the weight of a given volume of two substances. Objects with the same volume, but different mass will have different densities. A fluid of high density has a higher number of mass per unit than a lighter fluid and thus have a higher weight per unit. For example, drilling mud typically has a density of 1300 to 1500 kg/m$^3$ and is lighter than cement slurry with approximately 1700 to 1950 kg/m$^3$. The relation between mass and volume are given:

$$\rho = \frac{m}{V}$$  \hspace{1cm} (2.1)

Further, specific weight is defined as the weight per unit of volume. The weight will depend on the density of the and the gravitational force (g) acting on it. In fluid settlement, gravity plays a big role. The gravitational force acts on the mass of higher density and forces this to be positioned below the fluid of lower density. According to Newton’s second law, the relation between the mass density and the weight (w) is:

$$w = \rho * g$$  \hspace{1cm} (2.2)

2.2.2 Density of water vs. temperature and salinity
The density of water varies with temperature changes (see Table 2.1). The density is highest at 4°C with decreasing density on either side of the temperature scale (Shapley, 2001). The fluid of higher temperatures holds higher kinetic energy and has more vibration of the molecules, which leads to a larger volume. This gives a lower density seen in formula 2.1. In addition, water density depends on salinity. The density increases with an increasing salinity, therefore salt can be used as a weighting agent in water solutions (Figure 2.5).

This knowledge can be used to create water with different densities. For example, in a container the fluid of the lowest temperature tends to be positioned below the fluid of the higher temperature.
Table 2.1 Density of liquid water of different temperatures (Shapley, 2001)

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Density (kg/m³)</th>
</tr>
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<tbody>
<tr>
<td>25</td>
<td>997.0479</td>
</tr>
<tr>
<td>22</td>
<td>997.7735</td>
</tr>
<tr>
<td>20</td>
<td>998.2071</td>
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<td>10</td>
<td>999.7026</td>
</tr>
<tr>
<td>4</td>
<td>999.9720</td>
</tr>
<tr>
<td>0</td>
<td>999.8395</td>
</tr>
</tbody>
</table>

Figure 2.5 Water density dependence on temperature and salinity

2.2.3 Viscosity

Viscosity is a measure of a fluid’s resistance to flow and describes the internal friction of the moving fluid. Viscosity (μ) is defined by the ratio between shear stress (τ) and the shear rate (γ):

\[ \mu = \frac{\tau}{\gamma} \]  

(2.3)
The viscous force will affect the flow of the fluid. If an object moves inside the fluid, the object will be exposed to this viscous force. Larger viscosity means greater force acting on the object. This effect is also seen in flow of the fluid. When pumping fluid at constant pressure, the liquid of higher viscosity has the lowest flow rate due to higher internal force. For example, honey with high viscosity flows slowly and water with low viscosity flows easily. Consequently, water is easier displaced than honey.

2.2.4 Density hierarchy
The density hierarchy describes the arrangement of fluids with different densities. During a displacement operation the density of the displacing fluid is usually greater than that for the displaced fluid. This is done to achieve a sufficient displacement efficiency. For example, the density hierarchy seen in cementing operations are:

\[ \rho_{mud} < \rho_{spacer} < \rho_{cement} \]  \hspace{1cm} (2.4)

In a cementing sequence, the technique used will determine the fluid hierarchy during the cementing operation. For a reverse primary cementing operation where the fluid train is pumped directly into annulus, the fluid hierarchy will be negative. This means that the denser spacer and cement slurry is pumped on top of the lighter drilling fluid creating a heavy over light fluid arrangement.

2.3 Fluid Flow
To better understand the displacement operation, knowledge of how the fluid flows is important. The flow pattern, its energy and the origin of the flow will all affect how the fluid behaves when displaced. To determine the efficiency of the displacement, the steadiness of the flow and the parameters which affect this steadiness can be investigated.

2.3.1 Natural/Forced Flow
Fluid can either flow naturally or forced. A natural flow is enforced by a natural means such as gravity or internal causes such as the buoyancy effect (Çengel, Cimbala, & Turner, 2017). In the case of a HOL fluid arrangement the gravity will act both on the heavy and light fluid. However, as the heavier fluid has a higher weight, the flow of the heavy fluid will be greater, causing it to flow in a downward direction penetrating the light fluid. Additionally, the properties of the light fluid will determine how the buoyancy will affect the flow. Forced flow
is influenced by an external force such as a pump or a fan (Çengel et al., 2017). In the cementing process, fluid is usually pumped into the well displacing the initial drilling fluid.

2.3.2 Steady/Unsteady Flow

A flow is considered steady when the flow has constant velocity, temperature and other properties at the same point in time (Çengel et al., 2017). An unsteady flow often has changes in volume, mass or energy. For a displacement to be steady, the interface between two fluids must move steadily along the displacement area. Meaning that the shape of the interface between the two fluids must be constant along the displacement profile as shown in Figure 2.6. For an eccentric annulus, this means that the shape of the interface does not change along the annulus.

For cementing operations, steady displacement is desirable as it ensures continuous and complete displacement around the entire annulus (Pelipenko & Frigaard, 2004). A steady displacement reduces mixing of the two fluids, avoids remaining drilling fluid in the annulus, and prevents mud channelling in the resulting cement.

*Figure 2.6 Illustration of steady displacement in an eccentric annulus (Project proposal; Steady displacements for conventional and reverse circulation primary cementing, 2019).*
2.3.3 Reynolds Number

Fluid which flows under steady state conditions will mainly flow in laminar or turbulent flow patterns with different velocity profiles as shown in Figure 2.7.

![Figure 2.7 Velocity profile of different fluid flow](image)

To determine if the flow is laminar, turbulent or somewhere in-between, Reynolds (Re) number is calculated as follows for Newtonian fluids:

$$Re = \frac{\rho v D}{\mu}$$  \hspace{1cm} (2.5)

The dimensionless Re number is a function of the fluid density ($\rho$), viscosity ($\mu$), and velocity ($v$) as well as the flowing area (D). High viscosity and low density often result in laminar flow as the viscous forces suppress the fluctuation in the fluid and maintains its straight flow direction. In turbulent flow, the inertial forces are too high for the viscous forces to be suppressed, resulting in a flow regime consisting of a high degree of fluctuations (Çengel et al., 2017). In other words, fluid in laminar flow can be characterized by its viscosity, and for flow at higher rate the behaviour becomes more dependent on inertial forces. As shown in Table 2.2, the flow regime is laminar if the Reynolds number is below 2300, transient between 2300 and 4000, and turbulent if above 4000 (Çengel et al., 2017).

<table>
<thead>
<tr>
<th>$Re$</th>
<th>Classification of flow regime by Reynolds number</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Re \leq 2300$</td>
<td>Laminar flow</td>
</tr>
<tr>
<td>$2300 \leq Re \leq 4000$</td>
<td>Transient flow</td>
</tr>
<tr>
<td>$4000 \leq Re$</td>
<td>Turbulent flow</td>
</tr>
</tbody>
</table>

Table 2.2 Classification of flow regime by Reynolds number
2.4 Rheology

To properly design and execute a drilling operation, it is important to study the behaviour of the fluids used. Fluid rheology is the study of the deformation and flow of matter and describes the behaviour of fluids under stress. The fluid rheology determines the relation between flow rate (shear rate) and pressure gradient (shear stress). Knowledge of the rheology is essential to design the best cement slurry and spacer to ensure sufficient fluid displacement. This is done by evaluating elements such as fluid mixability, fluid pumpability, and friction pressure as the fluid flows.

2.4.1 Newtonian/Non-Newtonian Fluid

The flow properties of a liquid are classified as either Newtonian or non-Newtonian. Newtonian fluids such as water, oil or syrup, have a constant proportionality between shear stress and shear rate. The viscosity is independent of the shear rate, which means the fluid will begin to flow immediately when pressure is applied (Çengel et al., 2017). This relation between shear stress and shear rate is a straight line, as can be seen in Figure 2.8. The slope of the line represents the viscosity of the fluid. This is considered to be constant and does not depend on flow conditions, but simply on temperature and pressure. The equation describing this relationship is as follows:

\[ \tau = \mu \gamma \] (2.6)

Where \( \tau \) is shear stress, \( \mu \) is viscosity and \( \gamma \) is shear rate.

Non-Newtonian fluids, such as drilling fluids and cement slurries, do not have a direct proportionality between shear stress and shear rate. Here, the viscosity depends on the shear rate and can either be shear-thinning or shear-thickening (Çengel et al., 2017). Most drilling fluids are shear thinning, and the viscosity of these fluids decreases as the shear rate increases (see Figure 2.8). For shear-thickening fluids, the viscosity increases with an increasing shear rate. Different models such as Bingham Plastic model and Power Law are used to describe the relation between shear stress and shear rate for fluids.
Additionally, some fluids have a gel strength and are thixotropic. Thixotropy is a property of fluids which causes the viscosity to be time-dependent and often results in a gel structure in static state. When a certain pressure is applied, the structure breaks down and the fluid eventually starts flowing. When the fluid is allowed to rest again, the structure will rebuild. For example some non-Newtonian drilling fluids will not start flowing immediately after pressure is applied, but will go through state of plug, laminar, and turbulent flow (Smith, 1987). Fluids with gel strength are more difficult to displace due to the higher pressure needed to make the fluid flow. This can lead to residual mud and later mud channels which make the displacement process less successful.

2.5 Fluid Instabilities

2.5.1 Raleigh-Taylor Instability
The Rayleigh–Taylor (R-T) instability is a buoyancy-driven mixing which occurs whenever fluids of different densities are subjected to acceleration in a direction opposite to that of the density gradient (Rayleigh, 1882; Taylor, 1950). A simple example is when a heavy fluid layer is supported by a lighter fluid, and a R-T instability occurs (Kull, 1991). Figure 2.9 shows the typical shape of an R-T instability, where the light-coloured heavy fluid falls into the dark-coloured light fluid in a mushroom like shape.
The instability is driven by the gravity and buoyancy forces acting on the fluids. The heavy fluid will fall into the lighter fluid, and the lighter fluid will rise into the heavy fluid. This results in a turbulent flow with a high level of mixing between the two fluids. Structures in the light fluid penetrating the heavy fluid are called bubbles and the fingers of the falling heavy fluid are called spikes. The R-T instability is complex, and there are several factors influencing it such as surface tension, viscosity, compressibility, geometry, time dependence of the driving acceleration, shocks, and a variety of forms of heterogeneity. Additionally, the fluid may also conduct heat or diffuse mass (described in section 2.5.3) (Sharp, 1984).

The R-T instability goes through three stages described by Taylor (1950) and Sharp (1984) (Figure 2.10). In stage one (a) the amplitude of perturbation is much smaller than the wavelength and the growth of the perturbation is exponential with time. In stage two (b), the amplitude is about half of the wavelength and now the perturbation growth becomes non-linear. The fluid is seen rising and falling in different shape scenarios highly dependent on the density ratio (Atwood number). When At ≤ 1 the light fluid moves into the heavy as bubbles while the heavy fluid falls as spikes between the bubbles. In stage three (c), interactions among bubbles of different sizes are seen, resulting in a mixing layer of where its thickness grows quadratic with time. Finally (d), we encounter the break-up of spikes and penetration of bubbles which results in chaotic and turbulent mixing of the two fluids.
2.5.2 Advection

Advection is the transport of a conserved substance by bulk motion of the fluid the substance is carried within. The advection requires motion in the fluid and cannot happen in solid material. Advection does not include macroscopic diffusion.

2.5.3 Diffusion

Diffusion is a spreading movement within a body of a substance from a region of higher concentration to a region of lower concentration. The net movement is driven by a concentration gradient, leading the substance to spread more uniformly. In fluids this can lead to mixing of different substances without requiring any bulk motion (advection).

2.5.4 Instabilities in density-unstable displacement

The diffuse mixing region in a HOL fluid arrangement with R-T instabilities has been investigated by several researchers. Debecq, Fanguet, Hulin, Salin, and Perrin (2001) characterized the diffusion coefficient and the front velocity of the exchange flow as a function of density ratio (At), fluid viscosity, and pipe diameter. They found that for a large At number, the effective diffusive flow could be characterized by a macroscopic diffusion coefficient, $D_M$. 

Figure 2.10 The tree regimes of R-T instabilities (Roberts, 2012)
$10^5$ times higher than for the molecular diffusion. For lower At numbers, the diffusion is limited by a sharp front moving with a velocity increasing with At. Further, Alba et al. (2013) studied the diffusive mixing regions for mixing with an imposed flow added to the exchange flow. They found that the spreading of the front could be both diffuse and non-diffusive. In addition to that the diffusion depends on the density difference (At), they found that the transition between diffusive/non-diffusive regime in a vertical pipe is a function of mean flow speed added to the exchange flow.

### 2.6 Flow governed equation and dimensionless numbers

#### 2.6.1 Hydrostatic Pressure

Hydrostatic pressure (P) at a given depth in a still fluid is linked to the gravitational weight of overlying liquids. The relation between pressure (P), density ($\rho$) and height (h) is as follows:

$$P(h) = \rho gh$$

(2.7)

In more general systems with moving and accelerated fluid, the pressure is linked to other forces via the Navier-Stokes equation. For Newtonian fluids the hydrostatic pressure will enforce flow when the fluid is not trapped. For example, fluid will flow in a pipe flow due to the gravitational force when the pipe ends are open. The flow velocity is linked to the pressure gradient along the pipe. If the column height is constant, the velocity will be constant as long as the density and viscosity is constant. With a decreasing height, the flow decreases. The flow velocity will also depend on the size of the open ends and the pipe walls friction.

#### 2.6.2 Atwood number

The Atwood number (At) is a dimensionless number used to study hydrodynamic instabilities in density stratified flow. It describes the density ratio between a heavy fluid and a light fluid which has the same surface plane. It is defined as the density difference between the light ($\rho_L$) and heavy fluid ($\rho_H$) divided on the sum of the two fluid densities:

$$At = \frac{\rho_H - \rho_L}{\rho_H + \rho_L}$$

(2.8)
Atwood’s number is an important parameter in describing the Rayleigh-Taylor (R-T) instabilities. The density ratio affects the rise of light fluid and fall off heavy fluid (Youngs, 1991).

2.6.3 Froude number
The Froude number (Fr) is a dimensionless parameter which gives the ratio between inertia force and gravity or buoyancy force. The densimetric Froude number is given:

\[ Fr = \frac{V_o}{\sqrt{AtgD}} \]  

(2.9)

where \( V_o \) is the flow velocity and \( D \) is the characteristic length, \( At \) is the Atwood number and \( g \) is the gravitational constant.

The Froude number is important in fluid dynamics where the weight of the fluid is important and is used to calculate the momentum transfer. Small numbers of the Froude number indicate that the effects of the density difference, ie. Buoyancy forces are dominating the system.

2.6.4 Péclet number
The Péclet number (Pe) is a dimensionless number used to study the transport in a fluid. Pe is defined as the relation between advection and diffusion motion:

\[ Pe = \frac{\text{advective transport rate}}{\text{diffusive transport rate}} = \frac{ul}{Di} \]  

(2.10)

where \( L \) is the characteristic length, \( u \) is the flow velocity and \( Di \) is the mass diffusive coefficient.

In fluid flow, Péclet number is often very large and the advection dominates the transport, thus diffusion is negligible ((Bittleston, Ferguson, & Frigaard, 2002).

2.6.5 Continuity and Navier-Stokes Equation
Two important governing equations for liquid in motion are the continuity equation and the Navier-Stokes equation. The continuity equation represents conservation of mass, while the Navier-Stokes equation represents conservation of momentum.
The continuity equation is defined as:

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0 \]  

(2.11)

If the fluid is homogenous and incompressible, the continuity equation becomes:

\[ \nabla \cdot \vec{u} = 0 \]  

(2.12)

The Navier-Stokes equation describes motion of viscous fluids. For a Newtonian fluid the Navier-Stokes equation becomes:

\[ \rho \left( \frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \nabla) \vec{u} \right) = -\nabla p + \mu \nabla^2 \vec{u} - \rho g \vec{i}_y \]  

(2.13)

The first term in the Navier-Stokes equation is inertia force, the second is pressure and the third is viscous forces. The last term is a hydrostatic pressure gradient where \( \vec{i} \) is unit vector in direction of gravity. If the fluid moves in a pipe with an inclination \( \beta \) relative to vertical the hydrostatic pressure gradient term becomes: \( \rho g \cos \beta \).
Chapter 3

3 Density-unstable displacement

3.1 Reverse circulation cementing job design

In reverse primary cementing the displacing fluid train is pumped directly into annulus and the drilling fluid is displaced up the drillstring as shown in Figure 3.1. In the start of the operation the whole drillstring and annulus are filled with drilling fluid. Then, spacer, flusher and, cement slurry is pumped into the well through the annulus leaving the heavier fluid on top of the lighter drilling fluid. This results in a density-unstable fluid arrangement called heavy over light (HOL). In this fluid interface mixing can occur and different instabilities can be observed (Alba et al., 2013). The reverse circulation cementing method rely on gravitational forces and density difference to aid the displacement of the drilling fluid in the well. This results in an exchange flow, and backpressure (by pumping) is often required to control the free fall of the cement slurry (Nelson & Guillot, 2006). The effect that induced flow has on the mixing in the fluid interface is yet unknown. Some studies have tried to identify the effect seen in a circular space, but studies of the effect seen in an annular space is lacking. In the next section findings in previous studies will be presented and later on the results of the experimental part of this paper will be discussed.

Figure 3.1 Schematic representation of cementing operation sequence
3.2 Previous research

3.2.1 Density-stable displacement
Malekmohammadi et al. (2010) studied density-stable conventional displacement of two miscible fluids, and found that it is possible to have a steady traveling front in an eccentric annulus. In their experiment the heavy fluid is displacing the lighter fluid up a circular pipe with annulus. They found that the steadiness of displacement is promoted by a positive ratio of viscosity and density, slow flow rates, and by small eccentricity. This means that the steadiest displacement is seen when the displacing fluid is both heavier and more viscous than the displaced fluid, and the eccentricity is low. Additionally, their experiment showed presence of a secondary counter-current flow above and below the advecting fluid interface. This flow contributes to the displacing fluid being advected to the wider side of the annulus, resulting in an advancing spike of focused fluid (Figure 3.2). Additionally, an elongation spike of displacing fluid interface could be seen along the narrow side annulus (Malekmohammadi et al., 2010).

![Figure 3.2 Typically displacement profile seen in Malekmohammadi et al. (2010)](image)

Furthermore, Jakobsen et al. (1991) studied steady displacement in an inclined well (60 degrees), and Skadsem and Kragset (2019) numerically studied conventional displacement of viscoplastic fluids in an irregular annulus. Skadsem and Kragset (2019) further discussed their results by the Effective Laminar Flow (ELF) guidelines presented by Couturier, Guillot, Hendriks, and Callet (1990). Another numerical 3D simulations of density stable displacement in annulus can be found in Etrati and Frigaard (2019). In all investigations, both experimentally
and numerical, the eccentricity favors flow in the wider part of the annulus and an azimuthal flow is seen, leading the fluid to the narrow side of the annulus (Malekmohammadi et al., 2010). There is agreement that mobilization of fluid in the narrow part (by pressure and/or buoyancy force) is favorable and results in an optimized fluid displacement.

3.2.2 Density-unstable displacement

For density-unstable displacement flows in an annular geometry there has been less research. Until now, as far as we know, there has been no experimental or numerical investigation of miscible displacement in such geometry. Alba (2013) et al. studied miscible density-unstable displacement of two Newtonian fluids in an inclined tube without annulus. The denser fluid is placed above the lighter fluid and the lighter fluid is displaced down the tube. The geometry is different from the one used in this thesis, but the fluid arrangement and fluid properties used are the same. Their study is a continuation of their previous study of unstable displacement flow in near horizontal channels and ducts. In this section, will be dedicated to summarize their findings for later use for comparison and discussion of our result.

Alba et al. (2013) stated that for high inclination (near horizontal) experiments, the dominant flow feature is viscous regime, but for low inclination (near vertical) the inertial effects become more dominant resulting in fluid instability and mixing as shown in Figure 3.3. In inclination equal to zero, a full diffuse regime occurs. The flow feature seen in horizontal and vertical pipes is significantly different, leaving the main focus in this paper to be on the experiments done with no inclination, i.e. vertical pipe.

![Figure 3.3 Varying displacement profiles seen in different inclination (Alba et al., 2013)](image_url)
Debacq et al. (2001) studied the exchange flow seen in static fluid HOL instabilities. They found that, fully diffusive, transitional, inertia and viscous flow can appear depending on the flow parameters. Further, they found that the transition between diffuse and non-diffuse regime is a function of density difference (At). Alba et al. (2013) investigated this transition regime, but with an imposed flow added to the exchange flow. They found that in addition to be a function of density difference, the boundary is a function of the mean flow speed. They further investigated if this extra imposed flow could have a stabilizing effect on the exchange flow or not. For comparison they used the work of both Debacq et al. (2001) and Séon et al. (2007). Alba et al. (2013) found that the imposed flow could have both a stabilization and a destabilization effect on the displacement depending on inclination, Re, and Fr. Their result is discussed using a plot showing Re*\cos(\beta)/Fr versus Fr. Here, the relation of Re/Fr is independent of velocity and Fr is proportional to the velocity.

“Interestingly we have found that the imposed velocity can have quite different effects (stabilizing and/or de-stabilizing) on the flow, all controlled by the parameter Re \cos \beta /Fr. In particular we found that the stabilizing effect of the mean flow found in Ref. 2 is valid up to Re \cos \beta/Fr \approx 270. Above this limit the imposed flow was found to progressively destabilize the flow up to Re \cos \beta/Fr \approx 500” (Alba et al., 2013, p. 20)

These studies highlighted are of same fluid properties as in the experiment in this paper i.e. miscible non-Newtonian fluids with no viscosity, as well as having the same inclination. For a categorization of flow types and front velocities in horizontal ducts see Taghavi, Alba, Seon, et al. (2012). For studies including displacement of viscous fluids, see for example Scoffoni, Lajeunesse, and Homsy (2001), Kuang, Petitjeans, and Maxworthy (2004) and Balasubramaniam, Rashidnia, Maxworthy, and Kuang (2005).
Chapter 4

4 Methodology

4.1 Experimental Setup

Figure 4.1 shows a schematic representation of the experimental setup. The experiment consists of a ~3 m long vertical acrylic pipe of 60 mm outer diameter and 50 mm inner diameter with an smaller inner pipe placed inside it. The inner pipe has an outer diameter of 32 mm leaving the annular space to be 8 mm. A ball valve is placed ~1 m from the top and is used to separate the light and heavy fluid before the displacement experiments is started. To eliminate the effect of the valve handling, a honeycomb flow straightener is placed after the valve opening. The bottom of the cylinder is connected to a hose, leading the flow through an electromagnetic flowmeter and then further on to a drain. The flow rate in the loop is controlled by a 1/4-inch ball valve placed after the flowmeter acting as the outlet of the loop. To ensure a constant liquid height, the fluid column is kept constant by continuously feeding the loop with more fluid than what is let out of the system. A pump is feeding the top of the cylinder with heavy fluid and a 45° T-coupling on top of the pipe ensure the fluid height are not rising by redirecting all access fluid back to the fluid tank (see point A. in Figure 4.1).

Figure 4.1 Schematic of experimental setup

A: Y-coupling  
B: Ball valve  
C: Pressure sensor  
D: Flowmeter  
E: Reservoir tank with pump  
F: Outlet valve
4.1.1 Scaling
In the scaling of the experimental setup, different geometrical similarities and dimensionless numbers were considered (see Table 4.1 through Table 4.3). To decide the diameter of the outer and inner pipe, the relation between the hole section and the casing size in an oil well was studied. In an oil well, a typical annulus is between a 17 1/2-inch hole section and a 13 3/8-inch casing. The relation between the hole section and the outer diameter of the inner casing is 1.27. This is also the case for the annulus between a 12 1/4-inch hole section and the 9 5/8-inch casing. For the lab setup, the outer pipe has an inner diameter of 50 mm and the inner pipe has an outer diameter of 32 mm. This gives a relation of 1.56. A higher relation was chosen to optimize the visualisation of the displacement.

When deciding on the length of the pipe, the relation between axial length and hydraulic diameter and circumference were considered. The ratio between axial length and hydraulic diameter is 109 in our experiment, and the ratio between axial length and flow circumference is 15. This should be sufficient enough in order to see dominating effects of the displacement.

Additionally, some dimensionless numbers are found to be governing for the displacement flow in this experiment. Table 4.3 shows what intervals are expected in the experiments.

<table>
<thead>
<tr>
<th>Hole section (inches)</th>
<th>OD Inner casing</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>17 ½ inches</td>
<td>13 3/8 inches</td>
<td>1.27</td>
</tr>
<tr>
<td>12 ¼ inches</td>
<td>9 5/8 inches</td>
<td>1.27</td>
</tr>
<tr>
<td>8 ½ inches</td>
<td>7 inches</td>
<td>1.21</td>
</tr>
<tr>
<td>50 mm</td>
<td>32 mm</td>
<td>1.56</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner diameter of cylinder</td>
<td>ID</td>
<td>50 mm</td>
</tr>
<tr>
<td>Outer diameter of inner pipe</td>
<td>OD</td>
<td>32 mm</td>
</tr>
<tr>
<td>Hydraulic diameter</td>
<td>Dh = ID - OD</td>
<td>18 mm</td>
</tr>
<tr>
<td>Parameter</td>
<td>Symbol</td>
<td>Value</td>
</tr>
<tr>
<td>----------------------------------------------------------------</td>
<td>----------</td>
<td>-------------</td>
</tr>
<tr>
<td>Total height of cylinder</td>
<td></td>
<td>3.09 m</td>
</tr>
<tr>
<td>Height up to ball valve (pipe with annulus)</td>
<td>L</td>
<td>1.96 m</td>
</tr>
<tr>
<td>Height above ball valve</td>
<td></td>
<td>0.96 m</td>
</tr>
<tr>
<td>Axial length/hydraulic diameter</td>
<td>L/Dh</td>
<td>109</td>
</tr>
<tr>
<td>Axial length/circumference</td>
<td>L/π((r_i+r_o))</td>
<td>15.3</td>
</tr>
</tbody>
</table>

Table 4.3 Parameter range for the experimental study

4.1.2 Fluid selection
For the purpose of this experiment, fresh water is used as light fluid, and water with dissolved salt and dye is used as heavy fluid. Water is used as it in our experiments can be considered to be an incompressible Newtonian fluid with constant viscosity, in addition to being a good solvent for the salt weighting agent. The density of the heavy fluid is controlled by dissolving NaCl. Additionally, a red dye is used to visually separate the two fluids, and tests were completed to determine if the colorant affects the density of the fluid. As shown in Table B. 1, the colorant has little effect on the density of the fluid, and salt acts as the main weighting agent.

4.1.3 Camera setup
For this experiment, a camera with mirror configuration on the side of the pipe is used to capture the fluid flowing downstream in the pipe. To distinguish between the heavy and the light fluid, Lissamin red dye is used. To ensure good picture quality, specially along the circular ends of the pipe a rectangular tank filled with water is placed around the cylinder as shown in Figure 4.2. A mirror is placed outside the tank to ensure that the camera can capture the whole area of the pipe circumference. The camera covers the whole 75 cm of the water filled tank. For improved neutral background a white cardboard plate is used.
For camera, a Nikon D5500 is used. It records 60 fps in video mode, and then the video is spilt into pictures by using MATLAB. The flow of the fluids is measured by studying the front movement on the pictures.

4.1.4 Electromagnetic flow meter

For this experiment, an Endress+Hauser Promag 53 Flowmeter is used to measure the flow velocity. An electromagnetic flow meter uses Faraday’s law of induction to measure the velocity and hence the fluid flow of a tube. According to Faraday’s law, a moving electrically conductive fluid inside a magnetic field generates an electromotive force (voltage). Further, the flow velocity is proportional to the inner diameter of the pipe and the magnetic field strength. In the electromagnetic flow meter, two electrodes are placed on each side of the inner pipe perpendicular to the flow direction. A magnetic field is set up by strong magnets perpendicular to the connecting line between the electrode. So when the fluid flows, the velocity is measured by the electrodes by capturing the voltage created while the fluid flows through the magnetic field (see Figure 4.3). The potential difference between the two electrodes reflects the fluid flow velocity. The electromagnetic flow meter only works for conducting fluids containing ions, such as water, and will not work on insulating fluids like oil. Some highly sensitive electromagnetic flow meters can work with oil-water systems with even slight conductivity.

Figure 4.2 Schematic representation of camera and mirror arrangement
4.1.5 Pasco Software and Pressure Sensor

Pasco is used as the instrument for pressure and velocity measurements in this experiment. It includes an 850 Universal Interface where the sensors are mounted, and the PASCO Capture Software for storing the recordings. For this experiment an absolute pressure sensor is mounted. A VWR silicone tubing is used to connect the pressure sensor nipple and the PASCO sensor. The flowmeter is connected from the Endress+Hauser Promag 53 Flowmeter trough a 270 Ohm resistor inside the flowmeter and to a Voltage PASCO sensor. Both the pressure sensor and the flowmeter is calibrated to ensure correct readings (see Appendix A.1 and A.2).

4.1.6 Density Meter

To measure the density of the light and heavy fluids, a Density Meter DMA 4100 M is used (Figure 4.4). The density meter works by using the oscillating U-tube method; the fluid sample is injected into a U-shaped glass tube and the density is determined by vibrating the glass tube at a characteristic frequency. The frequency depends on the density of the sample, and by determining the characteristic frequency of the fluid, the density can be calculated by the following equation (Anton Paar, 2012):

\[
\rho = KA \times Q_d^2 \times f_1 - KB \times f_2
\]  

(4.1)

Where KA and KB are apparatus constants, Q is the quotient of the period of oscillation of the U-tube decided by the period of oscillation of the reference oscillator. \( f_1 \) and \( f_2 \) are correction terms for temperature, viscosity and nonlinearity.
The density meter automatically measures and displays the density of the fluid on the screen. To minimize the errors of the density meter, the glass tube is cleaned before each measurement. White Spirit is used as cleaning agent one and Acetone is used as cleaning agent two. Additionally, the glass tube is dried between each sample using an air pump, for approximately three minutes until the density readings are stable. The fluid sample test can be investigated visually by using a camera recording of the U-tube shown on the screen. To ensure correct measurements, the u-tube should be fully filled with liquid. If the glass tube is not fully filled air bubbles shows up on the camera recording.

![DMA 4100 M Density Meter](image)

*Figure 4.4 Figure of DMA 4100 M Density Meter (Anton Paar, 2012)*

### 4.2 Experimental Procedure

The pipe and the hose below the ball valve is filled with water using a hose connected to a water tap. While filling the total length of cylinder up to the ball valve, some fluid is flooded through the flowmeter to ensure that there are no water bubbles tarped inside and that the hose is fully filled with water. The hose is transparent and when no air bubbles are seen, the outlet valve is closed and the cylinder filled to a predefined height over the ball valve. The ball valve is then closed and opened a few times to ensure there is no air trapped inside the ball valve. Air bubbles can be observed rising when doing this, so this is an important step to reduce disturbance in the heavy fluid when later opening the ball valve. The ball valve is left closed and the pre-mixed heavy fluid is filled into the pipe on top of the ball valve by a pump placed at the bottom of the loop. The liquid height is kept constant by using a T-coupling where the excess fluid is led back to the heavy fluid storage tank.
Once the experiment starts, the ball valve is first opened and then immediately after opening the ball valve the outlet valve is opened to ensure flow. The flow velocity and hydrostatic pressure are measured continuously and a camera records the flow inside the annular space.

In a typical experimental sequence, the Atwood number is fixed and the experiment is run with different increasing fixed flow rates. Each set of A and flow rate is run tree timers to ensure good data quality. Every set of experiments with the same At number is completed before starting the same experiments for the higher At number. Between every experimental run, the system is flushed with water to ensure no heavy fluid remains inside the cylinder and to dissolve residual salt.

### 4.3 Experimental plan

In Table 4.4 the experimental series are presented. The density of the light fluid is constant while the density of the heavy fluid is changed. Each set of fluid will be run with three different flowrates. To ensure good data each run is done three times.

<table>
<thead>
<tr>
<th>Series</th>
<th>Density of Displacing fluid (kg/m³)</th>
<th>Density of Displaced fluid (kg/m³)</th>
<th>Atwood number</th>
<th>Velocity (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1005</td>
<td>998.3</td>
<td>0.0035</td>
<td>0, 10, 20</td>
</tr>
<tr>
<td>2</td>
<td>1018</td>
<td>998.3</td>
<td>0.01</td>
<td>0, 10, 20</td>
</tr>
</tbody>
</table>

*Table 4.4 Densities used in the experiments*
Chapter 5

5 Results and discussion

5.1 Dimensionless parameters

The experimental results of flow rate, At, Re, Fr and the ratio between Re/F are listed in Table 5.1. As seen in the table there is some variation in the results. For the runs with At = 0.0035, At has small variations. It is unknown why we see these variation, but one explanation could be that the experiments with 0 mm/s were executed a day before the two with ~10 and ~21 mm/s. There is a small increase in the density of the heavy fluid from one day to the other. This could also be an effect of the change in temperature since the temperature of the newly made fluid is ~ 7 °C, and the next day it would be more equal to room temperature of ~ 21 °C. In the series with At = 0.01, all the runs were performed the same day and no variation of At is seen. In-between the last run with 10 mm/s and the first of 21 mm/s, an incidence occurred where some fresh water was accidently mixed into the heavy fluid. The heavy fluid was then tested, and a slight decrease in At could be observed. Because this change was so small, the remainder of the runs were completed with the same fluid.

Further, we see variation in the velocity for all sets. This is a result of a sensitive outlet valve. It is desirable to have the same velocity for all sets in the experiments, but this was found to be near impossible. Some runs were performed repeatedly to ensure a small enough offset from the planned velocity. This was the case for run 1.1.2, where the flow rate was too low and an additional set (1.1.3) was executed. To optimize the flow rate in further experiments, the outlet valve should be changed to be run automatically. The flowrate is calculated by using the equation found in the calibration of the flowmeter (see Figure A.6). From this, we get that flow in ml/s (y) is a function of recorded voltage (V), and can be calculated as follow:

\[ y = 68.998 \times V - 75.025 \quad (5.1) \]

Further, the flowrate in mm/s is converted to mm/s by using this formula:

\[ v = \frac{Q}{A} = \frac{Q}{\frac{\pi}{4} (ID^2 - OD^2)} \quad (5.2) \]
Table 5.1 Overview of the parameters for each experimental run

<table>
<thead>
<tr>
<th>Series</th>
<th>Flow rate (mm/s)</th>
<th>At</th>
<th>Re</th>
<th>Fr</th>
<th>Re/Fr</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0.1</td>
<td>0</td>
<td>0.00309</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>1.0.2</td>
<td>0</td>
<td>0.00309</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>1.0.3</td>
<td>0</td>
<td>0.00309</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>1.1.1</td>
<td>9.65</td>
<td>0.00334</td>
<td>174</td>
<td>0.397</td>
<td>438</td>
</tr>
<tr>
<td>1.1.2</td>
<td>5.48</td>
<td>0.00334</td>
<td>99</td>
<td>0.226</td>
<td>438</td>
</tr>
<tr>
<td>1.1.3</td>
<td>10.8</td>
<td>0.00334</td>
<td>195</td>
<td>0.446</td>
<td>438</td>
</tr>
<tr>
<td>1.1.4</td>
<td>9.65</td>
<td>0.00334</td>
<td>174</td>
<td>0.397</td>
<td>438</td>
</tr>
<tr>
<td>1.2.1</td>
<td>21.0</td>
<td>0.00329</td>
<td>378</td>
<td>0.868</td>
<td>435</td>
</tr>
<tr>
<td>1.2.2</td>
<td>21.0</td>
<td>0.00329</td>
<td>378</td>
<td>0.868</td>
<td>435</td>
</tr>
<tr>
<td>1.2.3</td>
<td>21.5</td>
<td>0.00329</td>
<td>388</td>
<td>0.893</td>
<td>435</td>
</tr>
<tr>
<td>2.0.1</td>
<td>0</td>
<td>0,01</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>2.0.2</td>
<td>0</td>
<td>0,01</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>2.0.3</td>
<td>0</td>
<td>0,01</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>2.1.1</td>
<td>10.2</td>
<td>0.01</td>
<td>186</td>
<td>0.225</td>
<td>760</td>
</tr>
<tr>
<td>2.1.2</td>
<td>9.65</td>
<td>0.01</td>
<td>175</td>
<td>0.231</td>
<td>760</td>
</tr>
<tr>
<td>2.1.3</td>
<td>9.05</td>
<td>0.01</td>
<td>164</td>
<td>0.216</td>
<td>760</td>
</tr>
<tr>
<td>2.1.4</td>
<td>10.2</td>
<td>0.01</td>
<td>186</td>
<td>0.245</td>
<td>760</td>
</tr>
<tr>
<td>2.2.1</td>
<td>19.8</td>
<td>0.01</td>
<td>359</td>
<td>0.472</td>
<td>760</td>
</tr>
<tr>
<td>2.2.2</td>
<td>19.8</td>
<td>0.01</td>
<td>359</td>
<td>0.472</td>
<td>760</td>
</tr>
<tr>
<td>2.2.3</td>
<td>20.4</td>
<td>0.01</td>
<td>369</td>
<td>0.486</td>
<td>760</td>
</tr>
</tbody>
</table>
5.1.1 Other uncertainties

When filling the lower pipe with fresh water, an amount of fresh fluid is left above the valve before closing it to ensure no air gap between the two fluids. This residual fresh water will mix with the heavy salt water and could affect the effective density difference. Also the amount of residual fresh water would vary from time to time, so it is hard to estimate the effect. The loop was flushed with fresh water between every run, but there might be some residual salt left in the system. This could then mix with the fresh water and thereby increase the density. It is assumed that the amount of residual salt will be low, therefore the effect on the displacement pattern is neglected.

Because the valve is handled manually, the time from the upper valve is opened to the lower valve is opened will vary with each run. This could affect the mixing that occurs between the two fluids immediately after the upper valve is opened. This effect is reduced by the honeycomb flow straightener, and since the area of interest is after the honeycomb, this effect is considered ok to neglect.

5.2 Visualization of the displacement

A visualization of the tank setup and different sides of annulus is shown in Figure 5.1. On the left side of the figure the tank is seen from the front with a measure along the left side. On the right side of the figure the tank is seen from the right through a mirror. In this way, the back side of the pipe can be seen as the left annulus space in the mirror. The black lines seen in the mirror are lines that are drawn on to the left side of the water tank. In-between the lines, it is 4 cm, and the lines are approximately 2 cm lower than for the same line seen in the red measure in the front picture. In the experimental runs, the displacement tends to start in different parts of the annulus randomly. This will be shown later, and the depth of the heavy fluid will be marked with a dashed line.
5.3 A typical displacement and the instabilities seen

In Figure 5.2 and Figure 5.3, a displacement sequence is shown to illustrate a typical experimental result. For this purpose, a displacement with a $v = 10 \text{ mm/s}$ and $A_t = 0.01$ was chosen. All instabilities, flow patterns and mixing seen in other experimental series are also seen here. Later, in section 5.4 and 5.5, the difference between the displacement and the effect of $A_t$ and velocity is further discussed.

As shown in Figure 5.2, the displacement fluid typically enters the pipe section in one or two parts of the annulus. Only a few seconds later, a backflow and a transverse flow is seen. The backflow is seen as a counter-current rising flow of light fluid as some displacement fluid falls downwards inside the pipe. The transverse flow is seen as a vertical flow, spreading the displacement fluid all around the annulus (see figure $t = 8 \text{ seconds}$). As the time goes, a pattern of diffusive mixing, transverse flow and backflows is developing (see second row in Figure 5.2).
As the displacement continues, the displacement fluid is taking up more and more space of the annulus. The mixing front is seen in a lower part of the pipe, but the transverse flow and backflow is still seen along the whole pipe section. The displacing fluid front tend to fall into the displaced fluid then spread along the annulus. After a given time, the whole annulus section is displaced. The displacement fluid is able to displace the lighter fluid but backflows and transverse flow are seen until the end of displacement.
5.4 Effect of density difference (Atwood number)

In this section the effect of the density differences of the displacing and displaced fluid are studied. Each set of a constant velocity and the two different At is compared. The result is presented as a series of pictures comparing the displacement front of the runs. The depth of the heavy fluid is marked with a yellow dashed line and the position is noted below each picture. The lower the y position number is, the lower in the pipe the fluid has reached.

5.4.1 Flow rate = 0 mm/s

In Figure 5.5 run 1.0.2 and 2.0.2 are compared by setting the picture for the same time next to each other in two columns. The pressure and the flow velocity are constant for both runs as shown in Figure 5.4. The mean pressure for the denser fluid is slightly higher than for the less dense fluid due to density difference.
The effect of density difference is seen to be most dominant for the static experiments (0 mm/s). This is also expected as the Fr number is smaller for the experiments only having exchange flow than for the experiments with an extra imposed flow. For the displacement fluid with the highest At number (0.01) the displacement front tend to fall at a higher rate than for the less heavy fluid (At = 0.0035). When studying the flow pattern of the two displacements, it seems that for the At = 0.01 displacement, the flow consists of less backflow and the same amount of transverse flow as for At = 0.0035. Additionally, the concentration of displacing fluid seems higher for the runs with At = 0.01 than for At = 0.0035. Consequently, this can mean that displacement with a higher density difference is most effective.
Figure 5.5 Time vs depth of displacement for both $At$ and $v = 0 \text{ mm/s}$
5.4.2 Flow rate = 10 mm/s

In Figure 5.6 and Figure 5.7 the 1.1.3 and 2.1.1 run are compared. From the Pasco readings we see that it takes some time before the flow velocity reach its constant rate, but this “build up” section is equal for both runs. The pressure reading shows a slight increase in pressure due to that the light fluid is displaced with a denser fluid.

In the series with v = 10 mm/s the density difference seems to be less dominating. The displacement front still travels with a higher rate for the At = 0.01 than for the At = 0.035, but the effects not as prominent. Now, the downward displacing and the transverse flow seems to become more dominating and less backflow are seen. The backflow is still present, but it tends to follow the downward flow and becomes less penetrating in the counter-current direction. Diffusive mixing and a pattern of displaced and displacing fluid is still seen all over the pipe section for both density differences.
Figure 5.7 Time vs depth of displacement for both $At$ and $v = 9.5 \text{ mm/s}$
5.4.3 Flow rate = 20 mm/s

Figure 5.8 and Figure 5.9 shows the result of the displacement run 1.2.2 and 2.2.1. The velocity for the run with At = 0.01 is higher than for the run with At = 0.003 but this seems to not affect the results. The flow uses some time to stabilize and as more light fluid is displaced the velocity increases due to the higher weight of fluid. It is uncertain why the pressure for run 1.2.2 is decreasing at the end of operation, but this is not seen in any other experimental data.

![Figure 5.8 Pasco reading for two runs with v = 20 mm/s](image)

In the displacement with flow of 20 mm/s the depth of displaced fluid with different At values is more equal to each other. The flow pattern is seen as more straight, and less transverse and backflow are seen compared to the runs with 0 mm/s and 10 mm/s. The backflow and transverse flow is often interrupted by the downward flow leaving more fluid to be fully displaced. Light parts of displaced fluid are seen as bypassed fluid and are less due to a backflow. With a flow rate of 20 mm/s, the downward flow seems to dominate over the density difference leaving the change in At to have little effect.
Figure 5.9 Time vs depth of displacement for both $A_t$ and $v = 20$ mm/s
5.5 Effect of flow velocity (Reynolds number)

In this section the effect of flow velocity is studied. Experimental runs with the same At but different velocities are compared. The depth of investigation is now set, and the time it takes the displacement front to reach this depth is compared. The time is reported as the time it takes the displacement front to travel from the top of the water tank to the given depth. Also, changes in the flow pattern and visual observation will be discussed.

In Figure 5.11, the Pasco readings for the same At but different velocities are shown. When the displacement is static (v = 0 mm/s), no variation in the velocity recordings are seen. Increasing the velocity results in an increase of variation in velocity. After opening the valve and inducing flow, it takes some time before the flowmeter readings shows the fixed velocity. With time, the flow velocity tends to increase, and the increase is observed to be greater for the 20 mm/s velocity than for the 10 mm/s. This means that the flow in the pipe will have a higher velocity at the end of the displacement than in the start. When studying the displacement visually, it is hard to see if this has an effect on the flow pattern or not. The amount of mixing is high for all experimental runs, therefore it can be assumed that, this slight increase will have little or no impact on the displacement efficiency.

When studying the displacement in the pictures in Figure 5.12 and Figure 5.13, the randomness of the flow pattern becomes clear. The heavy displacement fluid is seen entering the pipe in a random position for all experimental runs. The mixing of fluids, transverse flow and backflow are seen at all depths for both At = 0.0035 and At = 0.01. This indicates that the mixing does not stop, but a difference in flow pattern are seen. The impact of transverse and backflow are seen as decreasing with increasing flow velocity. When increasing the velocity, the downward flow tends to dominate over the backflow and slow the counter-current flow down. The light displaced fluid rising in the backflow tend to travel along with the downward flow, resulting in displaced fluid being pushed down with the displacing fluid. Some example of this is shown in Figure 5.10. The effect of this dominating downward flow is increasing with increased velocity. This results in that the displacements with a higher velocity having a higher efficiency than the displacements with lower velocities.
On the other hand, when comparing the displacements shown in Figure 5.12 and Figure 5.13, it seems that the velocity has no effect other than resulting in less time to reach a given depth. The same pattern of displacing and displaced fluid can be seen for all runs. This indicates that displacement of different velocities has the same displacement efficiencies. However, the results are best shown when studying the displacement in the video recording, and it seems like the increased velocity results in a better displacement due to the downward pushing flow.
Figure 5.11 Comparison of Pasco readings for all flow velocities

(a) At = 0.0033 \( v = 0 \) mm/s

(b) At = 0.0033 \( v = 21 \) mm/s

(c) At = 0.0033 \( v = 10.8 \) mm/s
5.5.1 \( At = 0.0035 \)

\[ v = 0 \text{ mm/s} \quad v = 9.5 \text{ mm/s} \quad v = 20 \text{ mm/s} \]

\[ t = 9, \ y = 650 \quad t = 2.5, \ y = 650 \quad t = 3, \ y = 650 \]

\[ t = 35, \ y = 450 \quad t = 10, \ y = 450 \quad t = 8.5, \ y = 450 \]

\[ t = 97, \ y = 250 \quad t = 16, \ y = 250 \quad t = 14, \ y = 250 \]

*Figure 5.12 Displacements pattern at given depths for \( At = 0.0035 \) and all velocities*
5.5.2 $At = 0.01$

- $v = 0$ mm/s
- $v = 9.5$ mm/s
- $v = 20$ mm/s

*Figure 5.13 Displacements pattern at given depths for $At = 0.01$ and all velocities*
Chapter 6

6 Conclusion

For all experimental runs a high level of mixing is seen. A transverse flow is seen spreading the displacing front all around the annulus, a counter-current backflow is seen in the rising of light fluid and diffusive mixing is seen lowering the concentration of the displacement fluid in the front.

The volume of such instabilities and flow patterns are found to be dependent on density difference and flow velocity. In the static experiments where there is only exchange flow between the two fluids, the change in the density difference is observed to be most governing. As expected, when the velocity is low the buoyant forces dominates the flow feature. When increasing the density difference from 0.0035 to 0.01, the velocity of the displacement front increases and the concentration of heavy fluid is observed to be greater. The same effect is also seen for the displacement with a 10 mm/s imposed flow in addition to the exchange flow, but the effect is less prominent. This could mean that the displacement becomes more effective when increasing the density difference for displacement with low velocities.

For displacement with velocity = 20 mm/s the flow velocity is found to be the most dominating parameter. With an increase in velocity, the level of transverse flow and backflow seems to decrease. The effect is most governing in this case, compared to other the flow velocities. Here the downward flow is observed to interrupt the development of counter-current flows. Transverse and backflows are still present, but the downward flow tends to push the displaced fluid down so that less rising of light fluid is seen. This could result in a more efficient displacement since more of the displaced fluid is pushed downwards in the pipe.

A high level of mixing of the two fluids is still seen in the most effective displacement in this study and a further investigation is needed. To sum up the area of improvements for the experiment in this thesis and to highlighted some areas of interests a recommendation to further work is presented in the next section.
6.1 Recommendation of further work

In this thesis, the main focus has been on Newtonian fluids with low viscosity. The viscosity in all the experiments are constant, while the densities of the fluids and the flow velocity was changed. In the oil industry, the drilling fluid used is often viscous and both water based and oil based mud is used. It would be interesting to investigate the effects of viscosity difference and to study the displacement of fluid with yield strength. Further, displacement of immiscible fluid could be studied.

The flowrate in the experiments are induced with opening the outlet valve. In the industry the displacement fluid is pumped into the well. The effect of forcing the fluid to flow by pumping could be studied. Further, a comparison to the findings of Alba et al. (2013), especially when coming to the stabilization/destabilization of the imposed flow, would be interesting. Here it would be helpful to study the velocity of the displacement front versus the average bulk velocity measured by the flowmeter. The experimental setup could further be modified to investigate different inclinations.

For the experimental setup and the visualisation of the result, some improvements are proposed:

- A higher concentration of colour on the displacement fluid to more clearly visualize the displacement front. Black dye and greyscale images could improve the results.
- It could be interesting to try running the experiments using pH sensitive displacement fluid. The mixing region of heavy and light fluid would then change colour and it would be possible to investigate the amount of mixing.
- A longer section of the water tank and several cameras capturing the whole length of the displacement. In these experiments, the displacement fluid enters the visualization tank approximately 10 cm below the honeycomb. It could be interesting to start the image capturing just below the honeycomb.
References


Project proposal; Steady displacements for conventional and reverse circulation primary cementing. (2019).


Appendix A  Calibration

A.1 Pressure sensor

To calibrate the pressure sensor, the cylinder is filled with water and the pressure is recorded in steps of decreasing height of the fluid column. The height is measured from the sensor and up and the data recorded from the Pasco pressure sensor are compared to a calculated theoretical pressure. Figure A.1, Figure A.2 and, Figure A.3 shows the Pasco recordings of the three test runs and Figure A.4 shows experimental data plotted against the theoretical pressure calculated by using \( P = \rho gh \). The measured and the calculated data differs about 30 mbar which indicates a good calibration of the pressure sensor.

Figure A.1 1st test run to calibrate the Pasco pressure sensor
Figure A.2 2nd test run to calibrate the Pasco pressure sensor
Figure A.3 3.rdt test run to calibrate the Pasco pressure sensor
A.2 Flowmeter

The flowmeter is calibrated by measuring the flow velocity manually and comparing this to the recorded flow from the flowmeter. The flow is set at a constant velocity and the flowmeter readings are recording from the flowmeter screen. To measure the flow manually the time it takes to fill a 5000 ml volumetric flask is measured. This procedure is done for three different velocities and the result are compared in Figure A.5. The results from the flowmeter and the manually measured result is nearly the same. The measured flow tends to be a bit higher than for the flowmeter reading for all velocities and the results are considered to be good enough for this purpose.

Further, to correlate the velocity readings on the flowmeter (ml/s) to the recorded Voltage (V) numbers on Pasco a study of ml/s vs V is done. The result and the linear correlation are shown in Figure A.6 which is further used to calculate mm/s. Here a good fitting of the result is indicated by the $R = 0.999$. 

![Calibration of Pressure Sensor](image)
Figure A.5 Flowmeter readings plotted against measured flow

Figure A.6 Correlation between Flow (ml/s) and Voltage (V)
## Appendix B  Fluid selection

### B.1 Density test

*Table B. 1 Test of fluid density with different concentration of colorant and salt*

<table>
<thead>
<tr>
<th>Solution</th>
<th>Density (g/cm³)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure water (test of density meter)</td>
<td>0.9983</td>
<td>20.02</td>
</tr>
<tr>
<td>100 ml distilled water + 5 g salt</td>
<td>1.0331</td>
<td>20.01</td>
</tr>
<tr>
<td>100 ml distilled water + 10 g salt</td>
<td>1.0667</td>
<td>19.9</td>
</tr>
<tr>
<td>100 ml distilled water + 15 g salt</td>
<td>1.0967</td>
<td>20.02</td>
</tr>
<tr>
<td>100 ml distilled water + 20 g salt</td>
<td>1.124</td>
<td>20.02</td>
</tr>
<tr>
<td>100 ml distilled water + 25 g salt</td>
<td>1.1545</td>
<td>20.02</td>
</tr>
<tr>
<td>100 ml distilled water + 30 g salt</td>
<td>1.1828</td>
<td>20.02</td>
</tr>
</tbody>
</table>

**Red food colorant**

<table>
<thead>
<tr>
<th>Solution</th>
<th>Density (g/cm³)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure water</td>
<td>0.9983</td>
<td>20.00</td>
</tr>
<tr>
<td>100 ml distilled water + 1.204g NaCl</td>
<td>1.0063</td>
<td>20.00</td>
</tr>
<tr>
<td>100 ml distilled water + 2.002 g NaCl</td>
<td>1.0121</td>
<td>20.02</td>
</tr>
<tr>
<td>100 ml distilled water + 2.002 g NaCl + 0.4 ml red food colorant</td>
<td>1.0125</td>
<td>20.00</td>
</tr>
<tr>
<td>100 ml distilled water + 2.002 g NaCl + 0.8 ml red food colorant</td>
<td>1.0127</td>
<td>20.02</td>
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</tbody>
</table>

**Lissamin red**

<table>
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<th>Solution</th>
<th>Density (g/cm³)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure water</td>
<td>0.9983</td>
<td>20.02</td>
</tr>
<tr>
<td>100 ml distilled water + 0.4 ml premixed lissamin red*</td>
<td>0.9983</td>
<td>20.03</td>
</tr>
<tr>
<td>100 ml distilled water + 0.8 ml premixed lissamin red*</td>
<td>0.9983</td>
<td>20.02</td>
</tr>
<tr>
<td>100 ml distilled water + 1.5 ml premixed lissamin red*</td>
<td>0.9983</td>
<td>20.02</td>
</tr>
<tr>
<td>100 ml distilled water + 2.0 ml premixed lissamin red*</td>
<td>0.9983</td>
<td>20.02</td>
</tr>
<tr>
<td>100 ml distilled water + 1.000 g salt + 2 ml lissamin red*</td>
<td>1.0053</td>
<td>20.00</td>
</tr>
<tr>
<td>100 ml distilled water + 1.000 g salt + 2 ml lissamin red*</td>
<td>1.0053</td>
<td>20.02</td>
</tr>
<tr>
<td>100 ml distilled water + 2.000 g salt + 2 ml lissamin red*</td>
<td>1.0125</td>
<td>20.03</td>
</tr>
<tr>
<td>100 ml distilled water + 3.000 g salt + 2 ml lissamin red*</td>
<td>1.0198</td>
<td>20.01</td>
</tr>
</tbody>
</table>

* premixed lissamin red = 25 ml distilled water + 0.200 g lissamin red powder
B.2 Visibility test

Samples of the two different colorant were mixed to test the best optical solution for the fluid. The samples were made with different concentration of colorant and compared. The samples were also shaken to see if foam is formed. This is to predict the effect of the centrifugal pump on the fluid. The effect on density of the two colorant were presented in the previous table. In this section the effectivity of colorant is shown.
B.3 Fluid preparation

The fluid for each run is premixed in a 10-liter plastic container. The volume of salt and color is calculated before mixing the fluid and the fluid properties is checked with the density meter before running the experiment. To dissolve the salt and colorant the container is well shaken until no salt particles are seen.
Appendix C  Pictures of the Experimental Setup

C.1 The pipe and its elements

Figure C.1 The full experimental setup
Figure C.2 T-shaped tube top of the cylinder

Figure C.3 Setup of visualization tank and cardboard

Figure C.4 Curtains used for visual optimization

Figure C.5 Camera setup
Figure C.10 Honeycomb and centralizer

Figure C.11 Honeycomb placed under valve

Figure C.12 Placement of inner pipe at top

Figure C.13 Honeycomb, centralizer and pipe installed
C.2 Valves

Figure C.14 Ball valve used to separate the two fluid

Figure C.15 Connection between pipe and valve

Figure C.16 Outlet ball valve

Figure C.17 Size and profile of outlet valve
C.3 Pressure sensor

Figure C.18 Pressor sensor connected to pipe

Figure C.19 Silicone tubing connected to Pasco Pressure sensor
**C.4 Flowmeter**

![Flowmeter Display](image1)

*Figure C.20 Placement of the flowmeter*

![Flowmeter Display](image2)

*Figure C.21 Flowmeter display*