NTNU – Trondheim
Norwegian University of
Science and Technology

Lab for heave motion during Managed Pressure Drilling

Camilla Sunde Gjengseth

Earth Sciences and Petroleum Engineering
Submission date: June 2012
Supervisor: John-Morten Godhavn, IPT

Norwegian University of Science and Technology
Department of Petroleum Engineering and Applied Geophysics

Abstract

A significant part of the world's remaining oil and gas prospects are challenging or impossible to reach by conventional methods. Examples are deep-water environments and depleted reservoirs with a narrow drilling window, requiering a more accurate control of the downhole pressure to be able to conduct the drilling operation as safe and efficient as possible. The Constant Bottomhole Pressure (CBHP) variation of Managed Pressure Drilling (MPD) addresses the challenges of drilling within a narrow drilling window by controlling the wellbore pressure by use of backpressure from surface and a choke manifold. It has been applied both onshore and offshore, but mainly from fixed platforms in offshore environment. However, some applications have been run also from floating drilling rigs in calm waters, whereas no MPD solution is available for North Sea conditions with severe heave motions.

This thesis addresses the challenges of downhole pressure fluctuations related to heave motion when drilling from a floating rig in rough environments during connections. By reconstructing such conditions in lab scale, a new developed control algorithm is to be tested to reduce the downhole pressure variations as much as possible. It is desired to obtain new information to continue the research and to come up with a solution for heave compensation during MPD floating rigs. This thesis presents the design of the MPD Heave Rig and functional specification of the components in the lab scaled model. The purpose of the model is to simulate the heave motion by moving a pipe up and down in a hole to obtain pressure fluctuations in the hole and apply a control system which controls these pressure variations based on the principles of constant bottomhole pressure MPD. By use of a water pump and a choke, the pressure variations in the hole are compensated for by adjusting the choke opening. A 900 meter long copper pipe is implemented in the model to simulate the time delay of a pressure transient traveling from the surface to the bottom of the well. A tailored system for the choke to be controlled by the control system has been developed and tested for a temporary prediction of the choke characteristics. A plan for further testing of technical components and parameters for the hydraulic model is presented for future work with the rig. It has been conducted a risk assessment considering the whole process of building, testing and running experiments. Measures are implemented and suggested to ensure operational and technical safety of people and equipment involved in the MPD Heave Rig project.

Sammendrag

En betydelig andel av verdens gjenværende olje-og gassreservoarer er utfordrende eller umulig å nå med konvensjonelle metoder. Eksempler er dypvannsmiljøer og trykkreduserte reservoarer med smalt borevindu, som krever en mer nøyaktig kontroll av nedihullstrykket for å kunne gjennomføre boreoperasjonen sikkert og effektivt. Constant Bottomhole Pressure (CBHP) er en variant av Managed Pressure Drilling (MPD) som løser utfordringene med smale borevinduer ved å kontrollere brønntrykket ved bruk av baktrykk og en choke manifold. Denne metoden har blitt anvendt både onshore og offshore, men hovedsakelig fra faste installasjoner. Enkelte MPD operasjoner har også blitt gjennomført fra flyterigger i rolig sjø, men det er på nåværende tidspunk ingen løsning for bruk av denne metoden i områder som Nordsjøen, hvor ekstreme værforhold er en utfordring.

Denne oppgaven tar for seg utfordringene med trykkvariasjoner som skapes i brønnen grunnet hiv-bevegelse under connections. Ved å rekonstruere slike forhold i labskala, skal en nylig utviklet kontrollalgoritme testes for å redusere disse trykkvariasjonene så mye som mulig. Denne oppgaven presenterer MPD Heave Rig modellen med alle komponentene som inngår. Hensikten med modellen er å simulere hiv-bevegelse ved å bevege et rør opp og ned i et hull for å skape trykksvingninger. Disse trykkvariasjonene skal kontrolleres ved hjelp av en baktrykkspumpe og en choke, basert på prinsippene til CBHP. Et 900 meter langt kobberrør er implementert i modellen for å simulere tidsforsinkelsen til trykkbølgene. Et skreddersydd system for choken, som skal kontrolleres av styresystemet, har blitt utviklet og testet for en midlertidig prediksjon av chokens egenskaper. En plan for videre testing av tekniske komponenter og parametere for hydraulisk modell presenteres for videre arbeid med riggen. Det har blitt gjennomført en risikovurdering av hele prosessen med bygging, testing og gjennomføring eksperimenter. Tiltak er iverksatt og foreslått for å sikre operasjonell og teknisk sikkerhet for mennesker og utstyr involvert i MPD Heave Rig prosjektet.

Acknowledgement

Trondheim, June, 2012.

This Master of Science Thesis was carried out at the Department of Petroleum Engineering and Applied Geophysics at the Norwegian University of Science and Technology, NTNU. It was conducted under supervision of Professor John-Morten Godhavn in the subject TPG4910 Petroleum Engineering - Drilling Technology. The thesis is a continuation of the fall project ”Heave Compensated Managed Pressure Drilling: A Lab Scaled Rig Design” on planning of the MPD Heave Rig, which was conducted by the author of this thesis and Tollef Svenum.

I would like to give a special thanks to Professor John-Morten Godhavn for dedicated guidance and help throughout the process. I would also like to thank Professor Sigbjørn Sangesland for good support. A special thanks goes to Jarle Glad for all help and effort on constructing the MPD Heave Rig.

I would also like to thank Tollef Svenum for great collaboration throughout the process, and for providing necessary inputs on the hydraulic model.

Further I would like to thank Professor Ole Morten Aamo and Hessam Mahdianfar, representing the department of Cybernetics, for participating in progress meetings to help us with information and knowledge regarding the control system.

The author of this work hereby declares that the work is made independently and in accordance to the rules set down by ”Examination regulations” at the Norwegian University of Science and Technology (NTNU), Trondheim.

Contents

List of Figures

List of Tables

1 Introduction

As the world is facing an ever increasing energy demand, the remaining oil and gas prospects are getting more challenging to access by conventional methods. The oil and gas industry is forced to develop new technology and techniques to be able to drill these prospects as safe and efficient as possible. Managed Pressure Drilling (MPD) is a method that is increasingly applied for drilling into challenging reservoirs with narrow pressure margins requiring a more precise pressure control. Several MPD solutions have been applied in drilling operations all over the world, and the methods are continuously improving. MPD has been applied both onshore and offshore, but mainly from fixed platforms in offshore environment. However, some applications have been run from floating drilling rigs in calm waters, whereas no back-pressure MPD solution is available for North Sea conditions with severe heave motions. Experiences show that up to 20 bar pressure variations can occur due to heave motions during connections, when the drill pipe is hung off and the heave compensation system is turned off. There are several challenges both mechanical related and control system related, where new algorithms are required for controlling the bottomhole pressure (BHP) to stay within the operational window.

This thesis addresses the challenges related to heave motion met while drilling with MPD from a floating rig in rough environments. By reconstructing such conditions in a lab scale, a new developed control algorithm is to be tested to reduce the downhole pressure variations as much as possible, it is desired to obtain new information to continue research and to come up with a solution for heave compensation during MPD from floating rigs. Two master students from the Department of Petroleum Engineering & Applied Geophysics are involved in this project writing one Master of Science thesis each.

1.1 Motivation

1.1.1 Safety and Efficiency

"MPD offers probably the only solution for many otherwise conventionally undrillable, challenging prospects. It reduces several drilling problems that cost time and money, and increases safety of drilling operations." Gala (2011)

Development of MPD from floating rigs in harsh environment, like the North Sea, is motivated by a number of factors, but most importantly safety and efficiency. Today's drilling operations are challenged by narrow margins between the pore pressure gradient and fracture gradient, uncertainties in pore pressure predictions, wellbore instability and high-pressure high-temperature (HTHP) reservoirs. All these challenging environments require an increasingly accurate pressure control. By application of conventional drilling methods in such environments a small change in the wellbore pressure can have a fatale impact on the drilling operation. Too much pressure can lead to damaged formation and drilling fluid losses, too low pressure can lead to influx from the formation that in worst case can lead to a disaster like the Deep water Horizon oil spill. MPD enables for a more precisely pressure management and allows for early kick-detection. In this way MPD provides a safer work environment on the rig and enables the drilling operation to continue more efficiently. The remaining oil and gas reserves are challenged by deep-water and harsh weather conditions, where only floating drilling rigs can be applied in the drilling operations. This is clearly a motivation for finding a solution MPD from floating rigs.

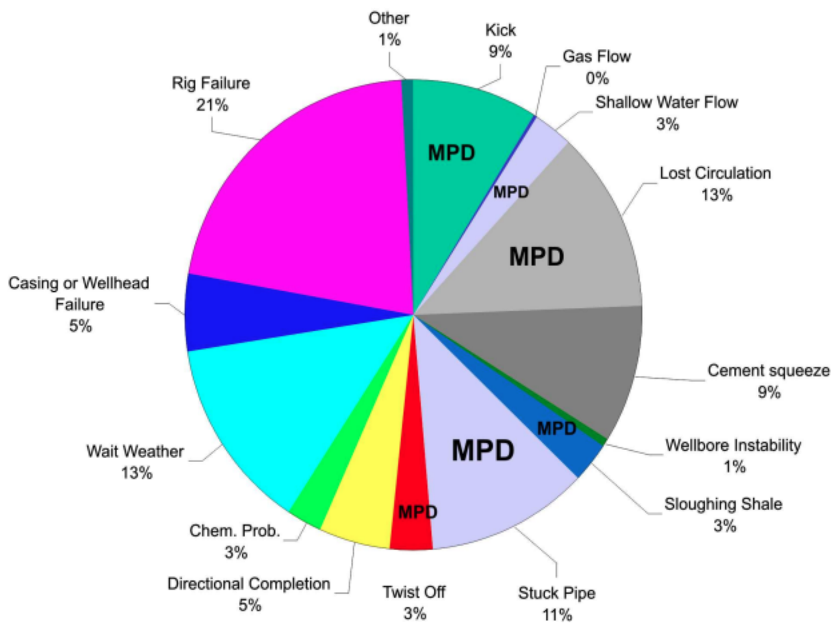


Figure 1.1: *22% of the days of the drilling operation lost to NPT. More than 40% of these problems were related to wellbore pressure issues that can be solved with correct application of MPD. Figure adapted from Hannegan (2007).*

According to Rehm et al. (2008) a major part of all problems during drilling operations are wellbore pressure related issues resulting in Non-Productive-Time (NPT). A study of drilling operations in the Gulf of Mexico in the period 1993 to 2003, conducted by James K Dodson (Hannegan, 2007), states that 22% of the days of drilling operation were lost to NPT. Figure 1.1 shows that more than 40% of these problems were related to wellbore pressure issues, which can be reduced or eliminated by application of MPD. The application of MPD has the greatest potential benefit when it comes to reducing NPT in offshore drilling operations where the cost of NPT incidents may cause major cost exceeding due to the high daily offshore rig rate compared to onshore rig-costs (Hannegan, 2011b). A reduction in NPT can play a significant role on the total cost of the drilling operation and make uneconomical prospects drill-able.

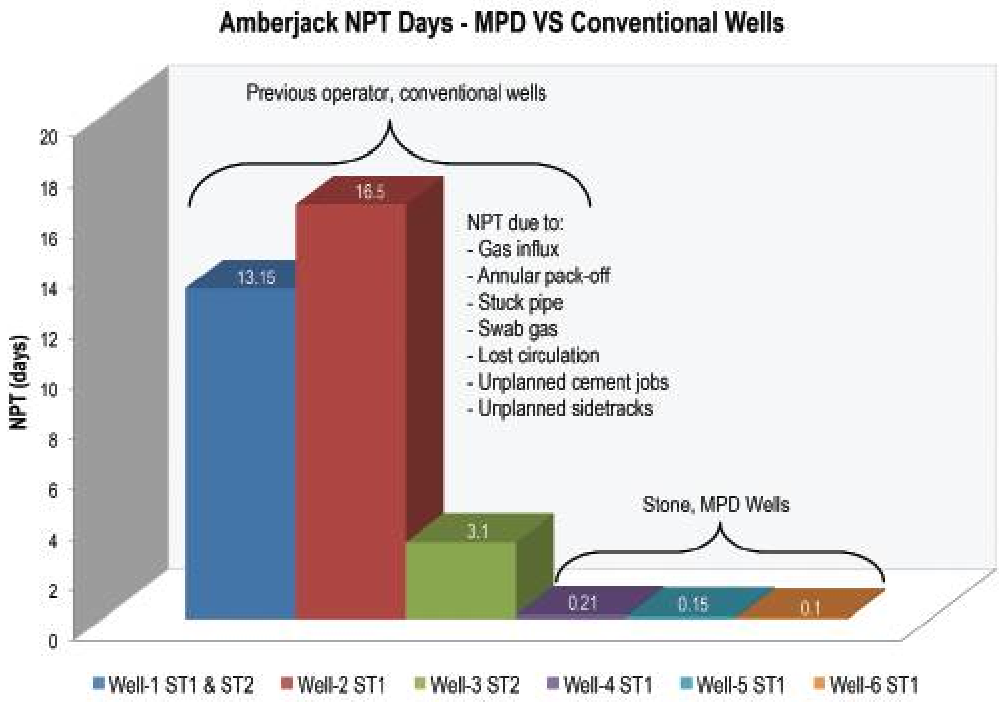


Figure 1.2: *NPT comparison of conventionally drilled offset wells and MPD wells. Figure adapted from Moreau and Fredericks (2011).*

Figure 1.2 addresses the value of MPD, where previous conventionally drilled offset wells are compared to three MPD wells drilled for redevelopment of the Amberjack field in the Gulf of Mexico. For the earlier conventionally drilled wells the total NPT was more than a month, compared to less than half a day for the three MPD wells. In this case, application of MPD proved to be highly valuable by overcoming troublesome drilling challenges related to geomechanical challenges and wellbore pressure variations. (Moreau and Fredericks, 2011)

The example above is one of many examples that proves that MPD has a great impact on reduction in NPT. This enables the drilling operators to predict a more certain estimate of how long the drilling operation will take. It is stated that the root cause of cost uncertainty in drilling operations is the risk of NPT (Sonic Energy Services LTD., 2012). In challenging "high-cost" offshore environment the ability of correct prediction has a major impact on the decisions made. Figure 1.3 illustrates a comparison between cost uncertainty for conventional drilling and MPD.

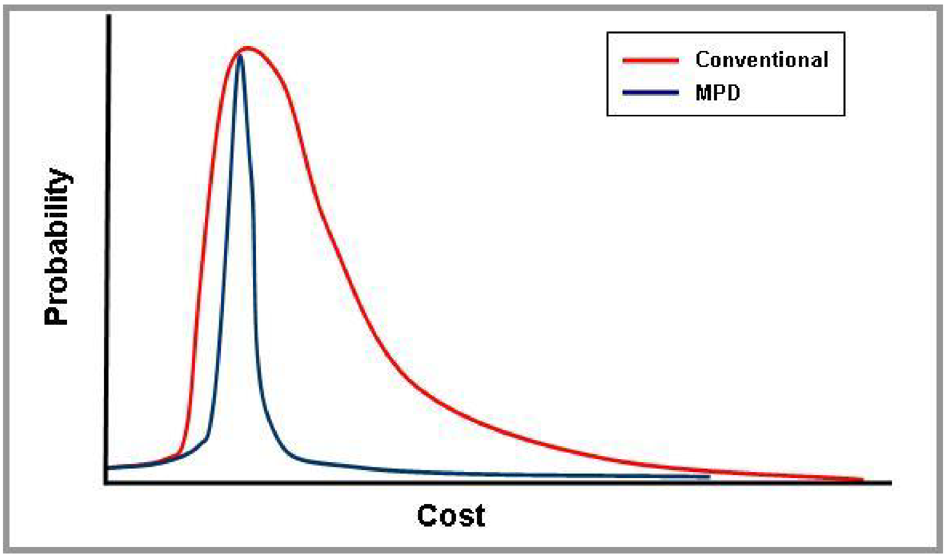


Figure 1.3: *Drilling Cost Uncertainty (Sonic Energy Services LTD., 2012).*

1.2 Scope and emphasis

The scope of this thesis will be to build the MPD Heave Rig and function test the system to prepare for experiments. A functional specification of the MPD Heave rig will be given together with the presentation of the rig functionality and design. Theoretical background of the MPD method applied and related to the technology will be presented to give the reader an understanding of the value of this project. A brief summary of previous work, both generally and specific related to this project, will be given in this thesis, however, the reader is referred to the project report ”Heave Compensated Managed Pressure Drilling: A Lab Scaled Rig Design” by Gjengseth and Svenum (2011) for more details regarding the planning of the MPD Heave Rig. A plan for commissioning tests of the MPD Rig devided into verification and identification will be presented. A risk assessment for the whole process of building and running experiments will be conducted to detect possible risks. As a response to the risk assessment mitigating measures will be implemented to avoid detected risks.

1.3 Outline of thesis

The outline of the thesis is as follows: Chapter 2 gives an overview over the ”State of the Art” by briefly presenting the principles of conventional drilling and MPD, in addition to application of MPD and challenges with implementing MPD from floating rigs. Chapter 3 gives a short presentation of previous work related to MPD in the industry and a brief recap of the planning effort of the MPD Heave Rig based on the project conducted in the fall. Chapter 4 presents the functionality and final design of MPD Heave Rig design with technical components and instrumentation. The results from the risk assessment are presented in chapter 5, however, the full report can be found in Appendix A. A plan for planned commissioning tests to verify and identify parameters of the MPD Heave Rig is given in chapter 6. The Detail Operation Plan of the planned commissioning tests can be found in Appendix B. The results of the conducted tests are presented in chapter 7. Discussion and conclusion of the work and recommendation for further work are presented in chapter 8 and 9 respectively.

2 State of the art

2.1 Conventional drilling

The principles of conventional drilling were developed already in 1901 at the Spindeltop field, Beamont, Texas, where a weighted mud column was applied in the drilling operations with an open-to-atmosphere mud return system (Kernche et al., 2011). Conventional drilling has gone through several improvements according to industry standards, however, the principles remain the same.

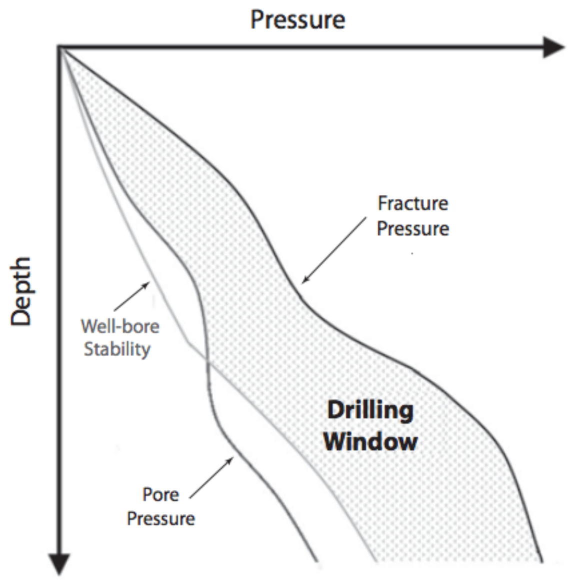


Figure 2.1: *Drilling window: The area between the pore pressure/wellbore stability curve and the fracture pressure. The pore pressure is often the lowest critical pressure, however wellbore stability, as a function of stress and well direction, might sometimes form the lowest limit for drilling fluid density; i. e. directional wells. Figure Adapted from Rehm et al. (2008).*

The drilling fluid circulation of conventional drilling, as we know it today, begins with the mud being pumped downhole from the mudpit through the drillstring and the drill bit, up the annulus, out the top of the wellbore to the mud-gas separator, solids control equipment and back to the mudpit. Unlike MPD, where a closed-loop drilling method is applied, the drilling operation is open to the atmosphere. By application of conventional drilling it is desired to stay within the drilling window (see figure 2.1) by use of a drilling fluid with a specific gravity greater than the pore pressure gradient/wellbore stability gradient and smaller than the fracture gradient.

The mud weight can be changed by circulating lighter or denser materials downhole. However, this can be a time consuming process, and while drilling in a very narrow mud window with rapid change in the pressure profiles, this can lead to a number of unwanted events like kicks, wellcontrol events and lost circulation. When the mud pumps are off the drilling fluid is considered to be in static condition and the BHP is determined by the hydrostatic pressure of the mud column (equation 2.1). During the circulation (dynamic condition) the BHP is determined by the sum of the hydrostatic pressure and the annular friction pressure (AFP) (equation 2.2) (Hannegan and Fisher, 2005).

$$BHP_{Static} = P_{Hyd} \tag{2.1}$$

$$BHP_{Dynamic} = P_{Hyd} + P_{AF} \tag{2.2}$$

Without adding denser or lighter materials to the mud, the only way to change the wellbore pressure profile is by adjusting the speed of the mud pumps. When drilling in a narrow mud window, the well can be under control in static condition, but when circulation starts, the addition of AFP can cause the equivalent circulation pressure (ECD) to exceed the fraction pressure, which can cause damage of the formation, often followed by lost circulation. Lowering the mud weight can cause influx of formation fluid when the well is static again. A kick-loss scenario is present. These scenarios are time consuming and cause NPT when drilling conventionally in narrow or relatively unknown drilling windows. MPD is a solution to this problem and enables to drill in smaller drilling windows than conventional methods, and allows for a more accurate control of the BHP. (Kernche et al., 2011)

2.2 MPD

Hannegan (2006) addresses MPD as one out of three drilling methods in the family of controlled pressure drilling technologies, which also includes Underbalanced Drilling (UBD) and Air or Gas Drilling. These three methods are considered as closed pressurized systems, and are all used to benefit the operation with cost reductions. An evaluation of the prospects to be drilled is needed to choose the best suited drilling method to be applied out of these three methods. Reasons to drill under-balanced or with air or gas as a drilling fluid can be a sub-normally pressured reservoir, hard rock, non-hydrocarbon bearing formation or to simply drill faster with an increased rate of penetration (ROP). Application of MPD is primarily motivated by reduction in NPT, reduction in pressure related drilling hazards and to be able to drill technically or economically un-drillable prospects (Kernche et al., 2011).

The Underbalanced Operations & Managed Pressure Drilling Committee of the International Association of Drilling Contractors (IADC, 2008) has made the following definition of MPD, adopted by the Society of Petroleum Engineers (SPE):

Managed Pressure Drilling (MPD) is an adaptive drilling process used to precisely control the annular pressure profile throughout the wellbore. The objectives are to ascertain the downhole pressure environment limits and to manage the annular hydraulic pressure profile accordingly. It is the intention of MPD to avoid continuous influx of formation fluids to the surface. Any influx incidental to the operation will be safely contained using an appropriate process.

- *MPD process employs a collection of tools and techniques which may mitigate the risks and costs associated with drilling wells that have narrow downhole environmental limits, by proactively managing the annular hydraulic pressure profile.*
- *MPD may include control of back pressure, fluid density, fluid rheology, annular fluid level, circulating friction, and hole geometry, or combinations thereof.*
- *MPD may allow faster corrective action to deal with observed pressure variations. The ability to dynamically control annular pressures facilitates drilling of what might otherwise be economically unattainable prospects.*

2.2.1 Closed pressurized fluids system

As previously mentioned, the MPD system is a closed and pressurized drilling fluid circulation system. A basic configuration of a MPD needs to involve the following three components (Aadnoy et al., 2009):

- Rotating Control Device (RCD)
- Dedicated drilling choke
- Drillstring Non-Return Valves

The RCD seals the annulus and allows for choke control of the annular pressure during drilling operation. The RCD is considered as the key tool to obtain a closed pressurized system and has a number of different designs depending on its application. For onshore drilling and drilling from fixed platforms, the RCD is usually mounted on top of or on the head of the blowout preventer (BOP). For floating rigs the RCD is typically placed on top of the marine riser in the moon pool area. However, there are a number of new solutions for RCD designs from floating rig already existing and under development. On floating rigs flexible flow lines connected to the RCD are implemented to compensate for the movement between the rig and the riser. (Aadnoy et al., 2009)

2.2.2 Categories of MPD

According to Hannegan (2006) there are two categories of MPD;

- Reactive
- Proactive

Reactive MPD applies MPD methods and/or equipment are applied as a contingency to react on drilling problems and downhole surprises arising during the drilling operation (Malloy, 2008). The well is often planned conventionally, with an open circulating system. However, MPD system with equipment and procedures can be activated when unexpected events occur during the operation. Application of a RCD is an example of a contingency tool in combination with BOP to prevent hydrocarbons escaping uncontrolled from the wellbore to the rigfloor . The Returns flow control/Health Safety Environmental (HSE) variation of MPD is often considered as reactive MPD. (Malloy, 2007)

Proactive MPD is a planned MPD operation with a closed pressurized system where a MPD method and/or equipment are selected to control the downhole pressure actively to reduce the NPT and to avoid possible well control events. Application of proactive MPD can benefit the drilling operation by reducing the number of casing strings, deeper casing seats, reducting the mud costs and better the pressure control for advanced warnings of unwanted events and mitigate the number of donwhole surprises (Malloy, 2007). Proactive MPD is the most common approach and has many variations. This thesis' focus is application of Constant Bottom Hole Pressure (CBHP) MPD from floating rig as a proactive MPD method to proactively control the BHP by application of back pressure from surface in combination with a choke manifold.

2.2.3 Variations of MPD

According to Aadnoy et al. (2009) MPD can be divided into four key variations, where each and one or a combination of two is developed with the intention of managing the wellbore pressure more precisely.

- Constant Bottomhole Pressure(CBHP)
- Returns Flow Control (HSE variation)
- Dual Gradient and Deep-water Dual Gradient
- Pressurized-Mudcap Drilling (PMCD)

It is desired to develop a solution for CBHP MPD for drilling operations from floating rigs operating in severe heave conditions. This thesis is presenting a set up for lab testing of a control system to control pressure variations due to heave motions by use of CBHP MPD. The principles of CBHP are explained in the following section, however a more detailed explanation of the other three MPD techniques can be found in Gjengseth and Svenum (2011).

2.2.4 Constant Bottomhole Pressure (CBHP)

The objective of CBHP is to maintain the BHP constant while drilling with a drilling fluid wether the well is in static condition or dynamic condition. This is done by applying backpressure from surface. The pressure variations can be sealed or released by a manually or automatically controlled choke manifold (see figure 2.2). (Malloy, 2007)

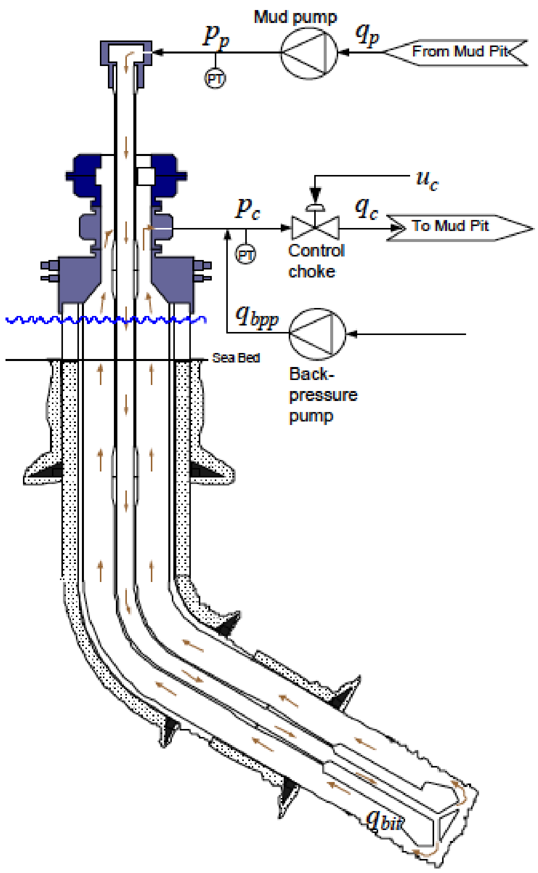


Figure 2.2: *Schematic of a CBHP MPD system with backpressure pump and choke manifold. Figure adapted from Landet et al. (2012).*

This implements a more instant control over the BHP compared to changing the mud weigh in the well, which, as previously mentioned, can be a time consuming process, especially in deepwater wells. The BHP in static condition can be expressed as the sum of the hydrostatic pressure and the applied backpressure from the back pressure pump at surface (equation 2.3).

The BHP in dynamic condition can then be expressed as the sum of the hydrostatic pressure, the AFP and the applied back pressure (equation 2.4). (Malloy, 2007)

$$BHP_{Static} = P_{Hyd} + P_{BP} \tag{2.3}$$

$$BHP_{Dynamic} = P_{Hyd} + P_{AF} + P_{BP} \tag{2.4}$$

Figure 2.3 compares conventional and CBHP MPD in static and dynamic condition. For conventional drilling, in a narrow drilling window, AFP may cause the wellbore pressure to exceed the friction pressure. However, with application of CBHP, the BHP can be maintained constant between the margins of a narrow drilling window whether the well is circulating or not; In static condition the drilling fluid weight is reduced, and backpressure is applied to compensate for the reduction when the well is static. During circulation, the applied back pressure is reduced to compensate for AFP, and the BHP is maintained constant. The ability of a more accurate control of the BHP, allows for deeper casing setting depths before drilling fluid density needs to be changed and increases the chance of being able to drill to total depth. Deeper casing depths, may also lead to a reduction in the number of casings. CBHP MPD allows for application of lighter drilling fluids compared to conventional drilling, and maintains the well closer to pore pressure. This minimizes the risk of damaging the formation and drilling fluid losses. A reduction in overbalanced pressure improves the ROP which is considered as a great economical gain. A more constant and reliable BHP reduces pressure variations and the promotion of wellbore instability. (Aadnoy et al., 2009)

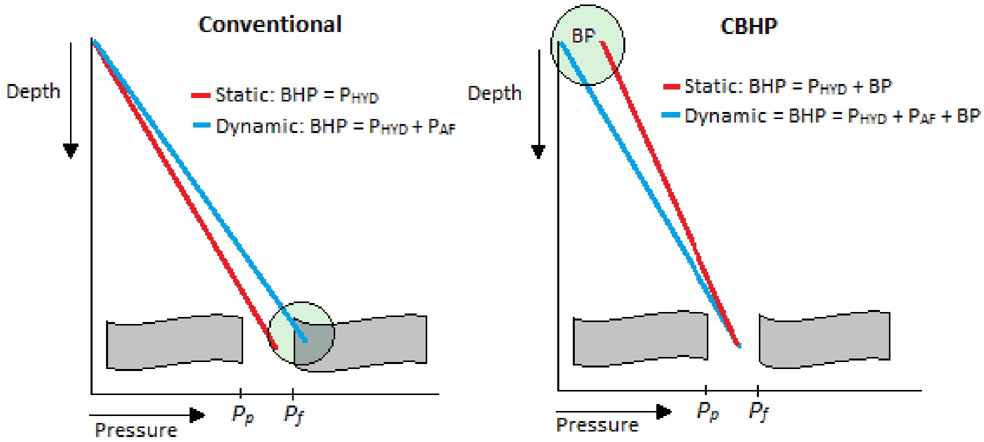


Figure 2.3: *To the left; Pressure versus depth illustration of conventional drilling. The BHP is increased in dynamic conditions due to the AFP (P_{AF}) and the BHP exceeds the fracture pressure (P_f). To the right; pressure versus depth illustration of CBHP. The mud weight is reduced and backpressure is applied to compensate for the reduction in static condition. In dynamic condition, the backpressure is reduced to keep the BHP to compensate for the AFP. Figure adapted from (Gjengseth and Svenum, 2011).*

2.3 Application of MPD

2.3.1 Narrow drilling window

MPD addresses the challenges related to narrow drilling window and allows for a more certain downhole pressure control. There are various environment where a small margin between the pore pressure gradient and the fracture gradient is present. HTHP fields, depleted reservoirs and deep-water drilling are all typical narrow drilling window cases where application of MPD can benefit the operation. In these environments, excessive heave motions can make drilling operation from floating rigs even more vulnerable when it comes to controlling the BHP. This is especially the case during drillstring connections where surge and swab effects can lead to major downhole pressure fluctuations affecting the BHP. (Rasmussen and Sangesland, 2007)

Pressure depletion is referred to as a reduction in pore pressure due to the volume change in the reservoir when oil and gas are produced. The reduction in pore pressure also leads to a reduction in fracture gradient (see figure 2.4), which in many cases is hard to predict prior to drilling into a depleted reservoir. This can result in a reduction of the drilling window as the reservoir produces (Hannegan, 2011a). Depending on if the depletion is even, uneven or unknown between the reservoir sections, unexpected pressures can be encountered during the drilling operations. Some of the layers may still have presence of initial pore pressure which can lead to influx from the formation (Nilsen, 2009). This unexpected well control event may be handled more instantly with application of MPD compared to conventional methods.

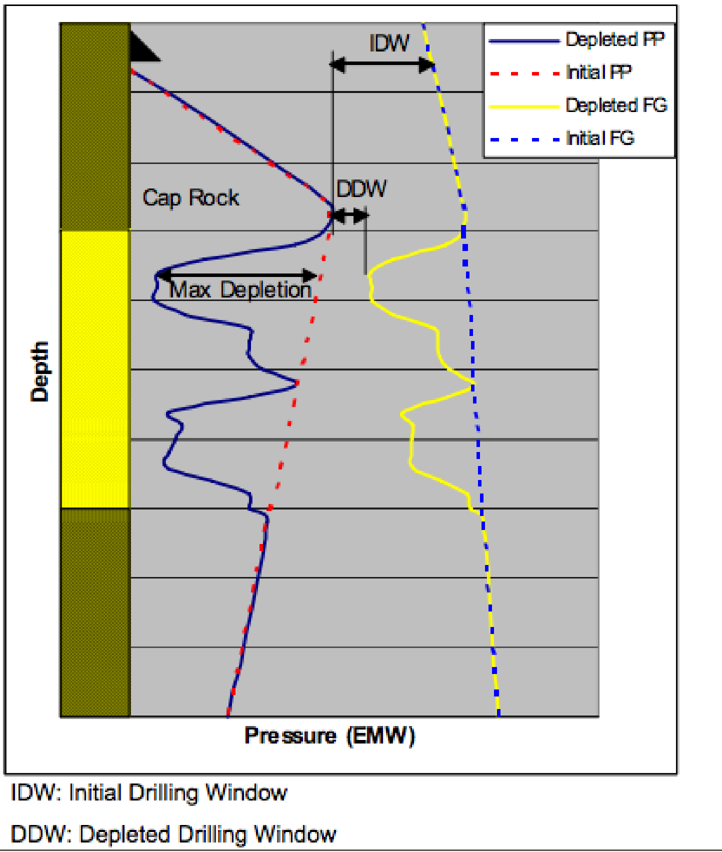


Figure 2.4: *Depleted reservoir: Production from the reservoir causes a reduction in the pore pressure followed by a reduction in fracture pressure. The reduction in fracture pressure is difficult to predict, and results in an uncertain pressure regime. Figure adapted from Nilsen (2009).*

The Kristin field is an example of a currently depleting reservoir, located in the North Sea. The field is classified as a HPHT with an initial pore pressure of 911 bar and a reservoir temperature of 172 ° C. Due to the high initial pressure, the pore pressure gradient is rapidly declining during production with a depletion factor estimated to be 0.65, meaning that the fracture gradient is lower than the pore pressure gradient, which results in a declining drilling window. In this field it is desired to apply MPD on new planned wells to better the control of the BHP. However, the Kristin field is also challenged by harsh weather conditions in addition to the narrow drilling window. When the bit is off bottom, during connections, the volume change due to heave motions can cause pressure fluctuations of 5-10 bar, which also needs to be encountered in the MPD control system to maintain the BHP pressure within the drilling window. (Solvang and Leuchtenberg, 2008)

Deepwater drilling is challenged by a decreasing fracture gradient due to the overlying water (see figure 2.5). With an increasing pore pressure and a decreasing fracture gradient, the operational drilling window may require more casing strings to stay within the operational limitations. As the casings are decreasing in size, the annular clearance between the drillstring will decrease. This may affect the magnitude of the downhole pressure fluctuations due to the surge and swab effect when drilling from a floating rig, and require a more precise pressure control that could be obtained by application of MPD. Aadnoy et al. (2009)

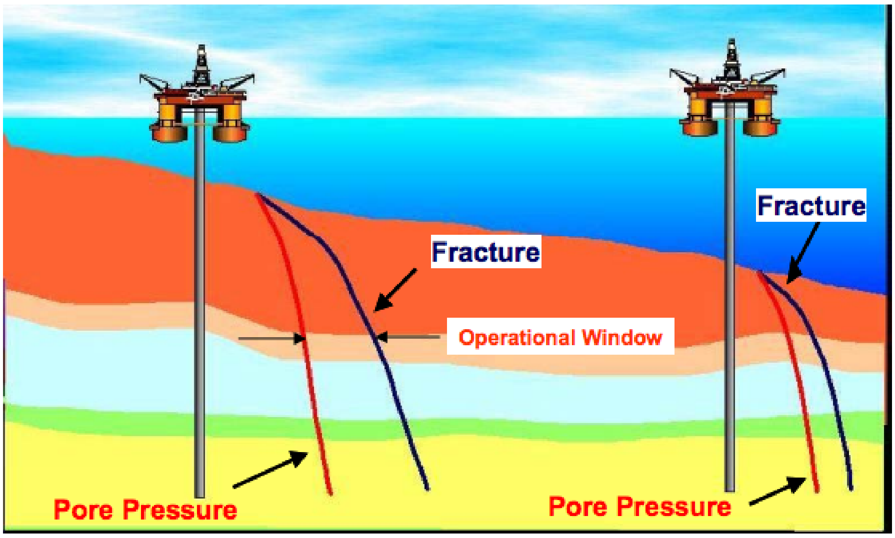


Figure 2.5: *Pore pressure and fracture pressure gradients comparison for different water dephts. The fracture pressure gradient decreases for deep-water due to the overburden water. Figure adapted from Rocha et al. (2003).*

2.4 Floating rig challenges

A number of challenges related to implementation of MPD on floating rigs are addressed in Gjengseth and Svenum (2011). Differences in equipment i.e subsea BOP and marine riser and RCD design make the implementation of MPD on floating rigs more challenging than for fixed platforms, which are more similar to land drilling rigs, where MPD has been practiced for decades (Hannegan, 2006). In addition to practical implementation of equipment and new design of tools and equipment, the drilling operation is also challenged by the continuous heave motion in the sea, especially in harsh environments like the North Sea.

2.4.1 Heave motion

The weather has a big impact on the operational window for a floating rig in the North Sea. During the fall and winter months, harsh weather and rough sea can stop the operation for many days in a row. During these storms the heave can be as high as 12 to 13 m and it is impossible to continue drilling operation. In normal conditions the heave can vary from 1 to 6 m, which can allow the rig to continue operations (Romstad et al., 2010). The maximum heave for operation is however depending on rig size, configuration and the type of operation.

2.4.2 Surge and swab effect

As previously mentioned, the wellbore pressure profile consist of dynamic pressure and static pressure. The static pressure is representing the hydrostatic pressure of the fluid in the well. The dynamic pressure is a sum of various components related to movements of the drilling fluid and drill pipe in the well; drillstring velocity, acceleration or decelerations during tripping operations, breaking the drilling fluid gel and pressure loss needed to return cuttings and drilling fluids (Bourgoyne et al., 1986).

When a pipe is lowered into the well the drilling fluid is forced to move upwards the annulus and out the flow line as the drillstring volume is displacing some of the fluid present in the well. At the same time the drilling fluid closest to the pipe is dragged downwards. This piston effect causes a pressure increase which is referred to as surge pressure. This differential pressure is added to the hydrostatic pressure and causes an increase in the BHP. When the pipe is pulled out of the hole, a similar differential pressure occurs and causes a decrease in the BHP. This differential pressure is referred to as swab pressure. Drilling problems related to swab pressures are borehole instability, kicks and in worst case blowouts. Surge pressure can cause damage on the formation when exceeding the fracture pressure followed by lost circulation. (Bourgoyne et al., 1986)

The surge and swab effect is continuously present whenever the drillstring is moved up or down in the hole causing downhole pressure fluctuations. However, the magnitude of the effect is dependent on many factors; i. e.

well-design and drilling fluid rheology. The challenges related to surge and swab effects are common knowledge in the industry, and drilling operators practice with maximum tripping velocities for run in hole (RIH) and pull out of hole (POOH to avoid surge and swab differential pressures that exceeds the operational window (Lal, 1983).

When drilling from a floating rig, where severe heave motions are present, tripping speeds and velocities for running casing and liners are no longer the only concern regarding the surge and swab pressure. During drilling and tripping mode, the heave compensator is activated and controls the position of the drillstring. However, during connections, when new segments (drillpipe stand or drill collar) are added to the drillstring, the mud pumps are ramped down and the drillstring is suspended in slips and moves vertically up and down with the heave motion. This can result in large surge and swab pressures downhole, which can lead to pressure increase or decrease resulting in unstable BHP. (Rasmussen and Sangesland, 2007) If these pressure fluctuations could be controlled by implementing an automatic MPD system on floating rigs, doors would open for drilling many of today's inaccessible reservoirs present in mature deepwater fields where challenging weather conditions, severe heave motions and narrow pressure margins are the major limitations in being able to conduct safe drilling operations.

Modeling surge and swab

As previously mentioned, the surge and swab pressure fluctuations are affected by many factors. Several models have been produced to predict the wellbore pressure profile concerning the surge and swab pressures when pipe is lowered in to the borehole. These models can be divided into steady state models and dynamic models, and are based on various parameters. The most common Steady State Models are developed by Burkhardt (1961) and Schuh (1964); Bingham model and Power-law model.

According to the Bingham model developed by Burkhardt (1961) there are three major effects that contribute to generating surge and swab pressures; gel Strength, fluid interia and viscous drag. Mitchell (1988) states these steady state predictions are neglecting important parameters that have an impact on the wellbore pressure profile, i.e. compressibility (Rehm et al., 2008). As a response to this dynamic models, also known as transient models, were developed to simulate the relation between the pipe movement and pressure as a function of time (Rehm et al., 2008). In most cases, steady state models give a conservative result which can be sufficient for many purposes.

However, it is believed that transient pressure models give a more accurate result for surge and swab prediction in deeper wells (Rehm et al., 2008). The transient models are more complex and are developed as technology has improved with better tools and computers. Halliburton offers the Landmark Wellplan Surge Module which is commonly used in the industry (Halliburton, Halliburton). This program is based a dynamic surge model developed by Mitchell. According to Rehm et al. (2008) transient models consider the following factors:

- Fluid properties
- Drilling fluid gels
- Geometry of the wellbore and pipe
- Velocity of the pipe
- Compressibility of the drilling fluid and the wellbore
- Fluid interia
- Pipe distance off the bottom of the hole
- Drilling bit and nozzle
- Pipe elasticity and acceleration of the pipe

The size of the borehole, the drillstring and bottom hole assembly (BHA) diameter have an impact on the magnitude of the surge and swab pressure created in relation to the annular clearance in the well. As the pipe is lowered or lifted out of the hole the fluid will be displaced by the volume of the drillstring entering the hole. A very narrow annular clearance will cause a high pressure drop over the volume, especially the BHA, which has a larger diameter than the rest of the drillstring. Decreased annular clearance is also related to bit balling; caused by drilling cuttings packing around the bit. This can decrease the annular clearance even more, or in worst case block the flow path of the drilling fluid. Rudolf and Suryanarayana (1997) presents result from modeling of bitballing, where a significant increase in surge pressure is found due to the decrease in annular clearance. According to Rudolf and Suryanarayana (1997) larger hole diameter, caused by i.e. washouts, causes a reduction in compression of the drilling fluid below the bit since the drilling fluid can pass the bit more easily. Hence, the surge pressure is decreased.

The velocity of the drillpipe highly effects the magnitude of surge and swab pressures. The faster the drillpipe moves, the larger surge and swab pressures. As previously mentioned it is common to operate with maximum tripping speeds. However, there is no way to control velocity of the drillstring caused by the heave motion. To overcome troublesome heave motions, by implementing automatic MPD, is one the main motivations with this thesis. A comparison of surge and swab pressures in relation to maximum velocity of the drillstring can be seen in figure 2.6 (Rasmussen and Sangesland, 2007). The velocity of the drillstring applied is a simplified model, following the motion of a harmonic wave and is thought to be the velocity of the drillstring at surface. In a real case the actual velocity of the drillstring will be affected by factors like viscous drag, its elasticity, the friction between the hole and drillstring (Rudolf and Suryanarayana, 1997).

Amplitude ± (m)	Period (sec)	Max Velocity ± (m/s)	Surge/swab pressures ± (bar)	
			TTRD	Conventional
0.5	11	0.29	10.18	11.74
1.0	14	0.45	14.00	15.23
1.5	11	0.86	24.32	22.13
3.0	13	1.45	55.63	38.69

Figure 2.6: *Comparison for surge and swab due to heave motion between conventional system and Through Tubing Rotary Drilling (TTRD) in a 4000 m deep well. Conventional system: 5" drillpipe, 6" BHA, 8 1/2" bit. The table is adapted from Rasmussen and Sangesland (2007).*

2.5 Automated MPD

For CBHP MPD the choke can be controlled either manually or automatically. However, optimal application of MPD requires an automatic control to avoid human errors like reduced accuracy, slower response time and less repeatability (Godhavn and Knudsen, 2010). By implementing an automatic MPD control, the drilling crew are able to focus on other tasks as optimizing the drilling operation by maintaining a low risk and high efficiency on the operation.

The CBHP MPD method applied in this thesis is based on an automatic MPD system (see figure 2.7) consisting of two parts; A hydraulic model that estimates the BHP in real-time and outputs a desired choke pressure according to a desired downhole pressure set-point (Kaasa et al., 2011).

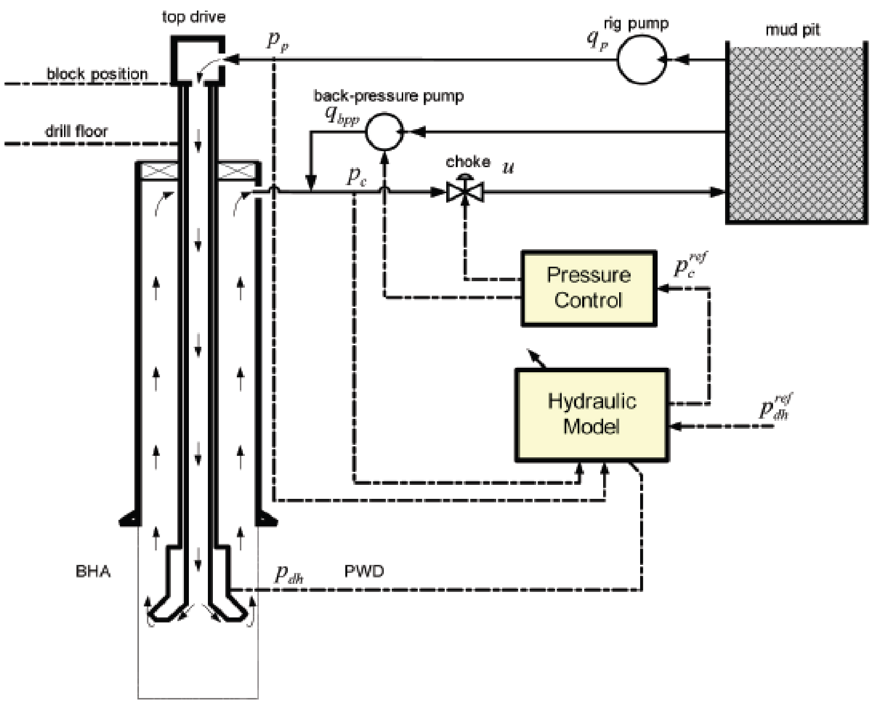


Figure 2.7: *Simplified illustration of automated MPD system. Figure adapted from Kaasa et al. (2011).*

3 Previous work

MPD and development of the technology, with various approaches, have been a highly focused field in the industry the past years, and it still has a growing interest as the claim for a more accurate downhole pressure control is present. Challenges and approaches to solutions of controlling the BHP with MPD from a floating rig in a narrow mud window have been topic in a number of papers, see Rasmussen and Sangesland (2007); Hannegan (2011a); Solvang et al. (2008). Results from research on control design of MPD to find systems that can handle rapid variations in BHP as a result of severe heave motions have been published by several researchers; Landet et al. (2012); Breyholtz et al. (2010).

The main goal with this work is to provide a test system for testing of the control system under development. The planning of the MPD rig started the fall of 2011, where three master students from the Department of Petroleum Engineering & Applied Geophysics were involved in the process to come up with a model for the MPD Heave Rig. Two project reports were submitted as an approach to the master's thesis spring 2012; Gjengseth and Svenum (2011) and Rashid (2011). A brief recap of the project report "Heave Compensated Managed Pressure Drilling: A Lab Scaled Rig Design" (Gjengseth and Svenum, 2011) is presented in the following subchapter.

3.1 Planning of MPD Heave Rig

3.1.1 Lab scale

The MPD Heave Rig model and the simulations conducted are based on field data of a 4000 m deep vertical well where a drill string of 5 inch diameter in a 8.5 inch diameter hole with a BHA of 70 m is exposed to a heave with an amplitude of 1.5 meters and a period of 11 seconds. Scaling of the field data down to reasonable lab scale in addition to meeting the requirements to the control system were an important part of the planning phase, and different cases where tested in Matlab simulations. In a real case the major contributions to surge and swab pressures in the well are pressure variations related to the different geometries in the well. The drillstring consists of a the drill collar and the drill bit with a diameter of 6.5 inch. In labscale these geometries were simplified to a one single diameter drillstring and a cylinder shaped volume representing the BHA. To simulate different surge and swab pressure drops over the BHA, the length and diameter of the BHA were changed in the simulations to decide which scale to be used in the actual rig model. Further evaluation of these aspect has been conducted by Svenum (2012).

3.1.2 Heave motion model

The actual motion of a floating rig is a complicated model, which is dependent on a number of factors, the mass load of the rig, alleviation of the movement of the rig and variations in the heave. For the purpose of testing in lab scale, it was decided to apply a simple harmonic wave in the modeling the position of the drillstring (equation 3.1). The velocity and acceleration of the drillstring will follow a cosine and sinus curve respectively (equation 3.2 and 3.3). The velocity of the drillstring can be changed by varying the period and the amplitude of the wave. The surge and swab pressures downhole will change accordingly. As a base of the simulations a period of 11 s and an amplitude of 1.5 m are used. This gives a maximum velocity of the drillstring of 0.86 m/s. A plot of the velocity of the drillstring due to heave motion with a period of 11 s and an amplitude of 1.5 m can be seen in figure 3.1.

$$z(t) = A \sin \frac{2\pi t}{P} \tag{3.1}$$

$$v(t) = \frac{dz}{dt} = \frac{2A\pi}{P} \sin \frac{2\pi t}{P} \tag{3.2}$$

$$a(t) = \frac{d^2 z(t)}{dt^2} = -A \frac{4\pi^2}{P^2} sin \frac{2\pi t}{P} \tag{3.3}$$

where z the drillstring position, v is the velocity of the drillstring and derivative of z, a is the acceleration and the second derivative of z, t is the time, A is the amplitude and P is the period.

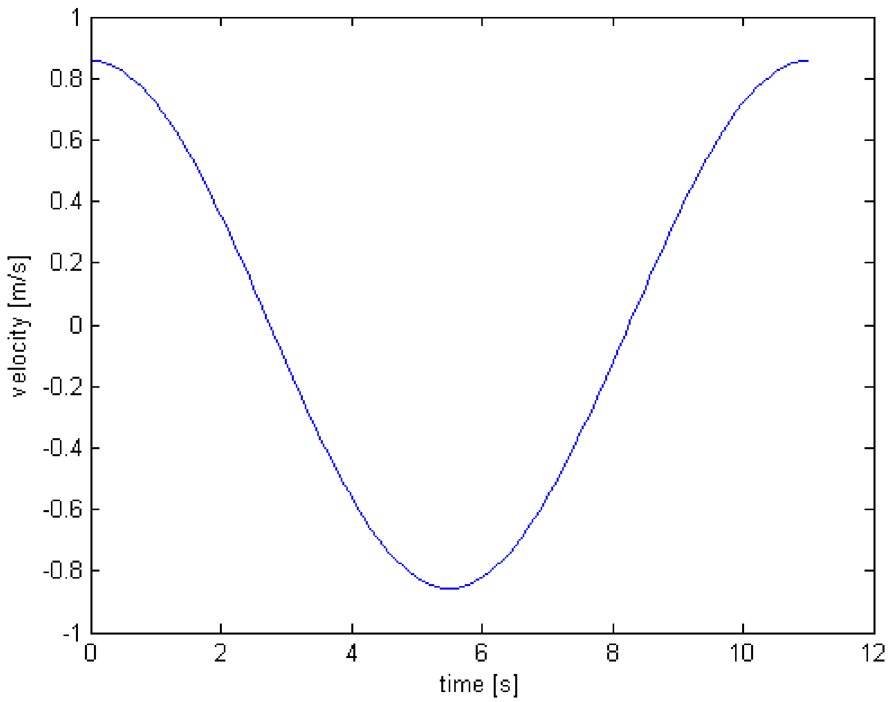


Figure 3.1: *Variation in drillstring velocity according to harmonic wave behavior. Figure adapted from Gjengseth and Svenum (2011).*

3.1.3 Pressure impulse delay

When pressure variations downhole are controlled by adjusting the choke opening at surface, the pressure impulse created by the adjustment will take time to propagate in a 4000 m deep well. To simulate a similar delay in the lab, a 900 m long copper pipe was introduced to the system. This length of the pipe is based on the propagation of pressure waves and a desired delay of 1/5 of a wavelength in the hose. Based on the time delay of the system, the control system require a period of heave of 3 s. To maintain the maximum velocity of 0.86 m/s, the amplitude for testing was adjusted to 0.41 m. The position plot of the movement of the drillstring with a period of 3 s and an amplitude of 0.41 m can be seen in figure 3.2.

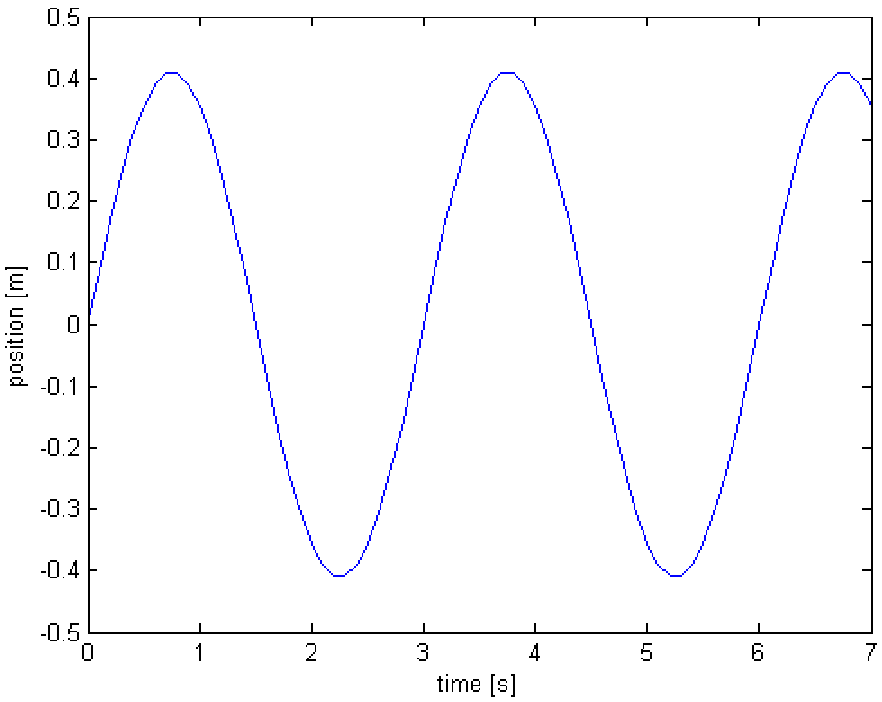


Figure 3.2: *Position plot of the drillstring movement. Figure adapted from Gjengseth and Svenum (2011).*

3.1.4 Displacement of water

The design of the model changed several times throughout the planning phase. More detailed explanations of these changes and assumptions can be found in Gjengseth and Svenum (2011). One concern when implementing a 900 m long hose was to overcome the high pressure losses in the pipe. It was decided to reduce the displacement of fluid moving back and forth out of the well as the drillstring moves up and down. To this point the drillstring consisted of an upper pipe connected and the BHA, similar to a drillstring applied in the field. By implementing a lower pipe with the same diameter as the upper pipe below the BHA, the water displacement was eliminated. The lower pipe would also make the whole system more stable and eliminate the problems related to a more freely movement of the drillstring.

From the control system's perspective simulations required flow in the path between backpressure loop and the well in order to recognize variations in the systems to recognize the pressure variations and keep a constant BHP. Simulations with a cross-sectional area 1%, 2% and 5% larger than cross sectional area of lower rod were run to detect how much displacement we could handle to get reasonable readings without too much noise. Based on these simulations the 5%-case was selected, resulting in a displacement flow of 1.2 lpm for maximum velocity of the drillstring (3.4). The diameter of the upper and lower steel pipe is then 25 mm and 24.4 mm respectively.

$$Q_{displacement} = v_{max} \Delta A_{cross-sectional} = 0,86 \frac{\pi}{4} \frac{25^2 - 24.4^2}{10^6} = 1,2 l/m \tag{3.4}$$

3.1.5 Pressure loss over BHA

The main contribution to the surge and swab pressures in the rig model is the pressure loss over the BHA, due to a very narrow annular clearance. The dimensions of the rig's components where carefully chosen to model an overall pressure variation of 4 bar, with an aim to maintain a constant BHP of 6 bar. The pressure loss over the BHA due to the heave motion is a combination of friction loss, entrance and exit losses. A plot of the total differential pressure over the BHA as the drillstring is moved up and down can be seen in figure 3.3.

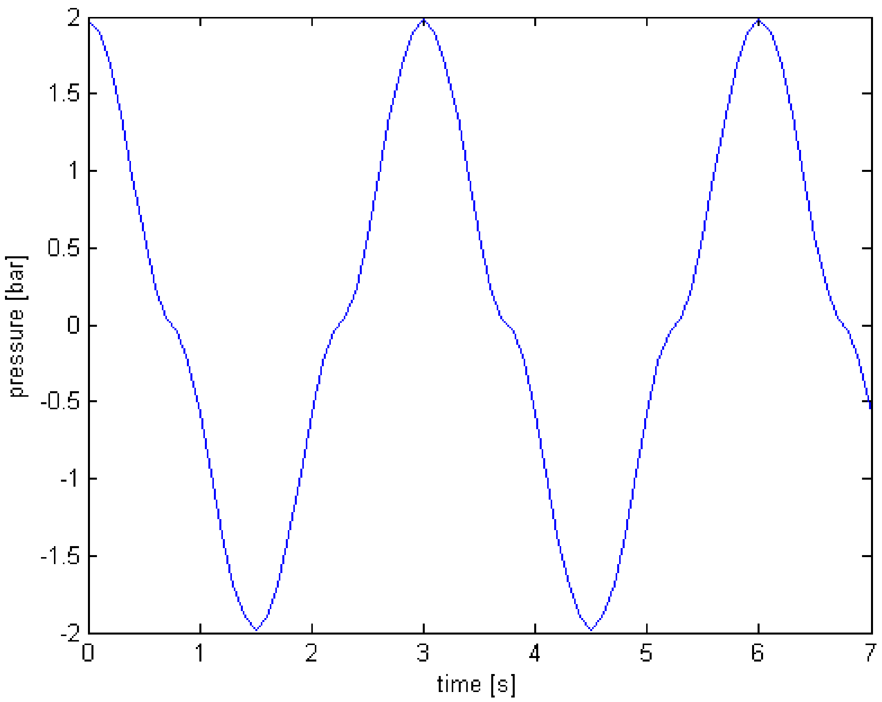


Figure 3.3: *Total pressure loss over BHA. Figure adapted from Gjengseth and Svenum (2011).*

3.1.6 Pressure variations due to acceleration

In addition to pressure variations over the BHA, the control system also needs to compensate for pressure variation due to acceleration of the water moving in the 900 meter long pipe. The maximum acceleration follows the cycle of a sinus wave and occurs when the velocity of the drillstring is zero. A plot of the acceleration can be seen in figure 3.4. The variation in pressure due to acceleration of the water can be seen in figure 3.5.

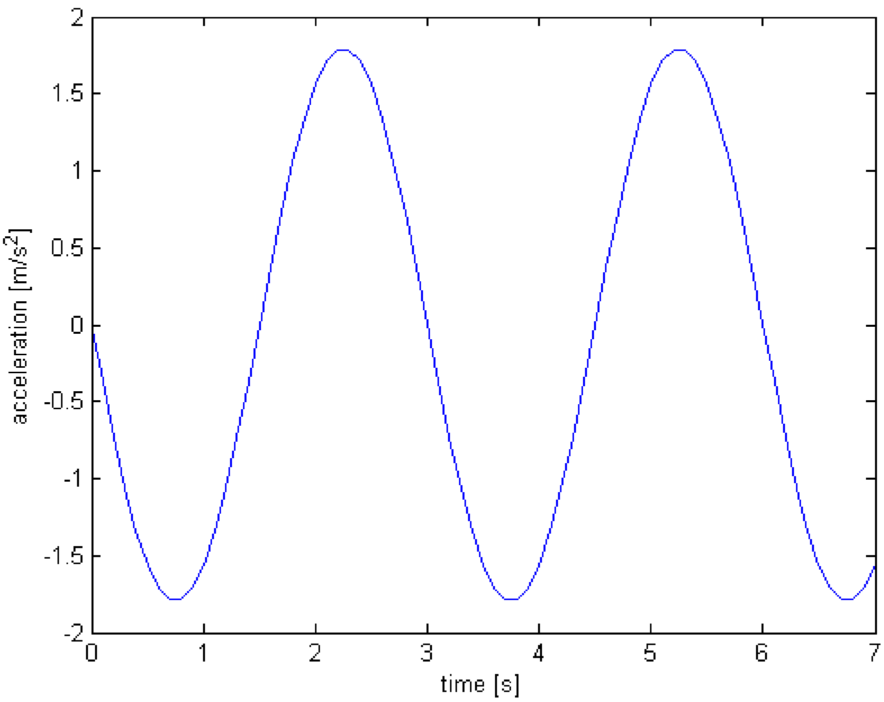


Figure 3.4: *Acceleration of drillstring. Figure adapted from Gjengseth and Svenum (2011).*

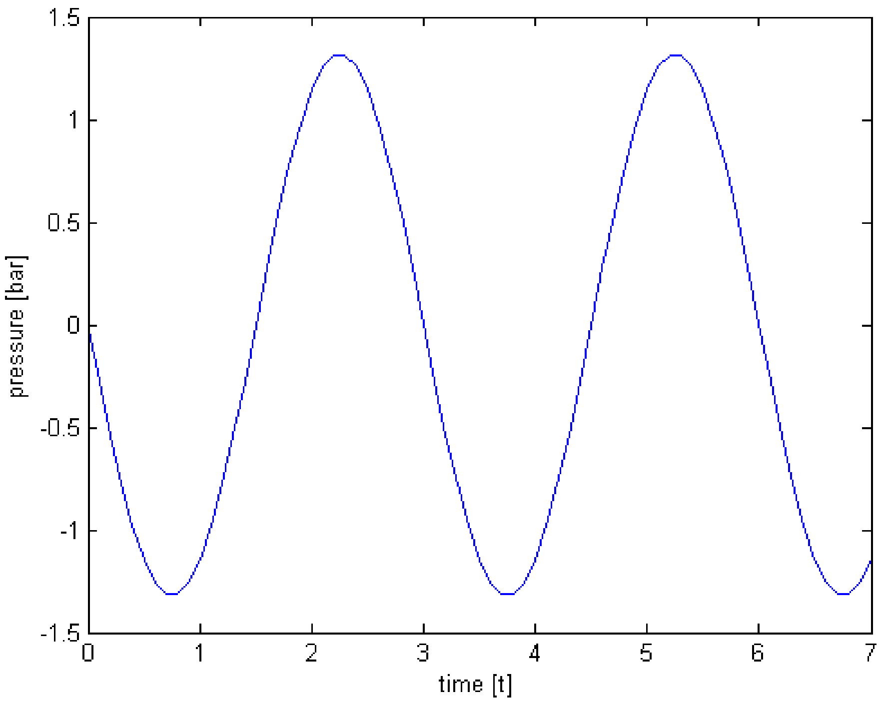


Figure 3.5: *Variation in pressure due to acceleration. Figure adapted from Gjengseth and Svenum (2011).*

3.1.7 Variation in BHP

As previously mentioned, the maximum pressure loss due to acceleration of the water in the system occurs when the velocity of the drillstring is zero. However, the maximum pressure drop over the BHP occurs when the velocity of the drillstring is maximum, in the case of these simulations when $v = 0,86 m/s$. Figure 3.6 shows the variation of pressure due to acceleration and pressure loss over BHA. A plot of the total BHP variation with a constant choke pressure of 6 bar, can be seen in figure 3.7.

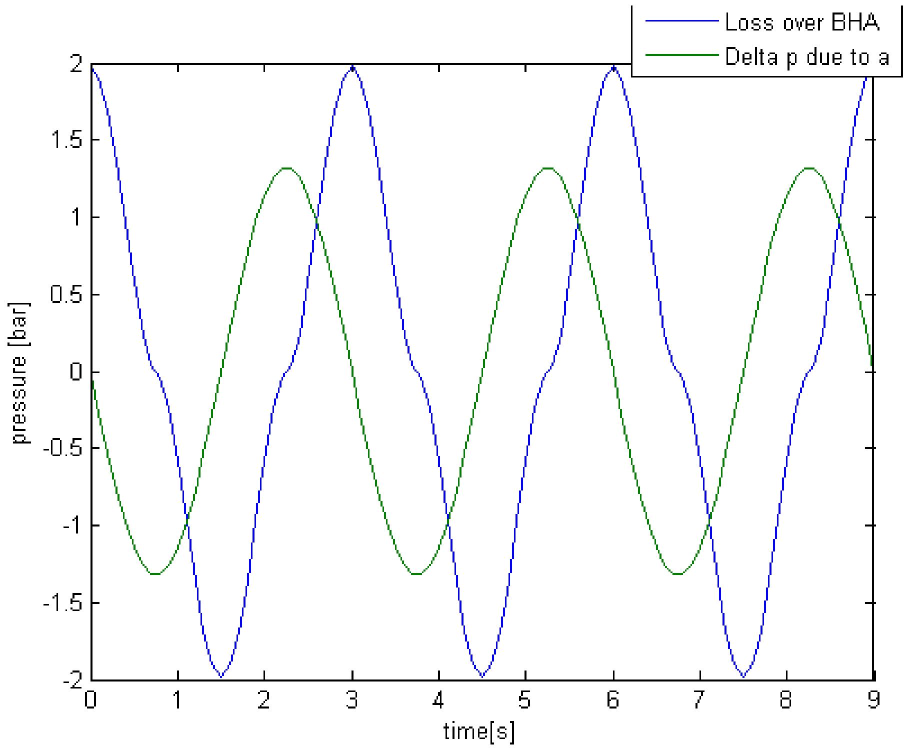


Figure 3.6: *The figure shows the pressure variations due to acceleration and losses over BHA separately. Figure adapted from Gjengseth and Svenum (2011).*

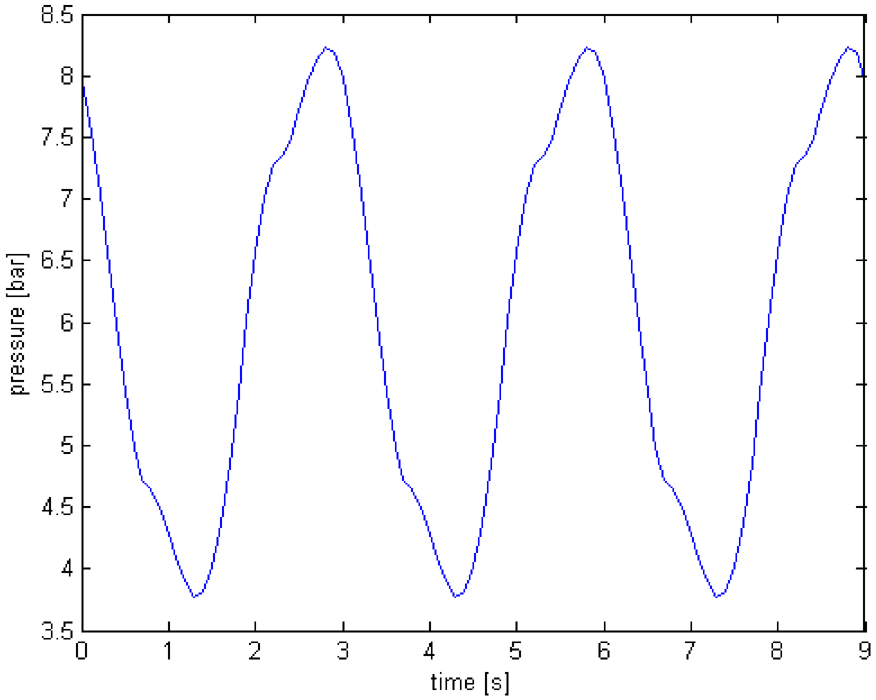


Figure 3.7: *The figure shows variations in BHP with a constant back pressure at the choke of 6 bar. Figure adapted from Gjengseth and Svenum (2011).*

3.1.8 Friction in the copper pipe

The friction between the moving water and the pipe wall may induce a significant pressure loss in 900 m long copper pipe. The flowrate in the copper pipe due to displacement in the hole will not exceed 1.2 lpm (chapter 3.1.4), with the original BHA diameter and the lower steel pipe diameter of 24.4 mm (Svenum, 2012). However, if it is decided to reduce the size of the lower steel pipe or eliminate it, the flowrate in the copper pipe due to displacement will increase. The maximum flowrate due to displacement when the drillstring is moved up and down, considering a drillstring without a lower steel pipe, is 25.3 lpm.

The friction pressure drop can be calculated from the following equations adapted from Gudmundsson (2010).

$$Re = \frac{\rho v d}{\mu} \tag{3.5}$$

Where ρ is density of water ($998.2kg/m^3$), v is velocity of water $0,105(m/s)$, d is pipe diameter $0.016m$ and μ is viscosity of water (Pas). Water has a viscosity of 0.001002 Pas at 20°C.

The Reynolds number is used to define the distinction between laminar and turbulent flow. According to Gudmundsson (2010), the flow is considered laminar for Reynolds number below 2000, and turbulent for Reynolds number above 4000. The flow can be either laminar or turbulent for Reynolds number between 2000 and 4000.

The friction factor for laminar and turbulent flow is given from the following equations respectively.

$$f = \frac{64}{Re} \tag{3.6}$$

$$\sqrt{\frac{1}{f}} = -1,8log((\frac{6,9}{Re})) + (\frac{k}{35d})^{1,11}) \tag{3.7}$$

Where k is the pipe roughness, in our case 0,0000015 m.

For flow with Reynolds number between 2000 and 4000 it is recommended to use an average value of the laminar and turbulent friction factor. The friction pressure drop for either laminar or turbulent flow can be calculated from the Darcy-Weisbach equation.

$$\Delta P = f\frac{L}{d}\frac{\rho v^2}{2} \tag{3.8}$$

Where ΔP is the friction pressure drop (Pa), L is the length of pipe (m), d is the pipe diameter, ρ is the density of water (kg/m^3) and v is the velocity of water (m/s).

Figure 3.8 shows the calculated friction drop in the 900 m long copper pipe with an inner diameter of 0.016 mm. It shows that the friction pressure drop increases as the flow rate increases. This significant increase in friction pressure drop was also one of the main reasons for introducing a steel pipe below the BHA to decrease the flowrate in the copper pipe. The calculations shows that the flow changes from laminar to turbulent when the flowrate is in the range 1.6 lpm ($Re = 2114$) and 3 lpm ($Re = 3963$). It is not accounted for additional losses due to curvature of the copper pipe in these calculations. There are also local bends in the copper pipe that are hard to predict. This may cause a larger pressure drop due to friction than the calculated losses plotted in figure 3.8.

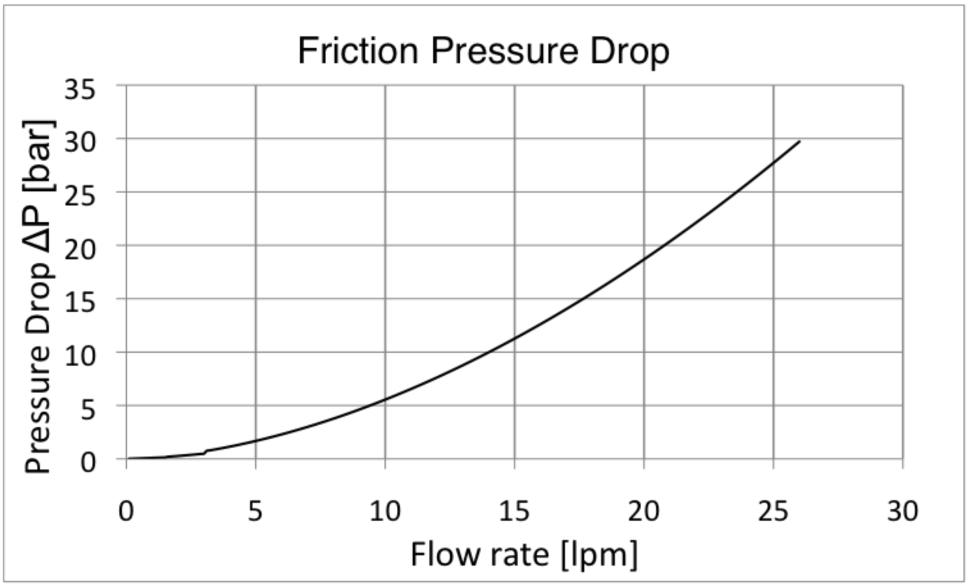


Figure 3.8: *Friction pressure drop for flowrates ranging from 0 - 26 lpm.*

4 Rig functionality and design

This chapter presents the final MPD Heave Rig model. The model has been modified several times prior to meet the requirements of the control system and the hydraulic model. Gjengseth and Svenum (2011) presents challenges, measures and modifications during the planning phase. Selection of sufficient equipment and ordering of the components needed was conducted by Rashid (2011) the fall of 2011, however, this process continued in the spring. As a result the final model with all components is presented here.

4.1 Rig functionality

The purpose of the MPD Heave Rig is to reconstruct the field challenges related to heave motion in lab scale. A new developed control algorithm is to be tested to reduce the downhole pressure variations as much as possible. In this way we can obtain new information to find a solution for controlling the downhole pressure due to severe heave motions in the field. The applied MPD method in the Rig model is based on the principles of CBHP (see 2.2.4), where the BHP is controlled by applying backpressure from the surface by use of a back pressure pump and a choke. The test scenarios focus on the case of connections when there is no circulation in the system. Hence, the model is simplified to a closed pipe model and there is no need for drilling fluid pump to provide circulation in the system. The MPD heave rig model can be divided into the following three systems:

- Backpressure System
- Heave System
- Well System
- Control system

Backpressure system

The backpressure system creates a loop which is continuously circulating water from the water tank. The pump provides water flow which is sealed or released by the choke to apply backpressure as pressure variations is created downhole by the heave system. The choke opening can be adjusted by controlling the choke motor via the control system. The differential pressure over the choke is measured by two pressure transmitters placed on either side of the choke. The flowrate provided by the pump is measured by a flowmeter downstream the pump and a flowmeter downstream the choke.

The heave system

The heave system creates heave motion by driving a motor connected to a wheel with a toothed belt. The toothed belt is mounted to the drillpipe which is moved up and down as the motor is controlled by the computer. Various periods can be applied to vary the velocity of the drillstring, however, the amplitude remains constant. The heave motion can either follow a constant velocity or the velocity of a harmonic wave.

The well system

The well consists of a pipe (well) and the drillstring inside of it, a 900 m long copper pipe and a bypass line. The drillpipe consists of a upper rod and a lower rod, and the BHA in between. To limit the volumetric displacement when the drillpipe is lowered into the well, the drillpipe is extended with a lower rod below the BHA (see 3.1.4). The main contribution to the surge and swab effect in the MPD Heave Model will be the pressure loss over the BHA, since surge and swab pressures over the drillstring can be neglected due to a relatively small diameter and short length. A number of pressure transmitters are applied to measure the pressure in system. The time it takes for the pressure impulse to propagate will have a great impact for timing a correct response from the control system to control the downhole pressure fluctuations. The flowrate upstream the well and upstream the copper pipe/by pass line is measured by flowmeters. Experiments can either include the copper pipe or bypass it. Inlets on the copper pipe also make it possible to run experiments with a shorter part of the copper pipe.

Control system

The control system apply a hydraulic model to predict the pressure variations to control the choke opening. The hydraulic model estimates the downhole pressure in realtime data, based on inputs given from the pressure- and flow measurements, and outputs a desired choke opening responding to the downhole pressure variation. The control system is using "Real-Time Windows Target" software, which is a software provided in Matlab by Mathworks Co. It is used for Running Simulink® and Stateflow® models in real time on PC for hardware-in-the-loop simulation of control system algorithms. To make the interface between computer and process a control cards from National Instruments are used. The card receives input signals from pressure and flow measurements from the system. Output signals and commands can be sent to the actuators of the choke system, heave system and pump.

4.1.1 Maximum working pressure

The maximum working pressure of the model is 10 bar. Based on the hydraulic model, the pressure variations in the well to be controlled will be in the range of -2 - 2 bar (4 bar) (Svenum, 2012). To maintain a constant downhole pressure of 5 bar, the pressure at the choke will range between approximately 3 bar and 7 bar depending on the movement of the drillstring (Gjengseth and Svenum, 2011). Hence, a maximum working pressure of 10 bar is sufficient. Based on this, the technical components and pipings will need to withstand this pressure. This has been one of the main criteria in selecting the best suitable equipment for the MPD Heave Rig.

4.2 MPD Heave Rig Model

The building of the rig is not completed due to time constraints on completing the control system and the control of the choke and heave motion. However, the planned rig including all technical components and instrumentation is presented in the Process & Flow Diagram (P&ID) diagram in figure 4.1. This subchapter will present technical specification and function of all the components in the model divided into Process components and Instrumentation. Some of the equipment was already available in the lab, however, most of the components are recently acquired.

The well system is currently not installed on the MPD Heave rig, however, it is completed and ready to be tested with the heave control. Figure 4.2 shows the P&ID of the model as it occurs in the lab today without the well. Two temporary valves (TV1 and TV2) are installed. In this way, we are able pressure test the system without the well. We are also able to bypass the well, including the copper pipe in order to be able to circulate water back to the water tank while testing the pump (see 6.3.3).

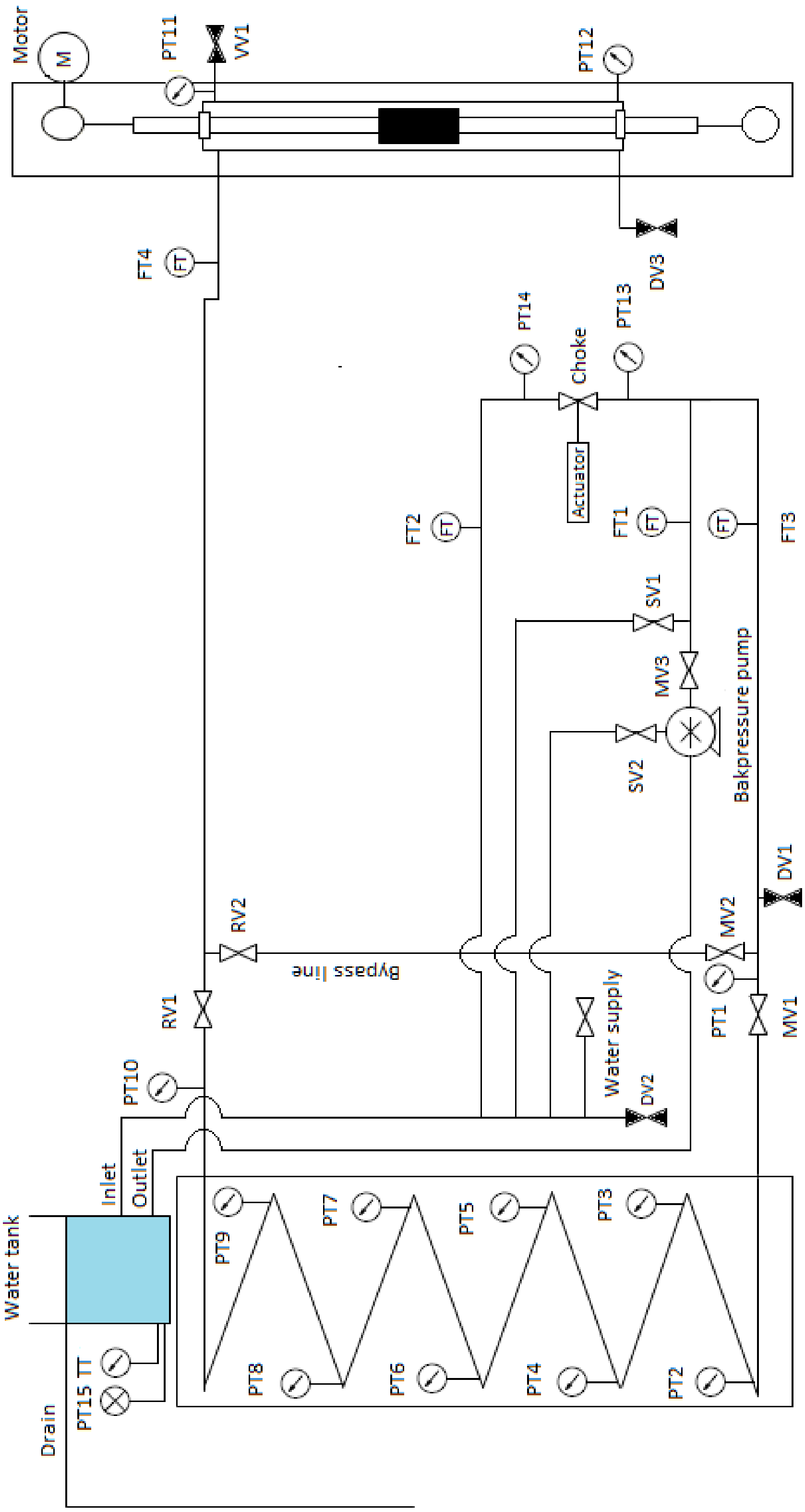


Figure 4.1: *P and ID of planned model.*

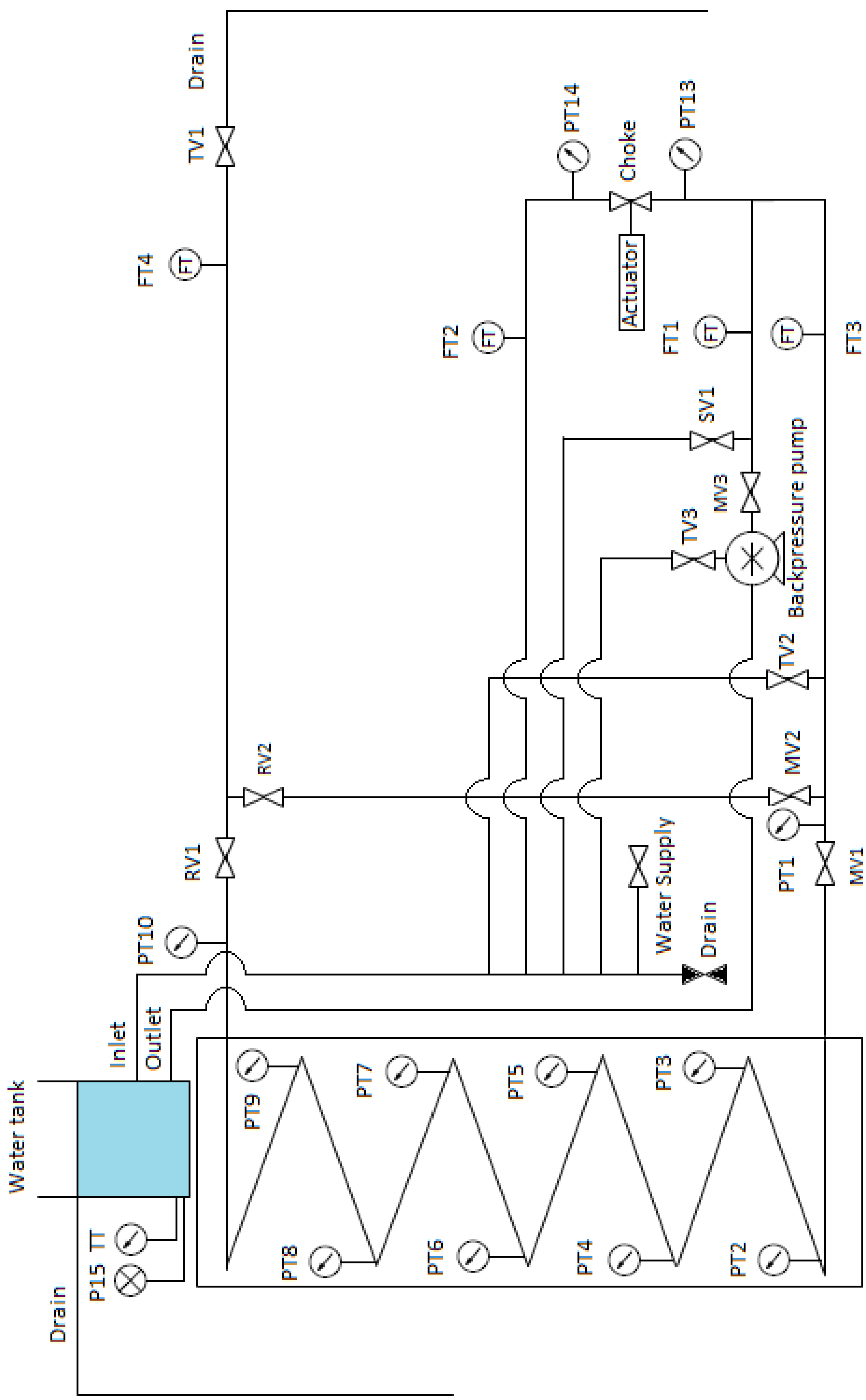


Figure 4.2: *P and ID of current model.*

4.3 Process components

4.3.1 The well

The pipe that is representing the annulus of the well is 1.74 m tall, extending from the bottom to top of the well where the drillstring moves up and down. The copper pipe is an extension of the annulus. The material of the well pipe is transparent PVC which makes it possible to see the drillstring inside the pipe. The drillstring consists of stainless steel, where the pipe above the BHA has a larger diameter than the pipe below the BHA (3.1.4). The BHA is a black cylinder in POM material. The black color makes it easy to keep an eye on when the drillstring is moved up and down. Two valves, one for drainage and one for ventilating, are placed in the bottom and top of the well respectively. These valves are normally closed. The drain valve can be opened manually, however, the vent valve is air operated. The pipe components are all manufactured by GPA and Tess Trondheim. The maximum working pressure for the well is 16 bar, however, this is not the maximum working pressure of the whole system, as some of the components has lower working pressure. Dimensions can be found in table 4.1. The original BHA diameter is 40.9 mm. It is possible to replace the current BHA with other sizes if it is desired to simulate other pressure drops than possible with the original BHA. The top and bottom of the well is sealed with caps which can be opened in case the BHA or steel pipe need to be replaced. The steel pipe moving through the caps is sealed with o-rings to prevent from leaks.

Component	Lenght (m)	Diameter (mm)
Hole	1,74	42,2 (ID)
Upper Pipe	1.5	25.0 (OD)
Lower Pipe	1.5	24.4 (OD)
BHA	0.33	40,9 (OD)

Table 4.1: *Dimensions of Well. OD = Outer diameter, ID = Inner diameter.*

4.3.2 Copper pipe

A 900 m long copper pipe (figure 4.3) is applied in the model to simulate a pressure pulse delay similar to the time a pressure impulse will take to propagate in the annulus in a well in the field. The inner diameter of the pipe is 16 mm, the outer diameter is 19 mm. The pipe is coiled around a framework of steel, where steel parts are welded together to form a cylinder with a diameter of 2.13 m and height of 2.3 m. A certified plumber was hired to splice together the copper pipe that was delivered in segments of 25 m. Outlet for pressure transmitters and valves are located every fifty meter and gives the ability to use a shorter part of the pipe if desired. Currently it is placed eight pressure transmitters in the pipe, and one at the inlet and one at the outlet for sufficient pressure measurement of the annulus pressure variations to control the downhole pressure. The pipe can be closed for flow by closing the valves upstream and downstream the pipe. The valve upstream the pipe can be manually closed at floor level. However, the downstream valve, which is located on top of the cylinder, is air-operated by an actuator that can be controlled from the control board.

Figure 4.3: *Copper pipe.*

4.3.3 Water tank

The water tank is located on top of copper pipe cylinder to provide sufficient suction pressure to the water pump. The capacity of the water tank is 300 L and is used to store water to continuously provide water to the system. When the whole system is filled with water, the backpressure loop will circulate water from the water tank to the pump, through the choke and back to the water tank with a flow rate of approximately 40 lpm. The water temperature is controlled by a thermometer. At a certain increase, the water supply valve is opened and cold water is supplied from the water outlet to avoid changes in the properties of the water due to heat energy from the pump. An overflow tube will drain out water when the water lever exceeds the upper limit when overheated water is replaced with cold water. The connection between the water tank and pump is a flexible hose. A pressure transmitter measures the pressure in the bottom of the tank and the water level in the tank can be calculated ($P = \rho gh$), this pressure is used as a reference pressure to the hydrostatic pressure in the rest of the hydraulic system. The water tank is secured with a wooden frame attached to the rough of the cylinder.

4.3.4 Valves

Four ball-valves are implemented on the model in order to control the direction of water flow in the system; through the copper hose or through the bypass line. Two of the valves (MV1 and MV2), upstream copper hose and upstream bypass line, can be reached from floor level and are therefore controlled manually. The other two (RV1 and RV2) are air-operated by an actuator that can be controlled from the control board. Manual drain valves are implement to be able to drain water without having to disassemble the well. To have the opportunity to vent possible air in the system it is implemented an air-operated vent valve in the top of the well.

Tag	**Purpose**	**Location**
MV1	Direction of flow	Upstream copper pipe
MV2	Direction of flow	Upstream bypass line
MV3	Pressure test	Downstream pump
RV1	Direction of flow	Bypass line outlet
RV2	Direction of flow	Copper hose outlet
DV1	Drain	Upstream bypass line and copper pipe
DV2	Drain	Water tank
DV3	Drain	Bottom of well
VV1	Vent	Top of well
SV1	Safety valve	Downstream pump
SV2	Safety valve	Pump

Table 4.2: *Tags and locations of valves according to P and ID for the planned model (4.1).*

4.3.5 Safety valves

The system involves one safety valve (SF1, See figure 4.4) as an assurance that the pressure does not exceed the maximum working pressure of 10 bar. The pressure in the system is controlled by the choke and the pump, hence the safety valve is placed between these two components.

It is also suggested to implement a safety valve on the pump (SF2), which will open for flow back to the water tank from the pump in case the other safety valve fails. This safety valve will also prevent damage on the system if the pump is running in a closed system causing pressure increase. However, there is currently no safety valve installed on the pump.

Figure 4.4: *Safety Valve.*

4.4 Instrumentation

Electrical components are located on different locations on the MPD Heave Rig model. Choke control, heave control and pump control are the three systems that are controlled by the computer. The control of the choke is based on pressure and flow measurements from the process.

4.4.1 Control cards

A Control card from National Instruments makes it possible to communicate between the control system and the process by running Simulink and Matlab by use of a PC. For directly logging of measurements, Windows Real-Time Target is implemented in Matlab on the computer.

The control card has 32 Analog Input channels and 4 Analog output channels. However, 48 digital I/O channels can also be applied in the process. Table 4.3 table shows the number of analog input channels that are implemented in the input card. The tachometer gives pulse signals to the control card. Table 4.4 shows the 4 output channels implemented in the control card. It is currently 23 channels input and 4 output channels in use on control card. This allows for implementation of additional 9 input channels in case of future expansion of the MPD Heave rig. To link the instrumentation to the control cards, two terminal connection boxes are used. The terminal boxes are connected to the computer and the control cards with a cable.

Chanel	Tag	Measurement	Location	Signal
1	PT1	Pressure	CP (Copper Pipe) inlet	4-20mA
2	PT2	Pressure	CP 100 m	4-20mA
3	PT3	Pressure	CP 200 m	4-20mA
4	PT4	Pressure	CP 300 m	4-20mA
5	PT5	Pressure	CP 400 m	4-20mA
6	PT6	Pressure	CP 500 m	4-20mA
7	PT7	Pressure	CP 600 m	4-20mA
8	PT8	Pressure	CP 700 m	4-20mA
9	PT9	Pressure	CP 800 m	4-20mA
10	PT10	Pressure	CP 900 m	4-20mA
11	PT11	Pressure	Top of well	4-20mA
12	PT12	Pressure	Bottom of well	4-20mA
13	PT13	Pressure	Upstream choke	4-20mA
14	PT14	Pressure	Downstream choke	4-20mA
15	PT15	Pressure	Water tank	4-20mA
16	FT1	Flow	Downstream pump	4-20mA
17	FT2	Flow	Downstream choke	4-20mA
18	FT3	Flow	Upstream CP/Bypass line	4-20mA
19	FT4	Flow	Upstream well	4-20mA
20	WP	Water Pump Feedback		0-10V
21	CM	Choke Motor Feedback		0-10V
22	HM	Heave Motor Feedback		0-10V
23	TM	Tachometer Feedback		Pulse

Table 4.3: *Analog inputs on I/O card PCI-6289.*

Chanel	Tag	Description	Signal
1	WP	Pump Control Digital	0-10V
2	WP	Pump on/off	0-10V
3	CM	Choke Position	0-10V
4	HM	Heave Motor Position	0-10V

Table 4.4: *Analog outputs on I/O card PCI-6289.*

4.4.2 Pump control

The water pump is a C 980 A Hawk pump which can deliver 140 bar at a flow rate 40 l/min (10,6 kW) at 1450 rpm and or 47.3 l/min (12.5 kW) at 1740 rpm. The maximum efficiency of the pump is much more than sufficient for the purpose of the MPD Heave Rig, since the maximum working pressure of the system is only 10 bar. However, the pump was already available in the lab, and it is therefore no need purchasing a new pump with a smaller reasonable size. The whole pump system set up, with frequency converter and additional components, has been used in former lab-projects, and is considered sufficient for the MPD Heave Rig. The frequency converter is used to communicate with the control system to turn the pump on/off and to select flowrate and pressure. It is currently installed an accumulator in the pump system. This accummulator is compensating for pressure increase in the system by compressing air. Since it is desired to control the pressure by the choke, this accummulator must be exchange with another solution or removed.

It is planned to control the pump by the computer. However, we are currently only able to control the pump manually. Figure 4.6 shows the manual control panel of the pump frequency converter. The pump must be tested to detect what flow rates it delivers to be able to control the flow properly (see 6.3.3). The pump was tested for a maximum capacity of 30 lpm. Because of this it is suggested to implement a feed pump in the water tank to increase the capacity of maximum flow rate, since a flowrate of 40 lpm throught the choke is desired with the current system.

The flow from the pump must at all times have the ability to circulate back to the water tank to avoid the pressure in the system to exceed the maximum working pressure due to resistance in the system. As previously mentioned, it is suggested to install a safety valve on the pump which will open for flow back to the water tank when maximum working pressure is reached. However, the safety valve installed on the pump was defect. It is currently possible to circulate water back to the water tank from the pump through a hose connection from the pump to the water tank. This bypass connection can be controlled by a manual valve (TV3, see figure 4.2) and a manometer with a display showing the pressure in the system to be able to pressure test the system. Although, this system is not optimal for the MPD Heave Rig, and further safety measures must be implemented to avoid exceeding pressures.

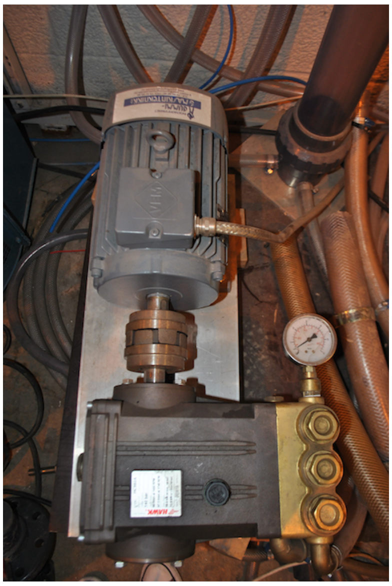


Figure 4.5: *The pump system. The mentioned accumulator, which can not be used, can be seen up to the right in the picture.*

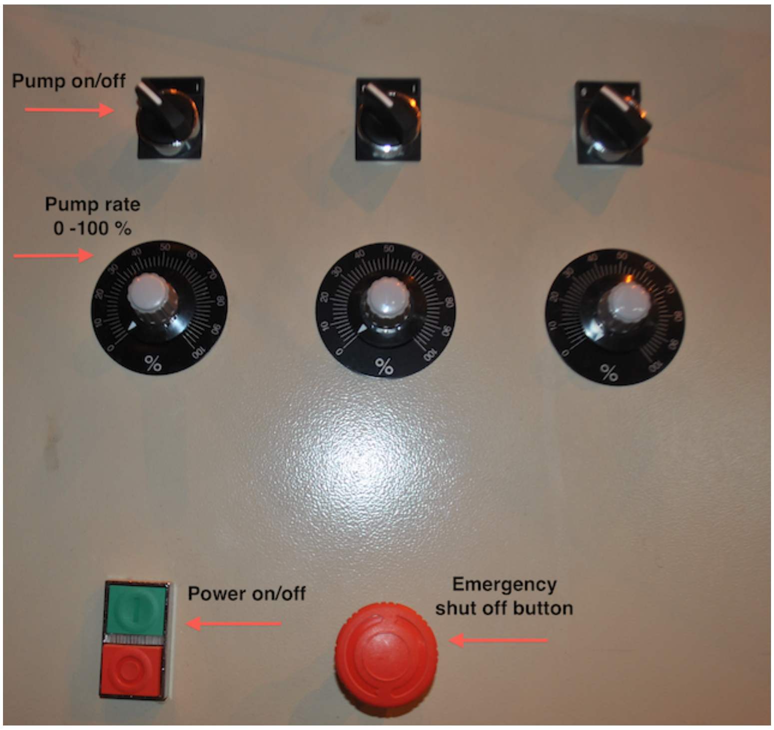


Figure 4.6: *Manual control of pump.*

4.4.3 Choke control

The solution for choke control is a tailored system consisting of a 90 degree 1/2" ball valve (see choke motor in figure 4.7) driven by to a three-phase AC motor supplied by Lenze. The rated power of the motor is 0.12 kW. The speed of the motor which controls the choke opening is precisely controlled by a frequency inverter (control box). This is done by sending analog output signals (4-20mA) from the control system to the frequency inverter. Analog feedback of the choke position will be sent as input signals back to the control system. The motor is selected based on the requirement of an accuracy of the choke less than 0.1% resolution/deadband and less than 2 seconds opening time from 0 -100% opening. With this tailored system the one rotation of 360 degrees of the ball valve takes 2 s. However, the the time for adjusting the choke from open position (90 degrees) to closed position (0 degrees) will take 1/4 of the time of rotating the ball valve 360 degrees and results in a closing time of 0.5 s. To control the pressure in the hole, the choke opening will range within a smaller window which is detected by testing the choke for different flowrates and openings to obtain the choke characteristics.

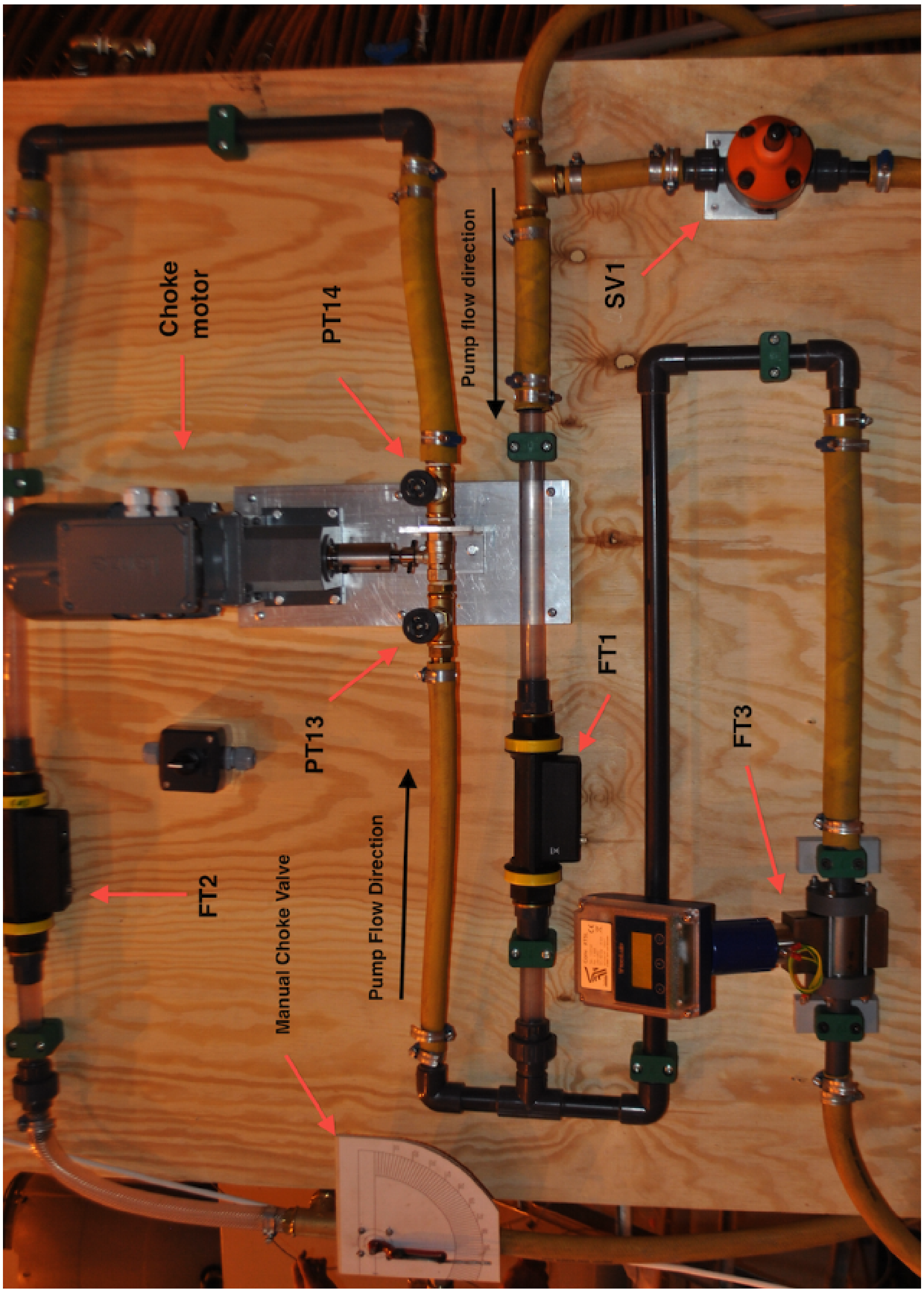


Figure 4.7: *Control board.*

4.4.4 Heave control

The Heave system consist of a similar system as the choke control. The motor is mounted to the upper gear wheel of the heave system which can be rotated by controlling the motor. When the wheel rotates, the drillstring connected to the toothed belt is moved by the frequency inverter-optimized motor. The system is supported by a steel plate wall attached to the copper pipe cylinder. The rated power of the motor is 0.750 kW based on motor calculations conducted by Rashid (2011). It is planned to use a tachometer to measure the speed of rotation to control the position of the drillstring, however, signals of motor position will also be given as input to the control system. The electrical equipment is placed above the well to avoid contact with water in case of leaks from the well.

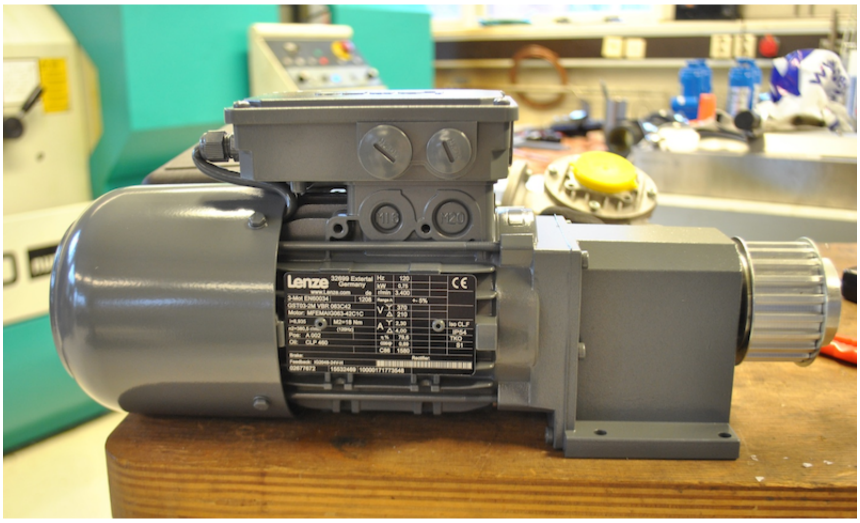


Figure 4.8: *Heave motor.*

4.4.5 Pressure measurements

Pressure Transmitters from Druck are used to measure absolute pressure in the hydraulic system as an input to the control system. One pressure transmitter, PTX1400 (see figure 4.9), is placed in the bottom of the water tank to measure the water level ($P = \rho gh$). It has a measuring range of 0 - 100mbar. The rest of the pressure transmitters are UNIK 5000 models with a pressure range from 0 - 16 bar. These are used to measure the pressure in the hydraulic system to give feedback to the control system. The pressure transmitters has an accuracy of 0.15 % which is considered sufficient for the purpose. The pressure transmitters give analog input signals of 4-20mA to the control system. For the location of the pressure transmitters see table 4.5 or figure 4.1.

Figure 4.9: *Pressure Transmitter PTX 1400.*

Label	Position	Model	Manufacturer
PT1	Upstream Copper Pipe	UNIK 5000 PS	Druck
PT2	Pipe100	UNIK 5000 PS	Druck
PT3	Pipe200	UNIK 5000 PS	Druck
PT4	Pipe300	UNIK 5000 PS	Druck
PT5	Pipe400	UNIK 5000 PS	Druck
PT6	Pipe500	UNIK 5000 PS	Druck
PT7	Pipe600	UNIK 5000 PS	Druck
PT8	Pipe700	UNIK 5000 PS	Druck
PT9	Pipe800	UNIK 5000 PS	Druck
PT9	Downstream Pipe	UNIK 5000 PS	Druck
PT10	Upstream Choke	UNIK 5000 PS	Druck
PT11	Downstream Choke	UNIK 5000 PS	Druck
PT12	Top Well	UNIK 5000 PS	Druck
PT13	Bottom Well	UNIK 5000 PS	Druck
PT14	Water Tank	PTX 1400	Druck

Table 4.5: *Location of pressure transmitters.*

4.4.6 Flow measurements

To measure the flow through the pump and downstream the choke, two turbine flowmeters are used, both of same type, delivered by Parker (See figure 4.10). The flowmeters are calibrated to measure flow in the range 4-100 l/min and converts the detected pulses to a 4-20mA. The maximum working pressure of the turbine flowmeters is 10 bar, and is currently the limitation of the hydraulic system. The turbine flowmeters were available in the lab and were considered sufficient for the purpose, since the pressure in the system will be kept below 10 bar based on the hydraulic model (Svenum, 2012).

Figure 4.10: *Turbine flowmeter.*

The flow upstream the well will vary in direction and follow the heave motion with a very small flow rate. This requires a sufficient accuracy to measure the variations in the low flow rate. Two magnetic flowmeters with additional converters, manufactured by Techfluid, is used for this purpose (see figure 4.11). One upstream the copper hose and bypass line, and one upstream the well. These flowmeters also give an analog output signal (4-20mA). The flowmeters has an accuracy of 0.5%.

Figure 4.11: *Magnet Flowmeter and converter.*

5 Risk assessment

A risk assessment has been conducted to ensure that hazardous activities and unwanted events are avoided. This involves sufficient planning of the various operations followed by identification of measures to minimize the risk of adverse events that may cause harm on humans, equipment and environment. The risk assessment report and attachments to the report are based on a template provided the Department of Energy and Process Engineering (Langørgen, 2012) and can be found in Appendix A. Assessment of technical and operational safety is considered in the risk assessment of the whole process which is divided into the following three subprocesses; Building period, commissioning tests and experiments. The risk assessment considers:

- What can go wrong?
- What is the possibility?
- What will be the consequences?
- What measures must be taken to minimize the risk?

5.1 Operational safety

During the whole process of building, function tests and experimental tests, an assessment of operational safety of the people involved in the process is required. A minimum measure to protect the personnel is use of the Personal Protective Equipment (PPE) when one is involved in operations in the workshop. Use of the following PPE is required in the workshop where the MPD Heave Rig is build:

- Coverall clothing
- Safety shoes
- Safety glasses
- Hard hat

5.1.1 Working at heights

For installation of water tank and instrumentation on top of the copper pipe cylinder, personnel are required to use safety harness to reduce the risk of fall from height. The ladder used to enter the copper pipe cylinder roof needs to be secured while people are climbing in the ladder.

5.1.2 Lifting operations

All lifting operations involving lift crane require sufficient planning and review of Safe Job Analysis (SJA) form provided by NTNU/SINTEF (Appendix A) (Langørgen, 2012). Lifting operations involved in the building of the MPD Heave Lab are installation of the copper pipe cylinder and the well. Responsible for conducting these operations are the employees working in the workshop hall where the MPD Heave Rig is located.

5.1.3 Welding operations

The framework of the copper pipe cylinder consists of steel parts welded together by a certified welding operator. During this operation proper eye protection and coverall clothing must be worn to avoid personal injury. The welding operation must take place in sufficient distance from other personnel in the workshop.

5.1.4 Water spills

Hose parts and pipes are currently secured with pipe clamps to avoid leaks (see figure 5.1). When pressure is working in the system, there is a greater risk for leaks from these connections, if these pipe clamps are not mounted sufficiently, there is a risk that they can pop off and cause water spills over a larger area. If this happens the pump can be stopped immediately by pushing the red emergency stop button (see figure 4.6). As a mitigating measure to prevent pipe clamps to pop off, it was implemented two pipe clamps on each connection between two pipe parts. These connections need to be inspected prior to experiments. When the rig was pressure tested, these connections failed and caused a large water spill as predicted. As a new mitigating measure, it is suggested to replace expandable hose parts with PVC pipe prior to continue commissioning tests of the system.

Figure 5.1: *Hose parts and pipe clamps on control board.*

5.1.5 Securing large components

Larger components as the water tank and the well must be secured properly to prevent these components from falling and cause personal injury or great damage on equipment. The water tank is secured with a wooden steel frame latched to the roof of the copper pipe cylinder. The well is latched to a steel plate which is mounted to the copper pipe cylinder with bolts supporting the whole plate.

5.2 Technical safety

A Hazard and Operability (HAZOP) analysis of the process is conducted to detect problems that may represent risks to technical safety. A HAZOP template included in the Risk Assessment template with a set of guidewords is used to detect possible complications that may induce risk during the test and experiment sequences. The HAZOP form can be found in Attachments to the risk assessment report in Appendix A.

5.2.1 Pressure

The maximum working pressure of the system is 10 bar. When the water pump is circulating water at a certain flow rate, the pressure in the system is controlled by adjusting the choke opening. Lowering the choke opening will increase the pressure in the system. The following measures are implemented and suggested to avoid the pressure exceeding the maximum working pressure when the pump is running, to avoid damage on the system:

Safety valves

As a safeguard it is suggested to install two safety valves in the system to ensure that pressure does not exceed 10 bar. The safety valve upstream the choke will react first. As a contingency, if this safety valve fails, the safety valve on the pump will be triggered. It is also suggested to implement a minimum choke opening in the control system to avoid exceeding the working pressure. The safety valve on the pump is currently not installed. However, as previously mentioned, it is possible to bypass the pump to avoid pressures over 10 bar in the system during pressure tests.

Water hammer

Another concern is the water hammer effect that may occur if the choke is closed instantly. With a flow rate of 40 lpm in a 1/2" pipe, the maximum water hammer would result in a pressure of 77.8 bar. (Svenum, 2012) This is a huge risk to both equipment, but worse human injury. As a mitigating measure it is suggested to implement a physical barrier on the choke to ensure that the choke is not able to close completely. This measure must be taken prior to implementing the motor control of the choke.

Pump emergency shut down

It is currently only possible to control the pump manually. In case the pump must be stopped immediately, the pump emergency shut down bottom may be used.

5.2.2 Leaks

When the system is filled with water, the MPD Heave Rig must be inspected to detect possible leaks. For optimal function of the rig, all leaking points must be eliminated. With the current status of the MPD Heave Rig, there is a larger risk for leaks, especially at the control board where hose parts and pipe clamps applied as flowlines. The measure of applying PVC pipes instead of hose parts and pipe clamps will reduce the risk of leaks significantly.

6 System commissioning

The MPD Heave Rig including all technical components and instrumentation must be function tested prior to experiments start up to ensure that the rig functionality is optimal and to detect possible failure. We were not able to function test the MPD Heave Rig due to time constraints in both completion of the control system, control of motors and completion of the MPD Heave Rig. This chapter presents the plan for system commissioning of the current MPD Heave Rig to verify the functionality of the the technical components and identification of parameters to the hydraulic model.

The objective of the verification tests is to test the functionality of all the technical components in the rig model. The list below presents all components that must be tested to ensure desired functionality of the MPD Heave Rig prior to implementing the control of the heave motor, choke control and control system:

- Pressure integrity
- Pump functionality
- Communication and Logging

When the above components are tested, the systems involving computer control must be tested to verify desired functionality. This includes the following components:

- Pump control
- Heave Motor functionality
- Choke Motor functionality
- Control System functionality

The objective of the identification tests to identify parameters of the hydraulic model. These tests can be conducted without involving computer control of the process. However a sufficient logging program is needed to be able to receive signals from the instrumentation on the rig. It is desired to identify the following parameters:

- Compressibility
- Friction
- Choke Characteristics

- Time Delay

6.1 Detail Operation Plan

Preliminary test procedures for currently planned tests are presented in the Detail Operation Plan (DOP) in Appendix B. The test procedures are divided into verification tests and identification tests. The currently planned tests are:

- Communication and logging
- Pressure integrity test of current system
- Pump test
- Identify friction in copper pipe
- Identify Choke Characteristics
- Identify Compressibility of copper pipe and water

6.2 Logging

Logging of measurements is done by application of Real Time Windows Target and Matlab which gives us the ability of optimal sampling collection of variable parameters in the process and to obtain sufficient results on propagation of pressure transients in the system.

The a prototype choke with the ability of controlling the choke opening manually was tested to obtain provisional indication of the choke characteristics. For this a portable data acquisition and logging system named DaqPro was used. This logging unit gives the ability to implement eight I/O channels to be logged at the same time. With this system it is only possible to log one sampling per second for each channel. However, this system was sufficient for a temporary test of the choke characteristics.

6.2.1 Preparation for system commissioning

Preparations for function tests are listed in "Preparations for operation" in the DOP1. This involves visual inspection of the lab and valve positions, and function test of the remote controlled valves and calibration of flowmeters.

The maximum pressure of the safety valves also needs to be set prior to system commissioning.

Calibration of instrumentation

The pressure transmitters and the magnetic flowmeters are delivered with calibration certificate and will give correct signals to the control system. The turbine flowmeters must be calibrated with the magnetic flowmeters as a reference to verify correct readings. This is done by checking the input signals from the turbine flowmeters while circulating water through one magnetic flowmeter and one turbine flowmeter. If the signals from the turbine flowmeter varies from the magnetic flowmeter log, the turbine flowmeter needs to be calibrated.

6.3 Verification tests

6.3.1 Pressure and flow meassurments

We are currently only able to log the pressures in the system, not the flow. For the planned tests the flow is displayed on the flowmeter converter display. Prior to testing, the pressure transmitter signals must be verified in the logging program. When there is no water in the system all pressure transmitters should give the signal of 0 bar. When the system is filled with water in static condission, the pressure transmitters should show the value of the hydrostatic pressure in the water tank, plus the pressure calculated from the vertical distance from the pressure transmitter (P15) in the water tank. The expected hydrostatic pressure difference from the reference point (P15) for all measuring points in the model can be seen in table 6.1. The control signal from the flowmeters are currently not implemented in the control cards. However, the flow measurements for the planned tests can be displayed on the flowmeter converter display of flowmeter F3 (see figure 4.2). When the flowmeters are implemented, these signals can be verified in static condition when there is no flow in the system. The verification test of pressure and flow measurement is named VER01 in the procedures.

Tag	L (m)	P (bar)
PT15	0	0
PT1	3.18	0.31
PT2	2.94	0.29
PT3	2.71	0.27
PT4	2.39	0.23
PT5	2.06	0.20
PT6	1.72	0.17
PT7	1.42	0.14
PT8	1.14	0.11
PT9	0.79	0.08
PT10	0.48	0.05
PT11	-0.83	-0.08
PT12	0.83	0.08
PT13	2.23	0.22
PT14	2.23	0.22

Table 6.1: *The hydrostatic pressure difference in the system relative to the reference pressure measured in the bottom of the water tank.*

The control signal from the flowmeters are currently not implemented in the control cards. However, the flow measurements for the planned tests can be displayed on the flowmeter converter display of flowmeter F3 (see figure 4.2). When the flowmeters are implemented in the control cards, these signals can be verified in static condition when there is no flow in the system.

6.3.2 Pressure integrity

The maximum working pressure of the MPD Heave Rig is 10 bar. Hence, the system needs to be pressure tested according to this pressure. The pressure test is divided into three subtests where the current hydraulic system is divided into sections for easier detection of failure in the system. The barriers between the sections are the valves in the system. The valve integrity will therefore be verified during these pressure tests. The control board is currently a small area with a number of connections between pipes and pipe clamps. This subsystem is considered as a greater risk when related to leaks, and is therefore pressure tested prior to testing the rest of the system. When the control board is pressure tested, the by pass line is included in the pressure test. The last section to be pressure tested is the copper pipe. If there is no leakage during the test it will be considered as accepted, however, if any leakage is detected, the test needs to be repeated after the leakage point is fixed. The pressure integrity test should be repeated 2-3 times for validation.

The procedure for pressure test of the current system including the control board, the bypass line and the copper pipe is named VER02 in DOP1. P&IDs illustrating the pressure tests are also included in the procedure.

6.3.3 Pump functionality

The water tank is placed on top of the copper pipe cylinder to provide enough suction pressure to the pump. The pump is controlled by control signals 0-1 from the control system, which is equivalent to 0-10 V signals transmitted to the pump. However, we are currently only able to control the pump manually. When the pump is tested, the flow is circulated from the water tank with a flow line bypassing the copper pipe and the well system is bypassed with a flow line back to the water tank (see figure 6.2). The flow rate is increased in steps from 0-100 % (see figure 6.1) and the flow rate is displayed on the converter display of the flowmeter FT3. The procedure for test of pump functionality is named VER03 in the procedure.

Figure 6.1: *The pump flow rate can be adjusted manually from 0-100%.*

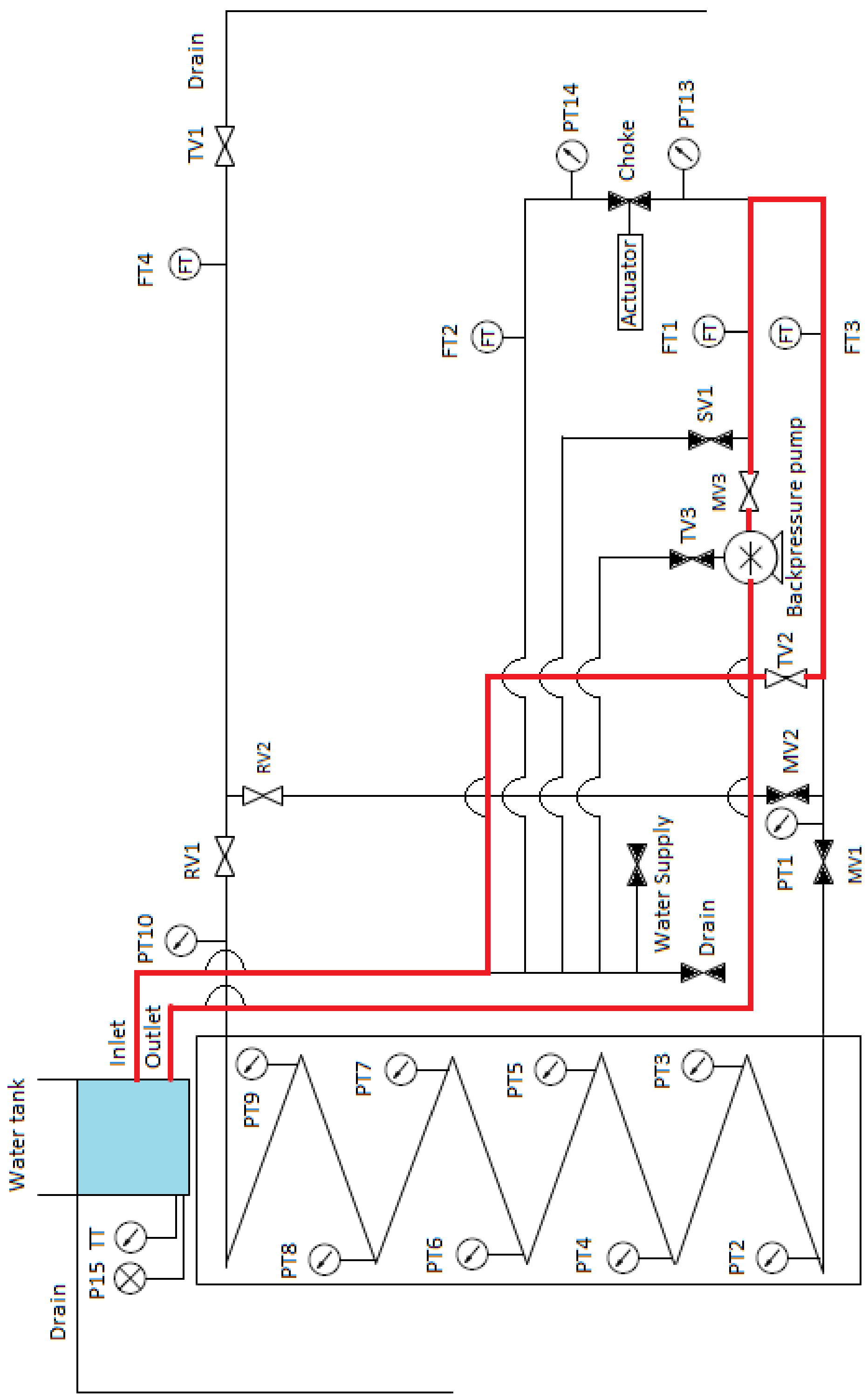


Figure 6.2: *The planned flow path for testing the pump on the current MPD Heave Rig.*

6.3.4 Heave motor control

The heave motor control needs to be tested prior to implementing the lifting of the drillstring. This is done by controlling the motor and verify correct behavior of motor control based on output and input signals in the control system. The amplitude of the heave motion is 0.41 m for all tests, however the period of the harmonic wave vary from 3-15 (Svenum, 2012). The motor control is tested for constant velocity and harmonic wave velocity with different periods. Because of the development of the control of the heave motor was delayed, we were not able to test the heave motor control.

6.3.5 Choke control

The choke valve is a tailored system that needs to be tested to identify choke characteristics prior to implementing the choke motor control. This was done by adjusting the choke opening of a prototype choke, similar to the choke operated mounted to the motor, manually (see 6.4.1). When implementing the control system, the communication between the choke-motor and the control system must be verified make sure the choke behaves according to commands given in the control system.

The tuning of maximum choke pressures, according to the choke characteristics, can be conducted when satisfying communication of the control system is implemented. By logging the differential pressure over the choke, when the choke opening is stepped from 100 % opening down to minimum opening, the maximum pressure of operating choke can be verified.

6.4 Identification tests

6.4.1 Identify choke characteristics

The choke control is a tailored system consisting of a 1/2" ball valve mounted to an actuator consisting of an AC motor which is controlled by the control system. Prior to implementing the control system and the motor, it is necessary to determine the choke characteristics of the choke. Since the control system was not ready this was done by logging the pressure difference over the choke by adjusting the choke opening of a prototype choke where the choke opening can be adjusted manually. This prototype choke is similar to the one implemented in the model, however, this choke can only be operated by the motor choke control via the control system. The choke is 90-degree Ball Valve, where 90 degrees opening is referred to a 100 % opening, and 0 degrees is closed position. A protractor was mounted to the handle of the choke to be able to see what the choke opening is when the handle is adjusted.

The two inputs needed to obtain the flow coefficient are the flowrate Q and the pressure drop ΔP over the choke. There are two flow coefficients that are considered as industry standards; the american C_v and the metric K_v. The two flow coefficients are defined from the following equations:

$$C_v = Q\sqrt{\frac{sg}{\Delta P}} \tag{6.1}$$

where C_v is american flow coefficient (gpm/psi), Q flow rate (gpm), sg is the specific gravity of the fluid and ΔP is the differental pressure (psi).

$$K_v = Q\sqrt{\frac{\rho}{\Delta P}} \tag{6.2}$$

where K_v is the metric flow coefficient $(m_3/h/bar)$, Q is the liquid flow (m3/h), ρ is the liquid density (kg/dm3) and ΔP is the differential pressure (bar) (Nesbitt, 2007).

The choke is tested by logging measurements when tap water was flowing through the choke. By stepping the choke opening from 90 degrees opening to 10 degrees, while logging the flow rate, and differential pressure over the choke opening, the choke characteristics can be calculated. To measure these parameters, a flowmeter was placed upstream the choke, and two pressure transmitters were placed on either side of the choke. By application of Daqpro and Daqlab, an all in one solution for data logging and analysis, in total four tests were run with different flowrates from the tap. An illustration of the test can be found in seen in figure C.1.

It is suggested to run the tests with the prototype choke with water supply from the pump prior to testing the choke motor control. When the pump is used to provide flow rate through the choke, we are able to choose flow rates more consequently compared to the tap water test. The procedures for tests of manual choke with water supply from the tap water and the pump are named ID01 and ID02 in the procedure.

6.4.2 Friction in copper pipe

With the current model with a lower steel pipe diameter of 24.4 mm, the water flow in the copper pipe will range between maximum -1.2 lpm and 1.2 lpm for a period of 3 sec (Svenum, 2012). However, it is decided to test for flowrates up to 5 lpm since the actual case my differ from the theoretical calculations. Table 6.2 shows the calculated friction pressure drop based on equations presented in chapter 3.1.8. The bends and curvature of the copper pipe is not accounted for in these calculations. The friction therefore expected to be higher than these numbers. A more detailed analysis of friction of the copper pipe can be found in the hydraulic model conducted by Svenum (2012).

Q (lpm)	**ΔP (bar)**
0,5	0,05
1,0	0,09
1,5	0,14
2,0	0,27
2,5	0,38
3,0	0,49
3,5	0,91
4,0	1,15
4,5	1,40
5,0	1,68

Table 6.2: *The table shows the calculated friction drop ΔP for flow rates ranging from 0,5 to 5 lpm.*

By measuring the pressure drop between PT1 and PT10 (see figure 6.3) and subracting the difference in hydrostatic pressure (table 6.1) for flowrates ranging from 0-5 lpm, the actual friction pressure drop can be detected. The water is circulated from the water tank to the drain (see figure 6.3). The water supply to the water tank is open, to maintain the waterlevel in the tank during the tests. The procedure for friction test is named ID03 in the procedure.

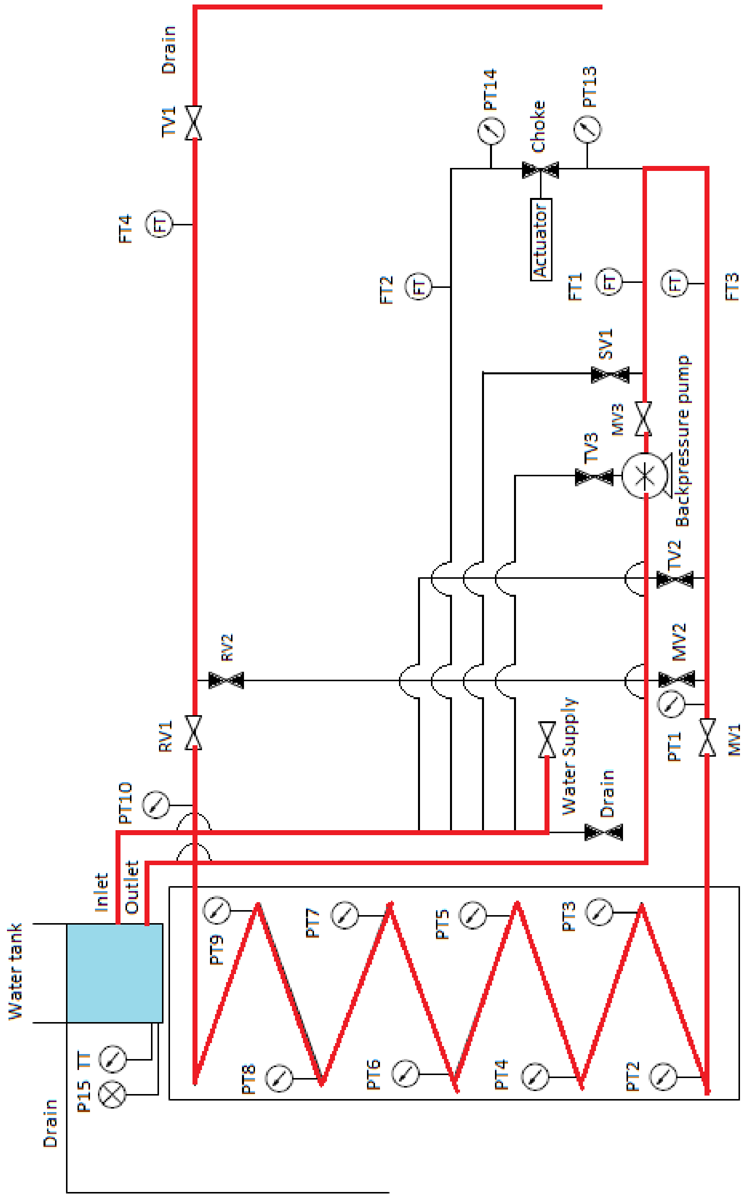


Figure 6.3: *The planned flow path for friction test of copper pipe on the current MPD Heave Rig.*

6.4.3 Bulk modulus

The isothermal bulk modulus β of the fluid is related to the stiffness of the fluid and can be expressed as the inverse of the compressibility of the fluid; $c = \frac{1}{\beta}$. According to Stamnes (2011) the bulk modulus is the most important property i determining the dynamics of the hydraulic system. The bulk modulus characterizes the dominating pressure transients in the system. For a typical MPD controller the pressure transients of a well are in the range of seconds to minutes (Stamnes, 2011). Pressure transients travel with the speed of sound following a pressure wave in the fluid. Where the velocity a can be expressed as

$$a = \sqrt{\frac{\beta_{effective}}{\rho}} \tag{6.3}$$

where $\beta_{effective}$ is the effective bulk modulus, including fluid and mechanical compliance of the hydraulic system, and ρ is the density of the fluid (Stamnes, 2011).

The bulk modulus decreases rapidly with small amounts of entrained gas/air, and/or mechanical compliance of the hydraulic system. In order to determine the effective bulk modulus, these aspects needs to be considered. Stamnes (2011) points out the difference in bulk modulus by comparing an example from the field and laboratory measurements from the Kvitebjørn field in the North sea. The bulk modulus of the drilling fluid was measured to 50000 bar in the lab, however, in the field the resulting effective bulk modulus was measured to be 15000 bar.

To be able to predict the pressure transients in the hydraulic system of the MPD Heave Rig, a good estimate of the effective bulk modulus is needed. The mechanical compliance of the whole system is uncertain. There may also be air in the system, which might be very difficult to detect, especially in the 900 m copper pipe. The hydraulic system therefore needs to be tested to identify this parameter to be able to control the downhole pressure fluctuations as precise as possible.

We are able to measure the differential volume ΔV over a known pressure drop ΔP. Hence we can calculate a bulk modulus that will tell us something about the expansion of the system under a certain pressure increase. Compression of the system of water and copper pipe can be expressed by the following equation

$$\frac{\Delta V}{V} = c_f \Delta P \tag{6.4}$$

where ΔV is the change in volume, V is the volume and ΔP is the change in pressure.

The volume of the copper pipe is

$$V = d^2 \frac{\pi}{4} L = 0,818 m^3 \tag{6.5}$$

when the diameter d is 0,016 m and the length L is 900 m.

When considering a compressibility of water c_f of $4.6{*}10^{-10} Pa^{-1}$, the volume change of pressurizing the copper pipe to 10 bar and releasing the pressure to 1 bar is

$\Delta V = 4.6 * 10^{-10} Pa^{-1} * 9 * 10^5 Pa * 0.181 m^3 = 4.16 * 10^{-5} m^3 = 0.075 l.$

However, this is only considering the compressibility of the water in the system. One suggestion to detect the compressibility of the water and copper pipe is to measure the differential volume of water ΔV when the pressure in the copper hose is stabilizing from 10 to 1 bar. The procedure for the compressibility test is named ID04 in DOP1.

6.4.4 Delays

The purpose of the copper hose is to simulate a delay of the pressure transients propagating in the hydraulic system. To be able to control the pressure with correct choke opening adjustment and correct timing, the magnitude of the time delays needs to be detected. From figure 6.4 we can see the time line from pressure is received at pressure transmitter downhole, to the actual time of when the choke opening is adjusted (Landet, 2011).

Figure 6.4: *Time line for delays in the system from pressure is registered by pressure transmitter to the choke opening is changed to desired choke opening. Figure adapted from Landet (2011).*

Ideally, the pressure transient produced by the change in the choke opening will travel with the speed of sound in water. The propagation of pressure transients is depending on the temperature of the water. For 20° C, the speed of sound in water $c = 1481 m/s$ (The Engineering Toolbox, 2012). For the MPD Heave Rig, the pressure transients are propagating between the choke and the bottom of the well. The $900m$ copper pipe results in a travel time of $0.60s$ ($t(s) = \frac{900m}{1481m/s}$) in theory (see table 6.3). However, compressibility of water and the system (see 6.4.3), temperature and pressure all have an impact on the behavior of the pressure transient which must be detected by testing the system by logging the time of the pressure transient propagating from one measuring point to another.

Tag	**Time (s)**
PT1	0
PT2	0,068
PT3	0,135
PT4	0,203
PT5	0,270
PT6	0,338
PT7	0,405
PT8	0,473
PT9	0,540
PT10	0,608

Table 6.3: *Time delay of pressure transient propagating in the 900 m copper hose based on a velocity of 1481 m/s.*

This is done by logging time and pressure between two measuring points while inducing pressure transients by adjusting the choke opening. The time delay between two measuring points can be detected by looking at the logging and detect the time between pressure transient induced and the time of pressure transient received at the measuring point. This require a very fast sampling frequency which is obtained by application of Real-Time Windows Target.

Because of time constraints we were not able to test for time delay in the system. However, to explain how the time delay can be detected, a simulation of a pressure wave propagating from the choke to the bottom of the well is included here. Figure 6.5 shows the time for when the pressure is induced at the choke and when the pressure is received at the bottom of the well. The distance from choke to bottom of well is about 1520 m. From figure 6.6 we can see that the choke opening is changed at the time of 80 s. The bottom hole pressure starts to change about 1 second later.

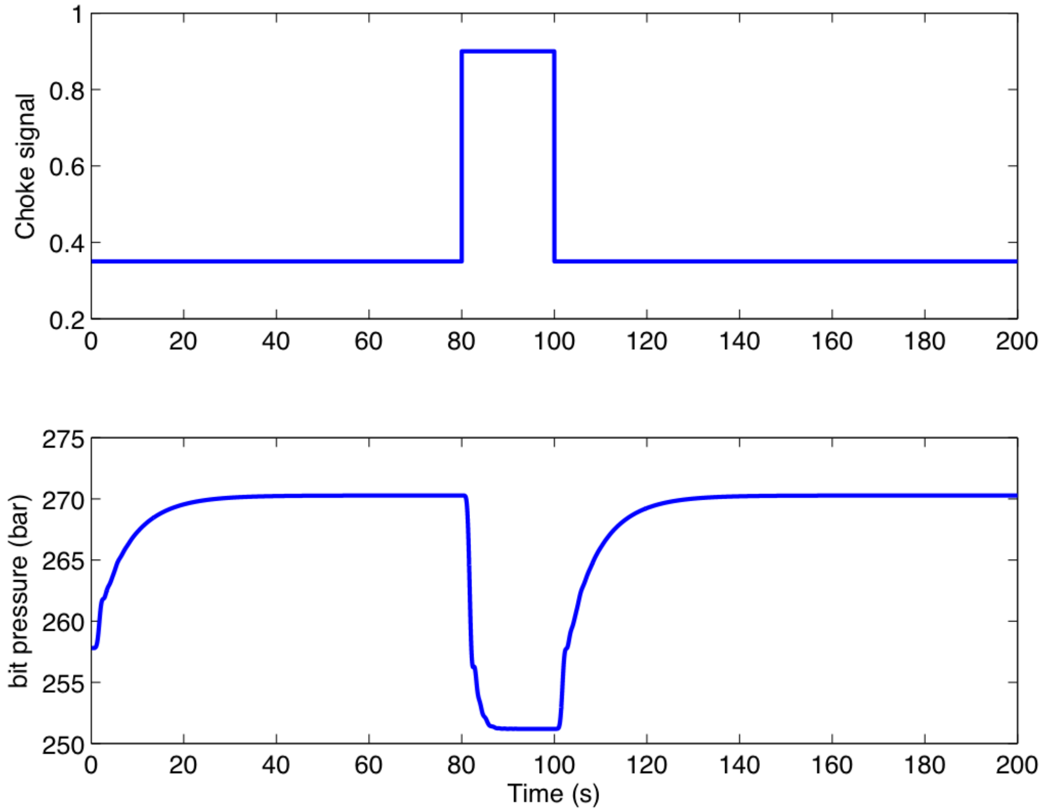


Figure 6.5: *The figure presents an example of simulating a downhole pressure increase when the choke opening is decreased in the period 80 s - 100s.*

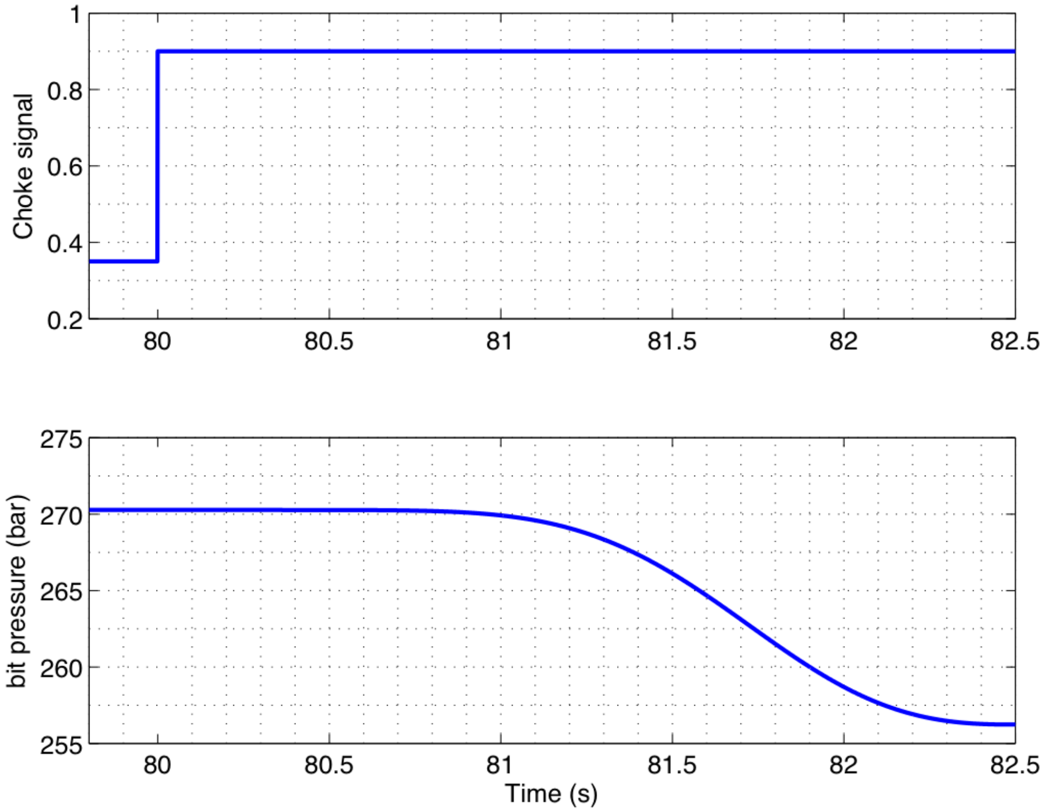


Figure 6.6: *The figure shows the same simulation as the previous figure in the time interval 79.5 s - 82.5 s. The choke opening is changed at time t = 80 s. From the simulation we can see that it takes about 1 s until we can see the effect on the bottomhole pressure.*

7 Results

Because of delays in the construction process of the MPD Heave Rig, the time to execute the planned test was limited. One attempt to pressure test the control board failed and resulted in a major leak when two pipe clamps popped off. It is therefore suggested to exchange all hose parts and pipe clamps with PVC pipe and screw fittings to maintain the pressure integrity of the system. It also turned out that the pump could only deliver 30 lpm. If it still is desired to obtain a flowrate of 40 lpm through the choke, it is suggested to install a feed pump in the water tank.

A prototype version of the choke was tested to identify the choke characteristics. The results are presented in the next subchapter.

7.1 Choke characteristics

The turbine flowmeter and the pressure transmitters measure flow in the range of 4-100 l/min and pressure in range of 0-10 bar respectively. The pulses detected are converted to a 4-20mA signal. Figure 7.1 shows the signals from the flowmeter and the pressure transmitters obtained in Daqlab plotted against time. The upper plot shows the pressure signals from the two pressure transmitters. The pressure upstream the choke is increasing as the choke opening is decreased with increments of 10 degrees for each step starting with 100 % (90 degrees) choke opening, while the pressure downstream the choke is maintained approximately constant. The signal from the flowmeter is plotted in the lower graph. It can be seen that the flowrate is decreasing as the choke opening is decreased.

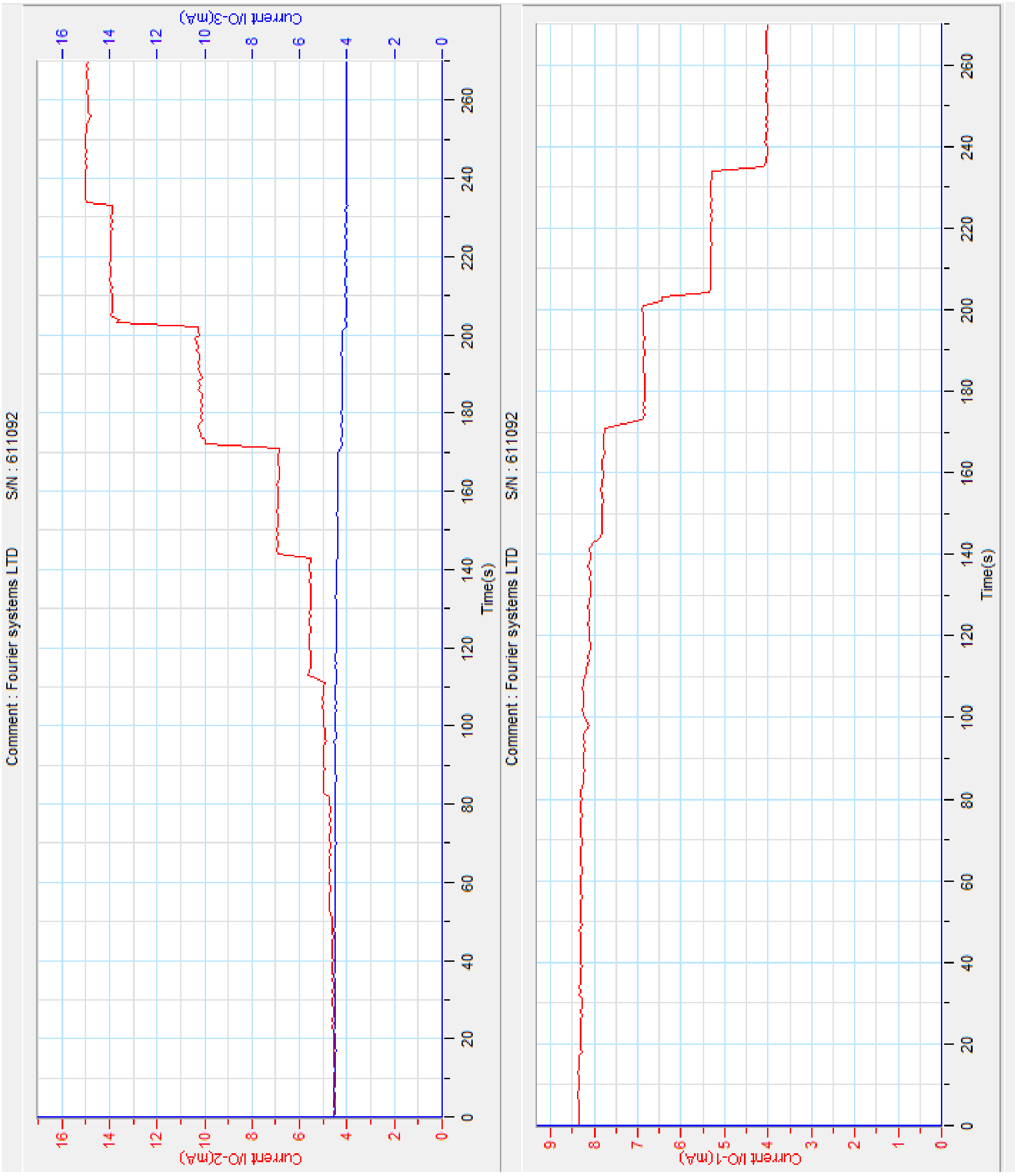


Figure 7.1: *Logging results from DaqPro. Current IO-1 is the signal from the flowmeter, Current IO-2 and Current IO-3 are the signals from the pressure transmitters upstream and downstream the choke respectively.*

Table 7.1 shows the test results with flowrate Q, pressure drop ΔP over the choke, and calculated K_v. The calculated K_v for the tests shows relatively similar values. However, the choke opening was adjusted manually, and might cause dissimilarities in opening position for each test.

	Test 1			**Test 2**		
$\theta(°)$	$Q(lpm)$	$P[bar]$	$K_v(m^3/h/bar)$	$Q(lpm)$	$P(bar)$	$K_v(m^3/h/bar)$
90	30.6	0.00	11.3	36.4	0.00	11.5
80	30.7	0.08	6.7	36.2	0.12	6.3
70	30.4	0.18	4.3	35.8	0.25	4.3
60	30.2	0.36	3.0	35.0	0.54	2.9
50	28.5	1.14	1.6	31.9	1.50	1.6
40	26.1	2.01	1.1	29.3	2.47	1.1
30	20.2	3.88	0.6	21.5	4.47	0.6
20	8.5	6.25	0.2	8.1	6.49	0.2
10	0.2	6.90	0.0	0.2	6.77	0.0
	Test 3			**Test 4**		
$\theta(°)$	$Q(lpm)$	$P(bar)$	$K_v(m^3/h/bar)$	$Q(lpm)$	$P(bar)$	$K_v(m^3/h/bar)$
90	21.5	0.00	12.1	26,5	0.00	11.6
80	21.4	0.04	6,4	26,4	0.06	6.5
70	21.2	0.08	4,5	26,1	0.14	4.2
60	21.0	0.17	3,1	25,9	0.26	3.0
50	20.4	0.63	1,5	24,6	0.84	1.6
40	19.5	1.12	1,1	23,5	1.53	1.1
30	16.6	2.80	0,6	18,1	3.75	0.6
20	7.8	5.90	0,2	8,5	6.06	0.2
10	0.2	6.93	0,0	0,2	7.04	0.0

Table 7.1: *Prototype choke test results and calculated K_v.*

The average K_v value is plotted in excel (see figure 7.2). Two trendlines are implemented in the plot to obtain a regression of the calculated K_v values based on the measurements. Equation 7.1 is valid for choke openings from 10° to 50°. Equation 7.2 is valid for choke openings from 50° to 80°.

$$K_v(\theta) = 0.0407\theta - 0.5226, \theta\epsilon[10, 50] \tag{7.1}$$

$$K_v(\theta) = 0.1604\theta - 6.5768, \theta\epsilon[50, 80] \tag{7.2}$$

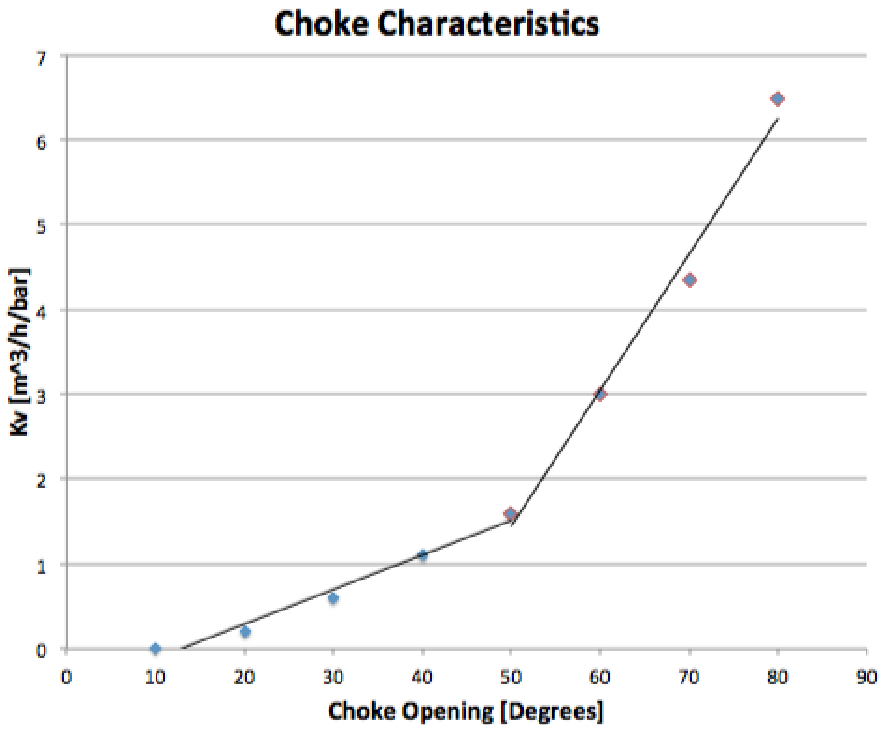


Figure 7.2: *The figure shows an excel plot of the average K_v value based on the four tests with different flow rates presented in table 7.1. Two trendlines are implemented in the plot to obtain a regression of the choke characteristics with respect to the choke opening θ.*

Based on the hydraulic model it is desired to maintain a constant bottomhole pressure of 5 bar. If the surge and swab pressures are varying in the range of +/− 2 bar, the pressure drop over the choke is ranging in the window 3 bar to 7 bar. When the drillstring is moved upwards, the pressure in the hole is decreasing towards 3 bar and the choke opening must be reduced to compensate for the pressure decrease. And opposite, when the drillstring is moved downwards, the bottomhole pressure is increasing towards 7 and the choke opening must be increased. The K_v value, considering a constant flow rate of 40 lpm, for 3 bar, 5 bar and 7 bar are 1.70 $m^3/h/bar$, 1.07 $m^3/h/bar$ and 0.91 $m^3/h/bar$ respectively. The choke opening θ for compensating for the the the three pressure drops at the choke is found by solving equation 7.1:

$\Delta P(bar)$	$K_v(m^3/h/bar)$	$\theta(°)$
3	1.70	46.9
5	1.07	39.2
7	0.91	35.1

Table 7.2: *Choke opening for 3 bar, 5 bar and 7 bar pressure given from equation 7.1*

.

Based on the current choke test it is suggested to implement a physical barrier on the motor driven choke to ensure that the choke can not be closed more than 33°. This measure is suggested to avoid an instant closing of the choke valve, which can lead to a major pressure increase in the system and to avoid exceeding the maximum working pressure of the system.

8 Discussion

The construction of the MPD Heave Rig has been a time-consuming process that has taken longer time than planned. This has resulted in limited time to conduct the commissioning test of the planned rig model. Since it was clear that the computer control of the motors and the control system would not be ready in time, it was decided to focus on the current situation of the rig, and to plan tests accordingly.

The result from the prototype choke test is a preliminary test that gives an indication of the choke characteristics and what windows we need to operate in to maintain a constant bottomhole pressure. However, the choke must be tested with flow provided by the pump to obtain a more constant flow rate through the choke as the choke opening is decreased. The test with manual adjustment of the choke opening could with advantage have been expanded with adjusting the choke opening in smaller steps (i. e. 5 degrees), however this would lower the repeatability of the tests since the adjustment of the manual choke handle is inaccurate.

To maintain a constant bottomhole pressure of 5 bar when the pressure variation in the system is varying between 3 and 7 bar respectively, the choke opening must be adjusted between 35.1° and 46.9°. However, this is without taking the friction in the hydraulic system into account. This the choke window may therefore be larger due to the friction pressure drop in the system.

The plan for identification tests presents tentative results, however, the due to the complexity of the model, the only way to detect correct values for time delay, compressibility and friction, is by testing the system. In this way the hydraulic model can be extended based on empirical correlations.

8.1 Improvements to the MPD Heave Rig

The pump in the lab was tested and could not deliver more than 30 lpm. To obtain the desired flowrate of 40 lpm through the choke, it is suggested to install a feed pump in the water tank. The accumulator on the pump is compensating for pressure increases in the system when the choke is sealed by compressing air. This is not optimal for controlling downhole pressures, as the pressure increase will be lower than desired when the choke opening is reduced. It is therefore suggested to remove or reduce the pump accumulator.

However, further measures to avoid possible disturbing noise during experiment must be implemented in case this is a problem when logging results are obtained.

It was initially suggested to implement two safety valves in the system. However, it is currently only installed one. A safety valve on the pump will work as a contingency if the first safety valve fails. If the pressure in the system exceeds 10 bar, the safety valve on the pump will circulate water back to the tank, to avoid a further pressure increase in the system.

Pipe components on the model, excluding the copper pipe and the well, are currently a mix of PVC pipes and hose parts. The fittings are secured with pipe clamps. One attempt of pressure testing this system failed and caused a major leak. It is therefore suggested to replace all hose parts with PVC pipes with screw fittings to ensure pressure integrity of the model.

The current design of the model is limited by a maximum working pressure of 10 bar of the turbine flowmeters. Based on the hydraulic model, the pressure in the hydraulic system does not exceed this pressure. However, if it is desired to simulate greater pressure variations, the turbine flowmeters can be replaced with flowmeters with a higher pressure range.

8.2 Further work

There are currently uncertainties in implementing the computer control of the motors and the control system in the model. Due to time constraints the involvement of these components in the plan for commissioning test has not been emphasized in this thesis. A new plan for commissioning testing should therefore be developed when the MPD Heave Rig is completed according to planned P&ID, and enough information about the computer controlled systems is obtained. The commissioning test of the current MPD Heave Rig, without well system and computer controlled systems, and tests for identifying parameters for the hydraulic model have been presented. However, executing these tests remains as further work. There is currently not implemented sufficient logging in the model, which must be established to be able to conduct the identification tests.

It is suggested to include all participants involved in the MPD Heave rig for a review of the risk assessment prior to commissioning and experiment start up. Hence a better perspective of potential risks in the project can be obtained.

9 Conclusion

The planned design of the MPD Heave rig including technical components and instrumentation has been presented. The maximum working pressure of the model is 10 bar which is currently sufficient according to the simulated pressure variations in the well. Preliminary test of a prototype choke indicates that the selected choke size is sufficient for the purpose of controlling pressures in the well.

The main contribution to the pressure fluctuations due to the heave motion in the model, is the pressure variation due to a narrow clearance between the well and the bottomhole assembly. The magnitude of the pressure variations is depending on the velocity of the drillstring and therefore also the period of the harmonic wave movement. The amplitude of the model remains constant, however it is possible to vary the period of the movement of the drillstring. Friction, compressibility and time delay in the system must be identified by tests to be able to control the pressure variations as accurate as possible.

The implementation of a 900 m long copper pipe to simulate the time delay of pressure waves makes the model realistic, and addresses one of the key challenges of timing the control of the bottomhole pressure. Logging measurements of the pressure and flow variations in the system in labscale will give a better understanding of the challenges met in the field.

It is important to ensure the technical and operational safety of the project. The risk assessment has detected a number of measures that need to be implemented to limit the risk of the operations of the MPD Heave Rig. One safety valve is currently installed in the system and it is suggested to install a safety valve on the pump. It is further decided to replace all hose parts in the model with PVC pipes to ensure pressure integrity of the system.

This study creates a foundation for further work with the MPD Heave Rig.

Nomenclature

AFP Annular Friction Pressure

BHA Bottom Hole Assembly

BHP Bottomhole Pressure

BOP Blowout Preventer

CBHP Constant Bottomhole Pressure

DOP Detail Operation Plan

ECD Equivalent Circulation Density

HAZOP Hazard and Operability

HTHP High-Temperature High-Pressure

MPD Managed Pressure Drilling

NPT Non-Productive Time

P&ID Process and Flow Diagram

PMCD Pressurized-Mud Cap Drilling

POOH Pull out of Hole

PPE Personal Protective Equipment

RCD Rotating Control Device

RIH Run in hole

ROP Rate of Penetration

SJA Safe Job Analysis

SPE Society of Petroleum Engineers

UBD Underbalanced Drilling

References

Aadnoy, B. S., L. Cooper, S. Z. Miska, R. F. Mitchell, and M. L. Payne (2009). *Advanced Drilling and Well Technology*. SPE.

Bourgoyne, A. T., M. E. Chenevert, and K. K. Millheim (1986). *Applied Drilling Engineering*, Volume 2. SPE Textbook Series.

Breyholtz, Ø., H. Siahaan, and M. Nikolaou (2010). Managed Pressure Drilling: A Multi-Level Control Approach. *SPE*.

Burkhardt, J. A. (1961). Wellbore Pressure Surges Produced by Pipe Movement. *SPE*.

Gala, D. M. (2011). Managed Pressured Drilling 101: Moving Beyond: "It's Always Been Done That Way". *The Way Ahead, SPE*.

Gjengseth, C. S. and T. Svenum (2011). Heave Compensated Mangaged Pressure Drilling: A Lab Scaled Rig Design. *NTNU*.

Godhavn, J.-M. and K. A. Knudsen (2010). High Performance and Reliability for MPD Control System Ensured by Extensive Testing. *SPE/IADC*.

Gudmundsson, J. S. (2010). Kompendium prossessering av petroleum. http://www.ipt.ntnu.no/~jsg/undervisning/prosessering/kompendium/2%20Trykktap%202010.pdf.

Halliburton. Wellplan Suite Well Operations Software. Available at: http://www.halliburton.com/ps/Default.aspx?navid=218&pageid=891.

Hannegan, D. (2006). Case Studies - Offshore Managed Pressure Drilling. *SPE*.

Hannegan, D. (2011a). Managed Pressure Drilling Applications on Offshore HTHP Wells. *Offshore Technology Conference*.

Hannegan, D. and K. Fisher (2005). Managed Pressure Drilling in Marine Environments. *IPTC*.

Hannegan, D. M. (2007). Managed Pressure Drilling Technology: Applications, Variations and Case Histories. *SPE*.

Hannegan, D. M. (2011b). MPD - Drilling Optimization Technology, Risk Management Tool, or Both? *SPE*.

IADC (2008, January). UBO&MPD Glossary. Available at: http://www.iadc.org/committees/ubo_mpd/completed_documents.html.

Kaasa, G., O. Stamnes, L. Imsland, and O. Aamo (2011). Intelligent Estimation of Downhole Pressure Using a Simple Hydraulic Model. *SPE/IADC*.

Kernche, F., D. Hannegan, C. Peña, and M. Amone (2011). Managed Pressure Drilling Enables Drilling Beyond the Conventional Limit on an HP/HT Deepwater Well in the Mediterranean Sea. *SPE*.

Lal, M. (1983). Surge and Swab Modeling for Dynamic Pressures and Safe Trip Velocities. *IADC/SPE*.

Landet, I. S. (2011). Modeling and Control for Managed Pressure Drilling from Floaters. Master's thesis, NTNU.

Landet, I. S., H. Mahdianfar, U. J. F. Aarsnes, A. Pavlov, and O. M. Aamo (2012). Modeling for MPD Operations with Experimental Validation. *SPE/IADC*.

Langørgen, E. (2012, March). Risk assessment report template. Provided by Department of Energy and Process Engineering, email: erik.langorgen@ntnu.no.

Malloy, K. P. (2007). Managed-Pressure Drilling - What is it anyway. *World Oil*.

Malloy, K. P. (2008). A Probabilistic Approach to Risk Assessment of Managed Pressure Drilling in Offshore Applications. Technical report, MOHR Engineering Division.

Mitchell, R. F. (1988). Surge Pressures: Are Steady-State Models Adequateurge Pressures: Are Steady-State Models Adequate. *SPE*.

Moreau, K. and P. Fredericks (2011). Automated MPD Improves Drilling Efficiency In Deepwater GoM. *Exploration and Production*.

Nesbitt, B. (2007). *Handbook of Valves and Actuators*. Valves Manual International.

Nilsen, L. H. (2009). Drilling in depleted reservoirs. *StatoilHydro*.

Rashid, S. A. (2011). Evaluation of Continious Circulation System for Compensation of Surge and Swab Pressures. *NTNU*.

Rasmussen, O. S. and S. Sangesland (2007). Evaluation of MPD Methods for Compensation of Surge-and-Swab Pressures in Floating Drilling Operations. *SPE*.

Rehm, B., J. Schubert, A. Haghshenas, A. S. Paknejad, and J. Hughes (2008). *Managed Pressure Drilling*. Gulf Publishing Company.

Rocha, L. A. S., P. Junqueira, and J. Roque (2003). Overcoming Deep and Ultra Deepwater Drilling Challenges. *Offshore Technology Conference*.

Romstad, T., H. Rogers, and T. Saetre (2010). Equipment Design Change Improves Cementing Operations from MODUs Operation in Rough Sea Environment: Case Histories for Two North Sea Jobs. *SPE*.

Rudolf, R. and P. Suryanarayana (1997). Kicks Caused by Tripping-In the Hole on Deep, Hight Temperature Wells. *SPE*.

Schuh, F. J. (1964). Computer Makes Surge-Pressure Calculation Useful. *Oil and Gas Journal*.

Solvang, S. and C. Leuchtenberg (2008). Managed Pressure Drilling Resolves Pressure Depletion Related Problems in the Developement of the HPHT Kristin Field. *IACD/SPE*.

Solvang, S., C. Leuchtenberg, I. Gil, and H. Pinkstone (2008). Managed Pressure Drilling Resolves Pressure Depletion Related Problems in the Development of the HTHP Kristin Field. *IADC/SPE*.

Sonic Energy Services LTD. (2012). Last checked: 24.05.12. available at: `http://www.sonic-energy.ca/PDF/MPD%20Tech%20Note%20-%20Generic.pdf`.

Stamnes, Ø. N. (2011). *Nonlinear Estimation with Applications to Drilling*. Ph. D. thesis, NTNU.

Svenum, T. (2012). Lab for heave motion during Managed Pressure Drilling. Master's thesis, NTNU.

The Engineering Toolbox (2012). Last checked: 05.06.12. available at: `http://www.engineeringtoolbox.com/sound-speed-water-d_598.html`.

APPENDICES

A Risk Assessment Report

Risk Assessment Report

[MPD Rig]

Project Title	Lab for heave motion during Managed Pressure Drilling
Students	Camilla Sunde Gjengseth/Tollef Svenum
Unit	NTNU
HMS-coordinator	Roger Overå
Line Manager	John-Morten Godhavn
Location	PTS
Room number	Workshop hall, Department of Petroleum Engingeering and Applied Geophysics
Rig Responsible	Jarle Glad, Sigbjørn Sangesland
Risk Assessment Conducted by	Camilla Sunde Gjengseth

NTNU SINTEF

TABLE OF CONTENTS

1 INTRODUCTION

MPD has been applied both onshore and offshore, but mainly from fixed platforms in offshore environment. However some applications have been run also from floating drilling rigs in calm waters, whereas no backpressure MPD solution is available for North Sea conditions with severe heave motions. Experience has shown that we can get up to 20 bar variations due to heave during connections, when the drill pipe is hung off and the heave compensation system is turned off.

A lab model named ”MPD Heave Rig” is designed to model such conditions in lab scale in the workshop hall of the Department of Petroleum Engineering and Applied Geophysics. Pressure fluctuations are generated by moving a pipe up and down in a sealed hole to simulate the movement of the drillstring in the borehole. The pressure fluctuations are controlled by an automatically controlled choke valve and water flow provided by a water pump.

This risk assessment consider the whole process from building the MPD Heave Rig to running experiments with the complete system.

2 ORGANISATION

Role	NTNU
Lab Responsible:	Sigbjørn Sangesland/Jarle Glad
Line Manager:	John-Morten Godhavn
HSE Responsible:	Roger Overå
Project manager:	Camilla Sunde Gjengseth/Tollef Svenum
Responsible Operators:	NTNU Representant: Jarle Glad

3 RISK MANAGEMENT IN THE PROJECT

The risk management is divided into assessment of technical safety and assessment of operational safety.

4 DRAWINGS & DESCRIPTIONS OF TEST SETUP

Drawings, photos and descriptions of test setup can be found in the main document (Master thesis).

5 EVACUATION FROM THE EXPERIMENT AREA

The workshop hall is marked with emergency exit signs in case of evacuation. For emergency evacuation meet at muster point (Parking Lot in front of Petroleum Technical Center).

6 WARNING

6.1 Before experiments

All experiments should be planned according to procedures. Experiment leader must ensure that the experiments are coordinated with other activity before start up.

6.2 Non-conformance

FIRE
If you are not able to put out the fire with locally available fire extinguishers, activate the nearest fire alarm and evacuate area. If possible, notify:

NTNU
HSE responsible: Roger Overå (73594983)
Department leader: Jon Kleppe (91897300)

PERSONAL INJURY
- First aid kit in the fire / first aid stations
- Shout for help
- Start first aid
- **Call 113** if there is or there is doubt whether there is serious injury.

Other Nonconformance
NTNU: Report nonconformance, Innsida, avviksmelding:
https://innsida.ntnu.no/lenkesamling_vis.php?katid=1398

7 ASSESSMENT OF TECHNICAL SAFETY

7.1 Hazard and Operability Study (HAZOP)

A Hazard and Operability analysis of the process is conducted to detect problems that may represent risks to technical safety.

Attachments: HAZOP form.
Conclusion: Security assured with existing and planned measures described in HAZOP.

7.2 Flammable, reactive and pressurized substances and gas

Does the experiment contain flammable, reactive and pressurized substances and/or gas?

NO	YES. Provide explosion document and/or documented pressure test

7.3 Pressurized equipment

Does the set up contain pressurized equipment?

NO	**YES** Equipment has to undergo pressure testes in accordance with the norms and be documented. Provide certificate for pressurized equipment.

Conclusion*:* Low pressure water (10 bar). No certificate needed. The MPD Heave Lab is pressure tested according to pressure test procedure in DOP1.

7.4 Effects on the environment (emissions, noise, temperature, vibration, smell)

Is there any risk of generating emission of smoke, gas, odor or unusual waste? Is there a need for a discharge permit, extraordinary measures?

NO	YES

7.5 Radiation

NO	**YES**, Radiation source needs to have an own risk assessment

The construction the framework of the copper pipe cylinder involves welding the steel parts together. During the welding operations it is important to wear additional protection in addition to the already required PPE to avoid hazards related to the activity. Coverall or jacket/trousers in cotton is required to protect the skin. Nylon should not be used, it melts easily, and there is great danger of combustion. The operator must wear proper eye protection to avoid serious eye damage due to the intense light associated with welding operations. Gloves should be worn to protect from burns from the welded steel. Welding light contains ultraviolet rays and has the same effect as the sun. Too much radiation can cause skin cancer. All clothes should be well buttoned up, so the skin is not exposed to the light during the operation. Only a certified welding operator is allowed to perform this operation.

7.6 Chemicals handling.

Does the experiment include use and/or handling of chemicals (Which and quantities)?

NO	YES, Conduct a risk assessment of the use

7.7 El safety (need to deviate from the current regulations and standards.)

NO	YES, El safety have to be evaluated

8 ASSESSMENT OF OPERATIONAL SAFETY

Assessment of operational safety is conducted to ensure that established procedures cover measures for all identified risk factors during the process and that technical operators have sufficient expertise.

8.1 Procedure HAZOP

Assessment: The operational safety of the system is ensured according to existing measures and procedures.

8.2 Technical modifications

Technical crew with rig responsible in charge is responsible for the building of the MPD rig. The two master students may support this process if necessary. The technical crew may conduct technical modifications that do not change the risk picture.

Modifications where technical equipment is replaced require a new pressure test of the whole system.

8.3 Personal protective equipment (PPE)

- It is mandatory use protective shoes, helmet and eye protection glasses in the lab and coverall in the lab.
- Use gloves when there is opportunity for contact with hot/cold surfaces.

8.3.1 Additional safety equipment

- For Working at Heights: Required to wear safety harness in addition to PPE to reduce the risk of fall from height.
- For welding operations: Required to wear eye protection, gloves, and coverall; make sure skin is not possibly exposed to the light during operation.

8.3.2 General Safety

Lab responsible must be present during operations. Operators are not allowed to leave during the experiment. Lab responsible needs to conduct sufficient training of operators prior to operation of MPD Heave Rig.

8.4 Safety protection

The control panel is placed on a table covered with a glass frame to protect the computer from water spills. The control panel is placed in sufficient distance from the MPD Heave Rig.

8.5 Special measures

Equipment mounted on the rig must be secured to avoid personal injury and damage on equipment.

- **Measures to prevent heavy components from falling:**

The water tank is placed on top of the 3 m tall copper pipe cylinder. It is secured with a wooden frame to the roof of the cylinder.

The well is sufficiently secured to a steel plate attached to the copper pipe cylinder.

- **Safe Job Analysis (SJA)**

Safe Job Analysis template is developed by NTNU/SINTEF must be completed before special operations. In this process these operations are:

  - Working at Heights
  - Heavy Lifting Operation where lift crane is involved

The SJA Template can be found in the attachments.

9 QUANTIFYING OF RISK - RISK MATRIX

CONSEQUENSES						
	Very High	E1	E2	E3	E4	E5
	High	D1	D2	D3	D4	D5
	Moderate	C1	C2	C3	C4	C5
	Low	B1	B2	B3	B4	B5
	Very low	A1	A2	A3	A4	A5
		Very low	Low	Moderate	High	Very high
		PROBABILITY				

Explanation of the colors used in the matrix

Color		Description
Red		Unacceptable risk. Measure must be taken to reduce risk.
Yellow		Assessment area. Measures must be considered.
Green		Acceptable risk. Measure can be taken based on other criteria

Activity/Event	Prob.	Cons	RV
Leaks	4	A	A2
Pipe clamps pop off when pump is circulating water from water tank and back	3	B	B3
Pipe clamps pop off during pressure tests	4	C	C4
Both safety valves fail	1	A	A1
Too much pressure in system	*2*	B	2B

10 CONCLUSION

- The rig is currently not secure for operations. It is suggested to improve the control board by implementing PVC pipes and fittings to reduce the risk of major leaks during pressure tests.
- New risk assessment must be carried if there are major alterations to the risk factors.

11 REGULATIONS AND GUIDELINES

Norwegian laws and regulations

See http://www.arbeidstilsynet.no/regelverk/index.html

- Lov om tilsyn med elektriske anlegg og elektrisk utstyr (1929)
- Arbeidsmiljøloven
- Forskrift om systematisk helse-, miljø- og sikkerhetsarbeid (HMS Internkontrollforskrift)
- Forskrift om sikkerhet ved arbeid og drift av elektriske anlegg (FSE 2006)
- Forskrift om elektriske forsyningsanlegg (FEF 2006)
- Forskrift om utstyr og sikkerhetssystem til bruk i eksplosjonsfarlig område NEK 420
- Forskrift om håndtering av brannfarlig, reaksjonsfarlig og trykksatt stoff samt utstyr og anlegg som benyttes ved håndteringen
- Forskrift om Håndtering av eksplosjonsfarlig stoff
- Forskrift om bruk av arbeidsutstyr.
- Forskrift om Arbeidsplasser og arbeidslokaler
- Forskrift om Bruk av personlig verneutstyr på arbeidsplassen
- Forskrift om Helse og sikkerhet i eksplosjonsfarlige atmosfærer
- Forskrift om Høytrykksspyling
- Forskrift om Maskiner
- Forskrift om Sikkerhetsskilting og signalgivning på arbeidsplassen
- Forskrift om Stillaser, stiger og arbeid på tak m.m.
- Forskrift om Sveising, termisk skjæring, termisk sprøyting, kullbuemeisling, lodding og sliping (varmt arbeid)
- Forskrift om Tekniske innretninger
- Forskrift om Tungt og ensformig arbeid
- Forskrift om Vern mot eksponering for kjemikalier på arbeidsplassen (Kjemikalieforskriften)
- Forskrift om Vern mot kunstig optisk stråling på arbeidsplassen
- Forskrift om Vern mot mekaniske vibrasjoner
- Forskrift om Vern mot støy på arbeidsplassen

Guidelines from the Labour Inspection (Arbeidstilsynet):
http://www.arbeidstilsynet.no/regelverk/veiledninger.html

Attachment to Risk Assessment report

MPD Heave Rig

Project name	MPD Heave Rig
Project leader	John-Morten Godhavn/Sigbjørn Sangesland
Department	Department of Petroleum Engineering and Applied Geophysics
HMS-coordinator	Roger Overå
Line manager	John-Morten Godhavn
Riggnavn	MPD Heave Rig
Plassering	Workshop hall, Department of Petroleum Engineering and Applied Geophysics

TABLE OF CONTENTS

NTNU SINTEF

• ATTACHMENT A HAZOP MAL

Project: MPD Heave Rig							
Ref #	**Guideword**	**Causes**	**Consequences**	**Safeguards**	**Recommendations**	**Action**	**Date Sign**
1.1	No flow	- Air in pump or low water level in water tank - Inlet filter on pump might be clogged	- Pump could be damaged	- Check water lever in tank prior to experiments - Check inlet filter prior to experiments			
1.2	Reverse flow	Not relevant					
1.3	More flow	- Non-conformance in pump flow and control-signal to pump	- Unexpected pressure regimes when choke opening is adjusted	- Verify correct flow according to control-signal to pump	- Function test pump control in open circulation system prior to experimental tests		
1.4	Less flow	See 1.3	See 1.3	See 1.3			
1.5	More level	Not relevant					
1.6	Less level	Not relevant					
1.7	More pressure	- Choke opening too small - Choke is instantly closed	- Damage on equipment - Water hammer effect may cause pressure increase	- Safety valves - Minimum choke opening implemented in control system	- Install safety valve between pump and choke - Install safety valve on pump		

Project: MPD Heave Rig							
Ref #	**Guideword**	**Causes**	**Consequences**	**Safeguards**	**Recommendations**	**Action**	**Date Sign**
			of 77 bar		- Physical barrier on choke so It cannot be closed instantly		
1.8	Less pressure	Leaks	- Large spills when system is pressure testet	- PVC pipes on control board			
1.9	More temperature	- Increase in water temperature	- Change in hydraulic properties	- Check water temperature	- Cold water supply when temperature is too high	- Thermometer implemented in water tank	
1.10	Less temperature	Not relevant					
1.11	More viscosity	See 1.9					
1.12	Less viscosity	Not relevant					
1.13	Composition Change	Not Relevant					
1.14	Contamination	- Growth of algae in the system caused by stationary water	- Could clog equipment and piping	- Remove all water in system is MPD Heave Rig going to be shut down for a longer period.			
1.15	Relief	- Not relevant					
1.16	Instrumentation	- Incorrect choke opening can cause pressure increase in system which	- See 1.7	- See 1.7	- See 1.7	- See 1.7	

Project: MPD Heave Rig							
Ref #	Guideword	Causes	Consequences	Safeguards	Recommendations	Action	Date Sign
		can damage equipment					
1.17	Sampling	Not relevant					
1.18	Corrosion/erosion	Corrosion due to water in the system for longer periods.	Failure on equipment, clogging	- Remove all water in system is MPD Heave Rig going to be shut down for a longer period.			
1.19	Service failure	Not relevant					
1.20	Abnormal operation	Not relevant					
1.21	Maintenance	Not relevant					
1.22	Ignition	Not relevant					
1.23	Spare equipment	Not relevant					
1.24	Safety	Electrical components in contact with water	- Damage on equipment - Personal injury	- Placement of electrical components	- Heave motor should be located above the well	Heave motor is placed above the well	

- **ATTACHMENT B FORM FOR SAFE JOB ANALYSIS**

SJA tittel:		
Dato:		Sted:
Kryss av for utfylt sjekkliste:		

Deltakere:		
SJA-ansvarlig:		

Arbeidsbeskrivelse: (Hva og hvordan?)
Risiko forbundet med arbeidet:
Beskyttelse/sikring: (tiltaksplan, se neste side)
Konklusjon/kommentar:

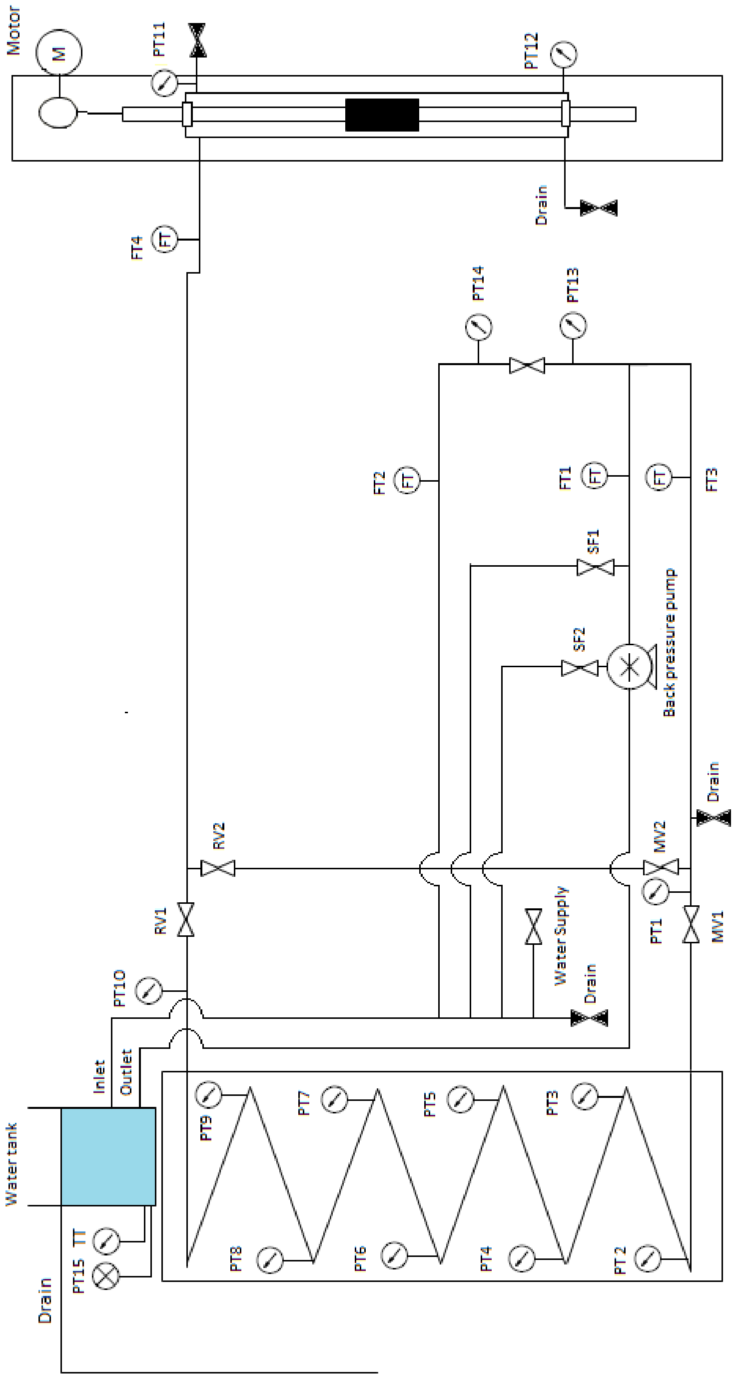
Anbefaling/godkjenning:	**Dato/Signatur:**	**Anbefaling/godkjenning:**	**Dato/Signatur:**
SJA-ansvarlig:		Områdeansvarlig:	

Ansvarlig for utføring:		Annen (stilling):	

HMS aspekt	Ja	Nei	Ikke aktuelt	Kommentar / tiltak	Ansv.
Dokumentasjon, erfaring, kompetanse					
Kjent arbeidsoperasjon?					
Kjennskap til erfaringer/uønskede hendelser fra tilsvarende operasjoner?					
Nødvendig personell?					
Kommunikasjon og koordinering					
Mulig konflikt med andre operasjoner?					
Håndtering av en evnt. hendelse (alarm, evakuering)?					
Behov for ekstra vakt?					
Arbeidsstedet					
Uvante arbeidsstillinger?					
Arbeid i tanker, kummer el.lignende?					
Arbeid i grøfter eller sjakter?					
Rent og ryddig?					
Verneutstyr ut over det personlige?					
Vær, vind, sikt, belysning, ventilasjon?					
Bruk av stillaser/lift/seler/stropper?					
Arbeid i høyden?					
Ioniserende stråling?					
Rømningsveier OK?					
Kjemiske farer					
Bruk av helseskadelige/giftige/etsende kjemikalier?					
Bruk av brannfarlige eller eksplosjonsfarlige kjemikalier?					
Må kjemikaliene godkjennes?					
Biologisk materiale?					
Støv/asbest?					
Mekaniske farer					
Stabilitet/styrke/spenning?					
Klem/kutt/slag?					
Støy/trykk/temperatur?					
Behandling av avfall?					
Behov for spesialverktøy?					
Elektriske farer					
Strøm/spenning/over 1000V?					
Støt/krypstrøm?					
Tap av strømtilførsel?					
Området					
Behov for befaring?					
Merking/skilting/avsperring?					

Miljømessige konsekvenser?					
Sentrale fysiske sikkerhetssystemer					
Arbeid på sikkerhetssystemer?					
Frakobling av sikkerhetssystemer?					
Annet					

- **ATTACHMENT C P&ID**



B Detail Operation Plan

		Detail Operation Procedure		
Rig	NA	MPD Heave Rig: System commissioning	Rev.	
Well #	NA		Date	01.06.2012
			Status	

Approved:

NTNU ______________________ Statoil

Administration: John-Morten Godhavn, Sigbjørn Sangesland and Ole Morten Aamo

1.0 Tool Box Safety Points:

- **Toolbox meeting in Lab**
- **Use time; Perform the job in correct way first time**
- **Use 4 - Point Check before the operation starts.**
  1. ***HOW*** shall I perform this job? - Develop a plan
  2. ***WHAT*** can go wrong? -Identify potential hazards
  3. ***WHICH*** actions do I have to initiate to avoid any hazards? - Implement correct preventative actions
  4. ***WHO*** do I have to inform?- Ensure all involved understand the plan and which safety measures that have to be implemented
- **If plan is not followed - STOP, contact your leader and evaluate.**
- **All lifting operations to be planned ahead**.

DOP	Detail Operation Plan
CS	Control System
HS	HS
MPD	Managed Pressure Drilling
S	Staoil
NTNU	Norges Teknisk Naturviten. Universitet

2.0 Well Information / Goals

Objectives:	Perform function tests of technical equipment for system commissioning. Identify parameters for hydraulic model.
Major Risks:	• Problems with equipment may create damage to the lab if not handled appropriate.
Well Information:	• NA
Barriers:	Primary: NA Secondary: NA
Technical information and operational limitations	*Maximum working pressure of system: 10 bar* *Dimensions* • *ID pipe: 42,6 mm* • *OD BHA: 40,9 mm* • *Upper DP: 25 mm* • *Lower DP: 24,4 mm* • *Capacity of pump: 47 lpm*
	NA

3.0 Equipment Check List

No	Responsible (Signature)	Equipment	Location	Comments
1.		**Water Pump** • Verify correct pressure setting on "Pop off" safety valve to 10 bar		
2.		**Safety valve** • Verify correct pressure setting on 10 bar maximum pressure		
3.		**Choke control** • Minimum opening accoding to maximum pressure drop at choke in CS software		
4.		**Hydralic system** • Tighten all pipe clamps		
5.		**Maual Valves** • Check position according to test procedure		
6.				

4.0 Preparations for Commissioning test

No	Responsible (Signature)	Preparations for operations	Comments
1.		Calibrate turbine flowmeter according to magnetic flowmeter.	
2.		Check position of manual valves according to test procedure.	
3.		Check water tank level and verify temperature of water.	
4.		Function test remote controlled valves.	
5.		**Pre job meeting all personnel** *Hold a start up meeting and Safe Job Analysis upfront of the test involving all participants during the test. (Camilla)*	
6.	All involved	During operation fill in comments and correct DOP. This will improve DOP for future operations.	General Lessons Learned
7.	All to sign here:		

5.0 Operations (Pilot/Acceptance Testing)

Time table and expected pressure values, flow values and delay will be presented as appendices to this document.

5.1 Function Tests of equipment

Overview of tests:
Ver01: Instrumentation
Ver02: Pressure integrity test
Ver03: Pump test (Manual control)

No	Resp.	Main activity / Operational Description / Risks	Comments
1.		**Ver01: Instrumentation (pressure and flow meassurments)** Verify sensors (Accuracy, data communication) Preparation • The signal from the instrumentation is verified when there is no water in the system and with water in the system according to hydrostatic pressure.	
2.		1. No water in system a. No water in system b. Verify signal from pressure transmitters	
3.		2. System is filled with water a. Verify pressure sensors in system according to hydrostatic pressure in static condistion b. Verify flowmeter in system according to no flow in static condition	
4.		**Ver02: Pressure integrity test** The procedure include pressure test of the control board, bypass line and copper pipe P&ID: Figure 1, 2, 3	
5.		1. Startup condition a. No circulation from pump b. Choke opening 0 degrees (closed) c. MV2, TV2, RV2 closed d. MV1, RV1, TV1 open	
6.		2. Fill up system with water a. Ramp up water pump to 10 lpm b. Circulate through copperpipe	Possible air needs to be circulated out prior to pressure test.
7.		3. Pressuretest control board a. Close MV1, MV2 and TV2 b. Adjust bypass valve on pump TV 3 to 10 bar pressure in system OR c. Ramp up water pump to 10 bar safty valve “pop off” d. Close MV3 e. Wait 10 min f. If pressure test successful – continue procedure g. Open MV2, RV2 h. Open TV3 fully i. Open MV3	The safety valve on the pump is currently defect Check for leaks, constant pressure
8.		4. Pressure test control board and bypass line	Check for leaks,

No	Resp.	Main activity / Operational Description / Risks	Comments
		a. MV1 and RV1 closed b. MV2, RV2, TV1 open c. Circulate through bypass line to drain d. Close RV2 e. Adjust bypass valve on pump TV3 to 10 bar pressure in system f. Close MV3 g. Wait 10 min h. If pressure testsuccessful – continue procedure i. Open RV2 j. Open TV3 fully k. Open MV3	constant pressure
9.		5. Pressure test control board and copper pipe a. MV2 , RV2 closed b. MV1, RV1, TV1 open c. Circulate through copper pipe to drain low flowrate d. Close TV1 e. Adjust bypass valve on pump TV3 to 10 bar pressure in system f. Close MV3 g. Wait 10 min h. If pressure test successful – continue procedure i. Open TV1 j. Open TV3 fully k. Open MV3	Check for leaks, constant pressure
10.		6. Repeat procedurde for Pressure Integrity test 2-3 times for validation	
11.		**Ver03: Pump test (Manual control)** P&ID: Figure 4 Preparation • MV1, MV2 closed position • Choke closed position • System filled with water • Water supply closed	
12.		7. Startup condition a. No circulation from pump b. Choke closed (0 degrees) 8. Turn on power supply 9. Start pump 10. Increase flowrate manually 0-100% with increments of 5 % flow a. Wait for steady flow for each step b. Verify flowrate on FT3 in log for each step 11. Ramp down water pump	

5.2 Identification tests

The objective of the identification tests are to provide data for identification of parameters of the hydraulic model.

Overview of tests:
Id01: Identify choke pressure drop (with tap water supply)
Id02: Identify choke characteristics (with pump water supply)
Id03: Identify friction in the system
Id04: Identify compressibility (water and copper pipe)

No	Resp.	Main activity / Operational Description / Risks	Comments
13.		**Id01: Identify choke pressure drop (with tap water supply)**	
14.		1. Startup condition a. No flow b. 90 degrees choke opening	
15.		2. Adjust water valve to provide sufficient flow a. Wait for steady flow	
16.		3. Start Recording (Daqpro) a. Adjust choke opening manually in steps from 90 degrees angle to 10 degrees angle. For each step wait 30 second. b. Stop log recording after 30 sec on last step c. Open choke to 90 degrees	
17.		4. Close water supply	
18.		**Id02: Identify choke characteristics (with pump water supply)**	
19.		1. Startup condition a. No flow b. 100 % choke opening	
20.		2. Ramp up waterpump to 40 l/min, 38 l/min a. Wait for steady flow	
21.		3. Step choke a. Step choke opening in 0,5 bar degrees to 10 bar choke bakcpressure b. Wait for steady flow	Based on results from Ident01
22.		4. Step choke a. Step choke opening in 5 degrees to 100 % choke opening b. Wait for steady flow	
23.		5. Repeat for test for the following flow rates: 38 lpm, 42 lpm	
24.		**Id03: Identify friction in the system** The main objective of the test is to provide data to: • Identify the friction characteristics Preparation: • MV2 and MV3 closed position • Choke closed postion • MV1, RV1 open position • TV1 open position • System filled with water • Water supply on	

No	Resp.	Main activity / Operational Description / Risks	Comments
25.		1. Startup condition a. No flow b. Choke closed	
26.		2. Circulate through copper pipe and to drain a. Ramp up water pump according to flow rate of 0,5 l/min b. Wait for steady flow c. Read pressure on PT1 and PT10 each step	
27.		3. Incrase flow rate with steps of 0,5 lpm up to 5 lpm	
28.		4. Ramp down water pump	
29.		**Id04: Identify compressibility (water and copper pipe)** The main objective is the test are to provide data to: • Identify the effective bulk modulus (compressibility) of the copper pipe	
30.		1. Startup condition a. System is filled with water b. No circulation from water pump c. Circulate water through copper pipe d. RV2, MV2, TV3 closed e. Choke closed f. MV1, RV2, TV1 open	
31.		2. Ramp up water pump to 10 lpm a. Circulate water from water tank to drain	Circulate out air in system
32.		3. Close TV1	
33.		4. Pressurize copper pipe a. Adjust bypass valve on pump TV3 to 10 bar pressure in system b. Close MV1 c. Ramp down water pump d. Wait 10 min	
34.		5. Pressure relief system a. Open TV1 b. Wait for stable pressure c. Not dV	Note dV

6.0 P&IDs

Figure 1: Ver02, Pressure Integrity test control board

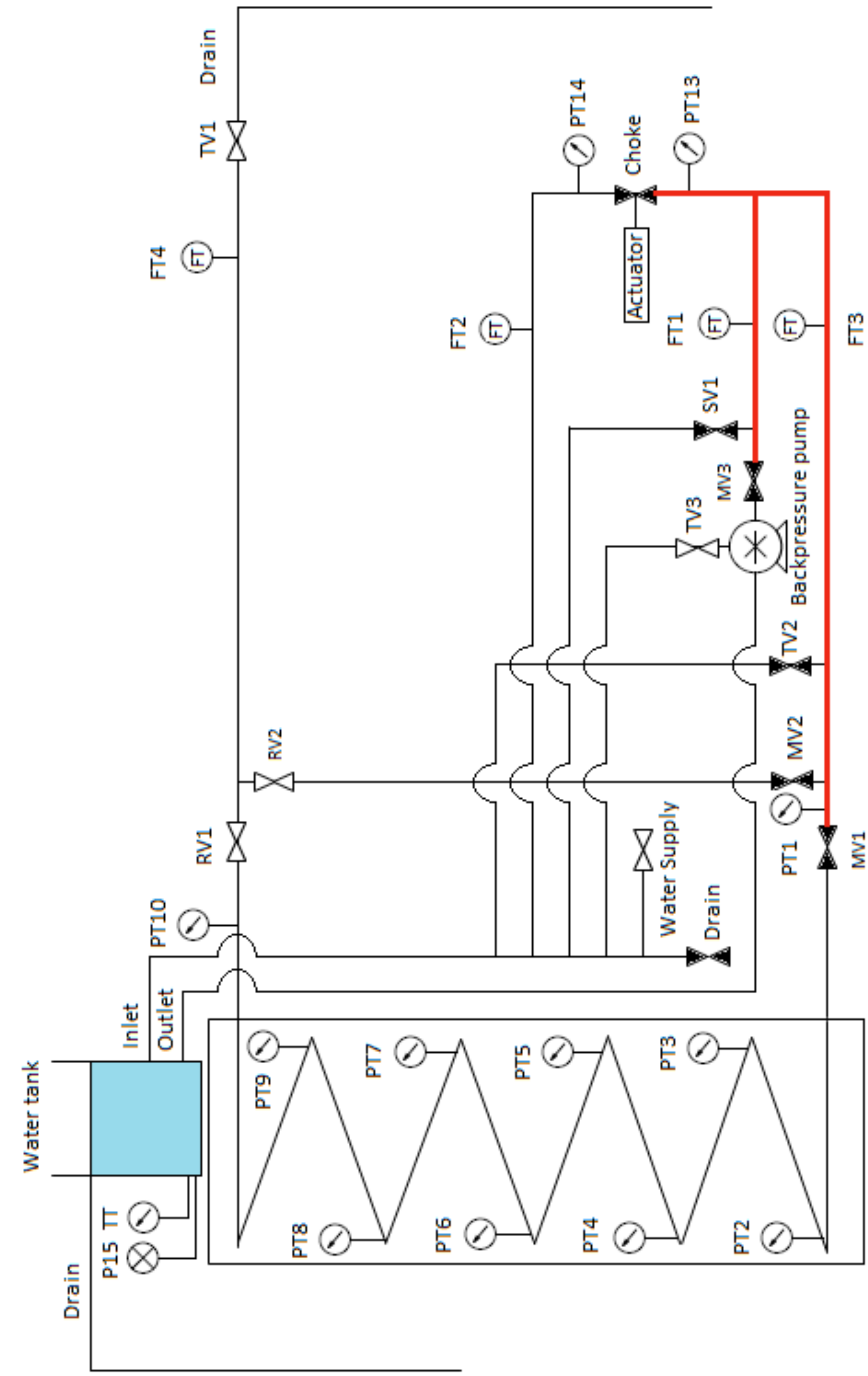


Figure 2: Ver02, Pressure integrity test control board and bypass line

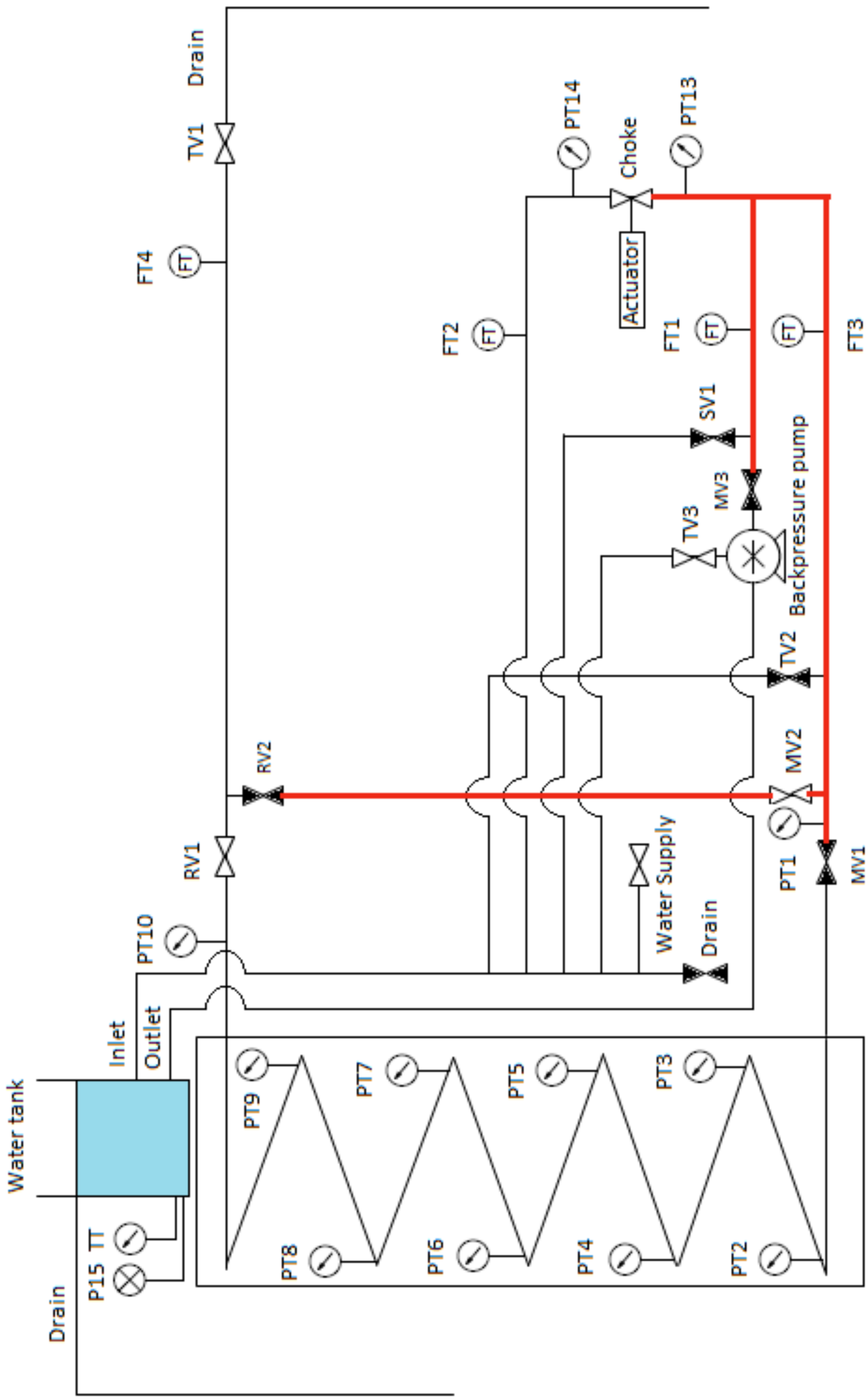


Figure 3: Ver02, Pressure integrity test controlboard and copper pipe

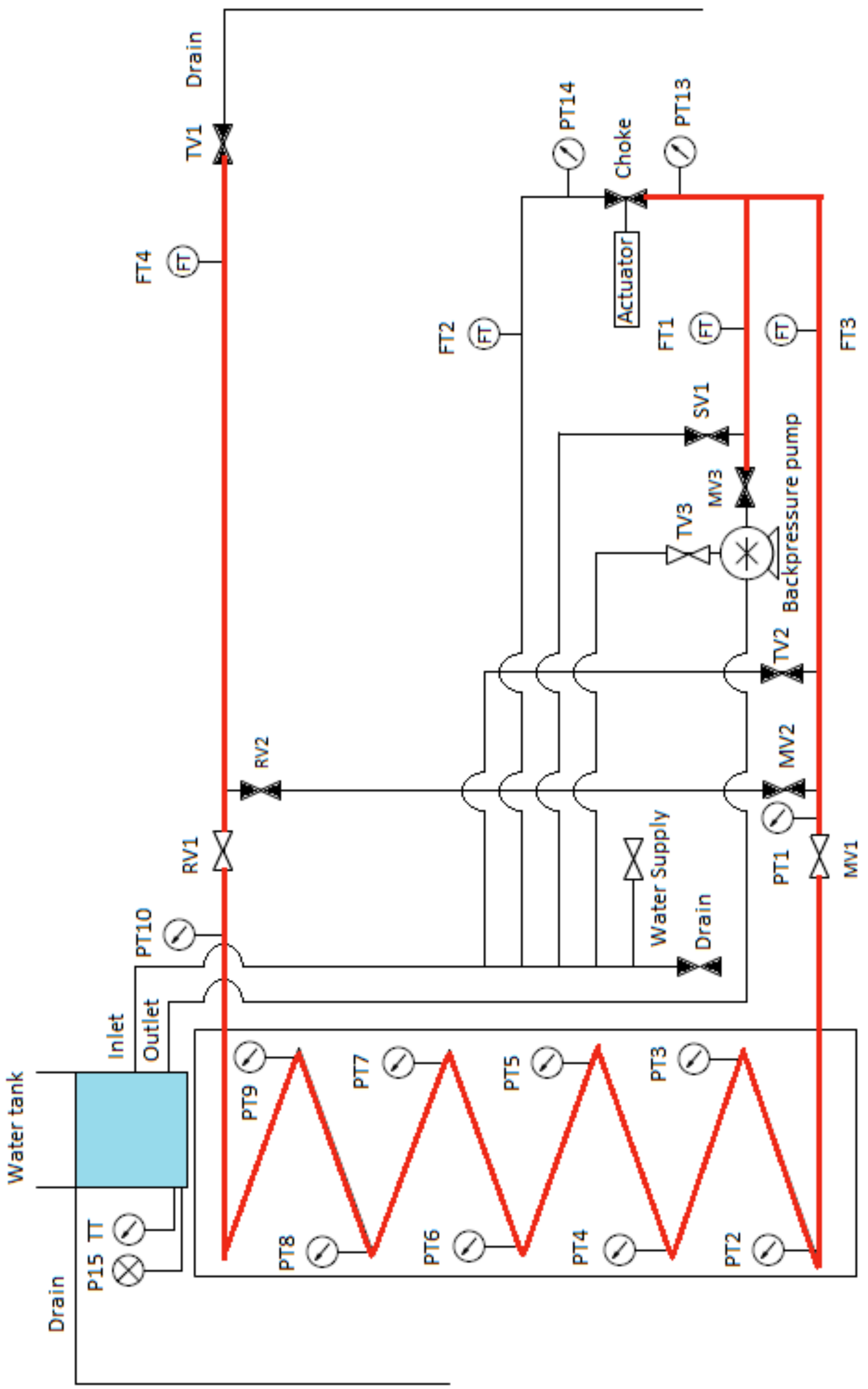


Figure 4: VER03, Pump flow path

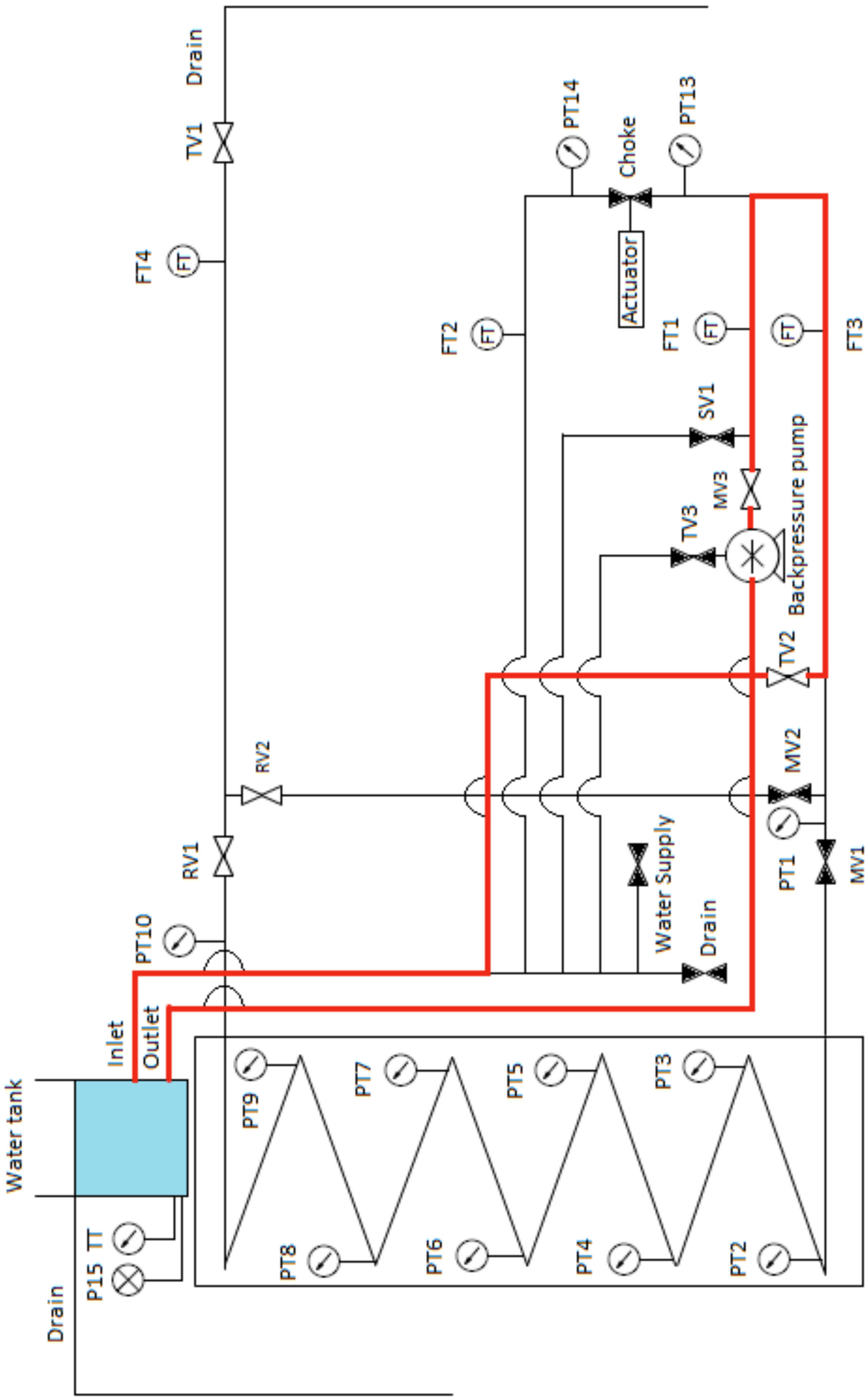


Figure 5: ID03

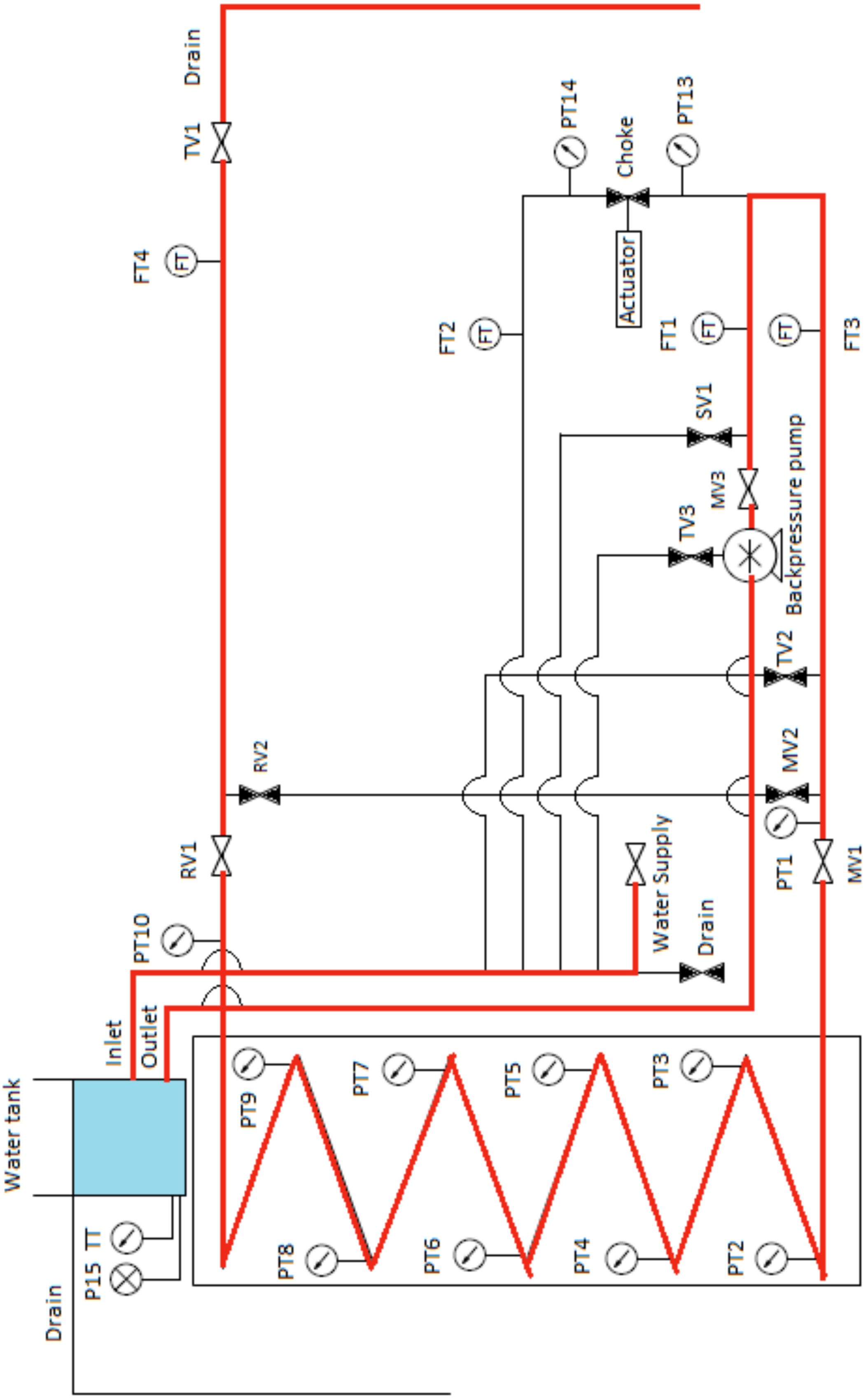
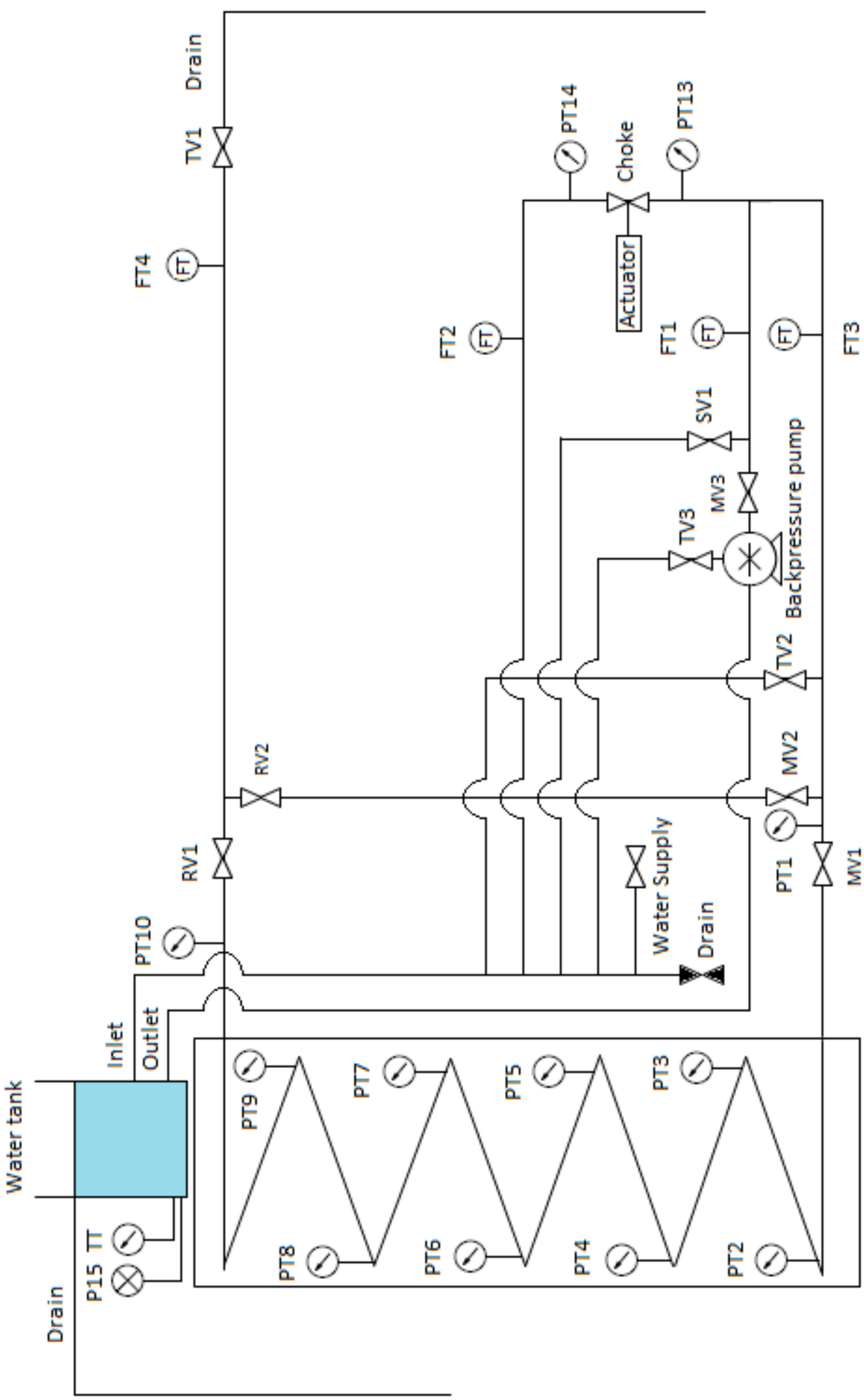


Figure 6: P&ID of current MPD Heave Rig



C Prototype choke test

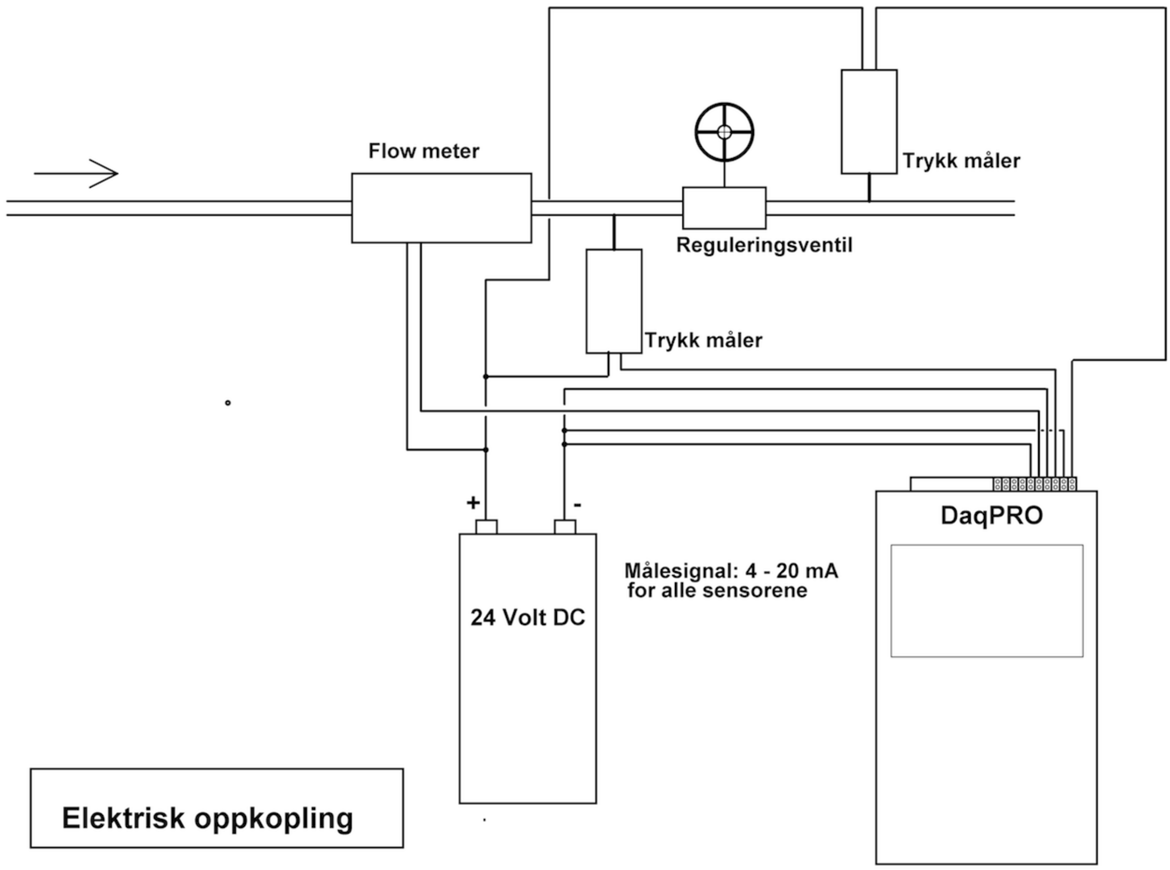


Figure C.1: *Set up for prototype choke test. Illustration conducted by Åge Sivertsen.*

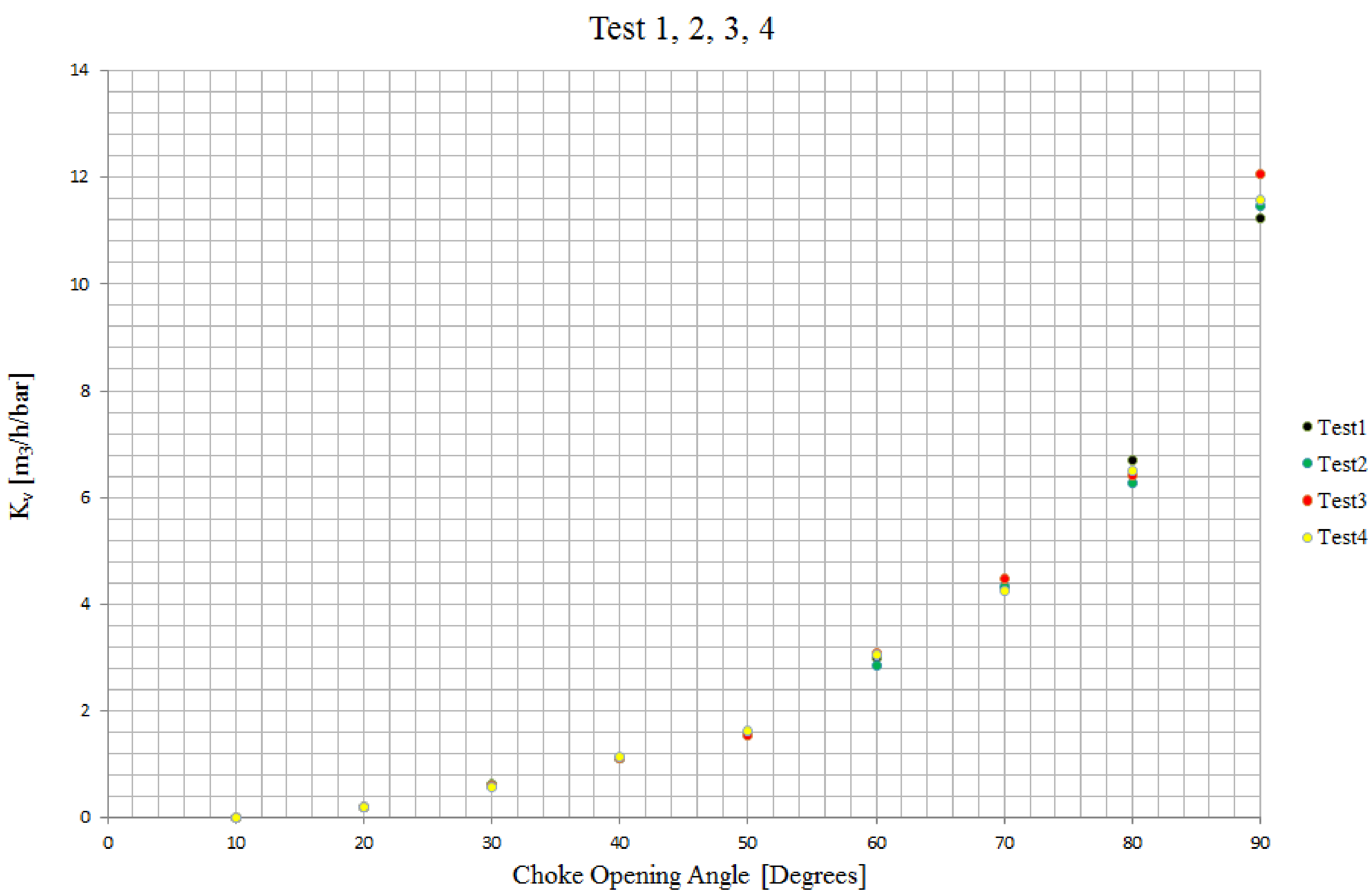


Figure C.2: *Calculated choke characteristics based on test measurements from the four test sequences.*