University of Stavanger

Faculty of Science and Technology

MASTER'S THESIS

Study program/ Specialization: Petroleum Engineering, Master's Degree Programme Drilling Engineering	Spring semester, 2012 Open
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Title of thesis: Automatic Detection of Reservoir Influx in Conventional Drilling, Managed Pressure Drilling and Dual Gradient Drilling	
Credits (ECTS): 30	
Key words: Kick Detection, Influx Detection, Mudlogging, Volume Control, Surface Circulation System, Automated Detection, Automated Drilling, MPD, DG	Pages: …………60…… + enclosure: ……17…… Stavanger, …14/06/2012…….. Date/year

Abstract

Reservoir influxes, or kicks, are well control incidents with the potential of severe consequences to health, safety and the environment, as well as economics. Although the main focus will always be to prevent such incidents from happening, drilling crew will also need to be able to spot reservoir influx as quickly as possible.

This thesis presents a method for automated detection of reservoir influx or losses based on simulations of the surface circulation system. Theoretical background for the causes of reservoir influx is presented. The rig circulation system and traditional mudlogging approaches are discussed, as well as a literature study of proposed new methods for the detection of reservoir influx. Focus has been on conventional drilling, but literature and applications for managed pressure drilling and dual gradient drilling have also been included.

MatLab simulation scripts have been generated to investigate the relationship between changes in pump rate and measured volumes at surface. The script is compared to data from the literature, as well as real drilling data, and tuned by the use of adaptive observer technology. Low-pass and high-pass filters are also employed.

Simulations show that the real volume behaviour of the circulation system on a drilling rig can be relatively accurately described through simple programming logics. The scripts demonstrate the possibility to remove these dynamics from the volumes being monitored, so that any observed changes will in fact be real indications of volume change.

While this thesis only presents the basics for such a method, a further development has the capabilities of being incorporated into an automated system. Fully functioning, this system would allow for setting closer alarms on the monitored volume, resulting in reduced amounts of false alarms as well as earlier kick detection.

Contents

Preface

This thesis is the conclusion of my studies at the University of Stavanger, resulting in a MSc. in drilling engineering. Having worked offshore as a mudlogger in Baker Hughes during the last 1.5 years of my studies, focusing on a project related to kick detection was all the more interesting. Experience from working in the industry has indeed been very rewarding, both during the studies and while working on this project. Although the combination of full-time work and full-time studies is both demanding and time-consuming, the experience and understanding gained is well worth the prize.

Starting out with only basic knowledge of programming, writing simulations from scratch in MatLab was indeed demanding, but also quite rewarding when it finally worked. Undertaking a project at this scale has provided learning and knowledge also in other fields of study than drilling engineering.

I would like to thank my supervisor, Gerhard Nygaard, for providing the project, and from pointing me in the right direction when needed. I would also like to thank the oil company that provided real well data so that the methods and simulations could be tested. I hope the results of this thesis will aid the work being done at IRIS. Finally, I would like to thank my fellow students during my five years at the university. Teamwork and curiousness has helped us through many long hours and weekends, to the benefit of everybody.

Sigmund Pettersen, June 2012

1 - Introduction

During drilling operations on a rig, there are many situations that can go wrong and have large consequences. Reservoir influx, also known as kicks, is one of these, which if not properly handled in due time, may lead to very dangerous and very expensive situations. This makes detection of reservoir influx an important part of the drilling operations.

Today, monitoring of the well is done both by the driller and the mudlogger. Although today's technology allows for setting alarms on more or less any parameter that is being monitored, both the decision of where to set the alarm and how to respond if the alarm goes off is generally based on human judgement, and thereby prone to human error. The alarm systems are usually linear with little or no "intelligence" or understanding of the rig dynamics, and will have to be reset frequently.

Developing a system that understands the dynamics of the rig operations while at the same time warning about real dangers would therefore be beneficial. Not only because it would reduce the amount of false alarms, but also because the effect of human error is reduced or in the long run even removed, depending on how advanced the system is.

This thesis presents the background and causes of reservoir influx situations, as well as proposed methods for detection of these situations. The rig circulation system and the parameters monitored with traditional mudlogging are also presented.

Special focus is given to the relationship between changes in pump rate and response in the measured volumes at surface. Detecting a kick during such a transient period is a lot harder than during steady circulation or a static well. The rig may have been fingerprinted for different flow rate changes in order to know how much and how fast the volume will change, but an expected volume change is not calculated real-time. Being able to have full control over these transient periods would be a great benefit, as more kicks can be detected at an earlier stage with fewer false alarms. This is positive for economics and HS & E, as well as for the working environment on the rig. In the long run, these benefits could also help in developing a more streamlined drilling process, allowing for the drilling of faster and cheaper wells.

Although the thesis includes information about both conventional, MPD and DG drilling, the main focus has been on conventional drilling. This is partly because it allowed for a more thorough focus on a specific project with respect to the programming and simulations, but also because the closed systems of MPD and DG allow for monitoring of other parameters than in conventional drilling, some of which make automated detection of kicks easier. Technology and learnings developed for conventional drilling is easier to transfer to the more advanced MPD and DG technologies, while going the other way may be more of a challenge, as some of the more advanced equipment is not regularly used in conventional drilling.

2 - Theoretical Background

2.1 - Methodologies of Drilling

In order to give an overview of the causes of reservoir influx and losses, a brief introduction of drilling methodologies will be given. This thesis will focus on three different drilling methodologies (conventional, MPD and dual gradient drilling), and the similarities and differences are presented in the following section.

2.1.1 - Conventional Drilling

A conventional drilling system is an open circulation system. The mud pumps circulate the drilling mud down the drilling pipe, through the BHA and bit and up the annulus. When the mud reaches surface, the remaining pressure is zero, and the pump pressure will be a direct indication of the pressure drop through the closed part of the circulation system. A conventional drilling system is shown in figure 2.1.1.

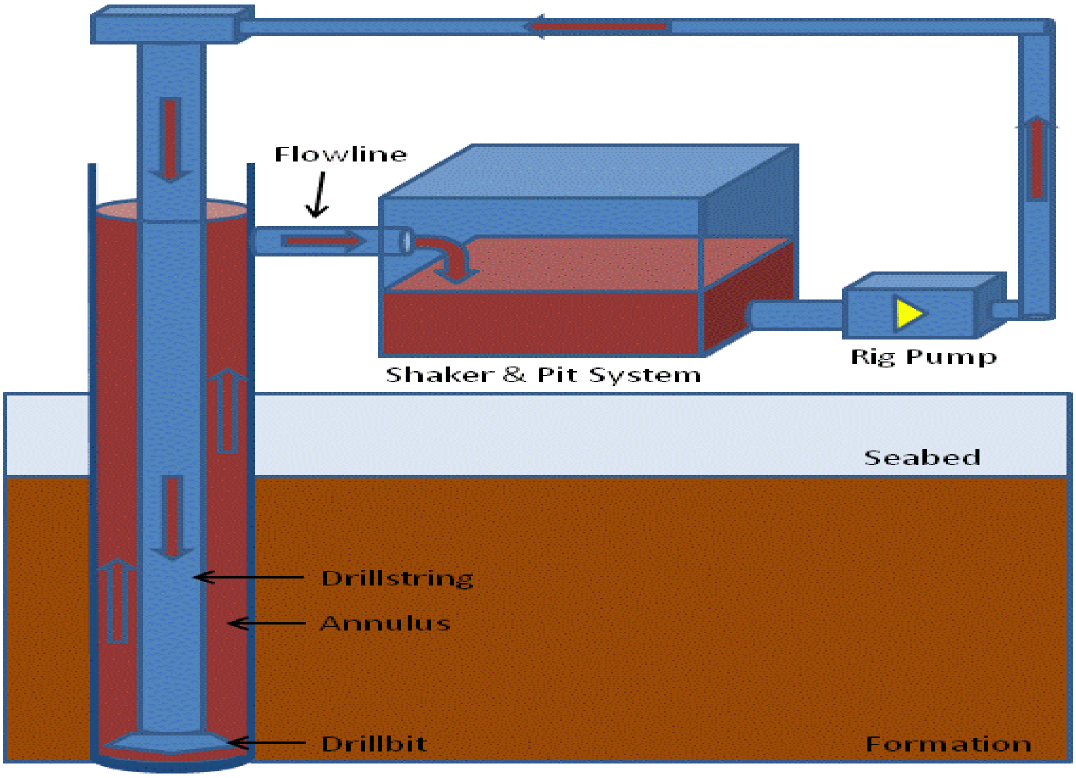

Figure 2.1.1: The basic circulation path of a conventional drilling system. As the system is open, atmospheric pressure will be seen at the flowline.

Conventional drilling is the simplest cheapest and most widely used of the drilling systems discussed in this thesis. In many applications it's good enough to drill the well in a safe and efficient manner, and the simplicity is preferred due to the lower cost. Being conventional, additional training in the use of special equipment is generally not needed.

During circulations the bottomhole pressure in a conventional drilling system will be given by the following equation:

$$BHP_{circ.,conv.} = MW_{static} + AFP \qquad \text{(Eq. 2.1.1)}$$

During connection (with the mud pumps shut of), there will be no annular friction pressure, and the bottomhole pressure will be given by the static mud weight:

$$BHP_{static,conv.} = MW_{static} \qquad \text{(Eq. 2.1.2)}$$

BHP: Bottom Hole Pressure, MW: Mud Weight (hydrostatic head, in pressure units), AFP: Annular Friction Pressure.

2.1.2 - MPD – Managed Pressure Drilling

As opposed to conventional drilling, MPD will have a closed loop circulation system. The general idea is being able to apply additional pressure to the system in order to avoid the differences between the downhole pressures when circulating and having a static well. One of the most common approaches to achieving this is an annular backpressure system. The bottomhole pressure is managed by applying pressure to the annulus. When the pumps are shut off, the backpressure is increased to compensate for the drop in the frictional pressure, keeping the bottomhole pressure constant. A sketch of a MPD system is shown in figure 2.1.2.

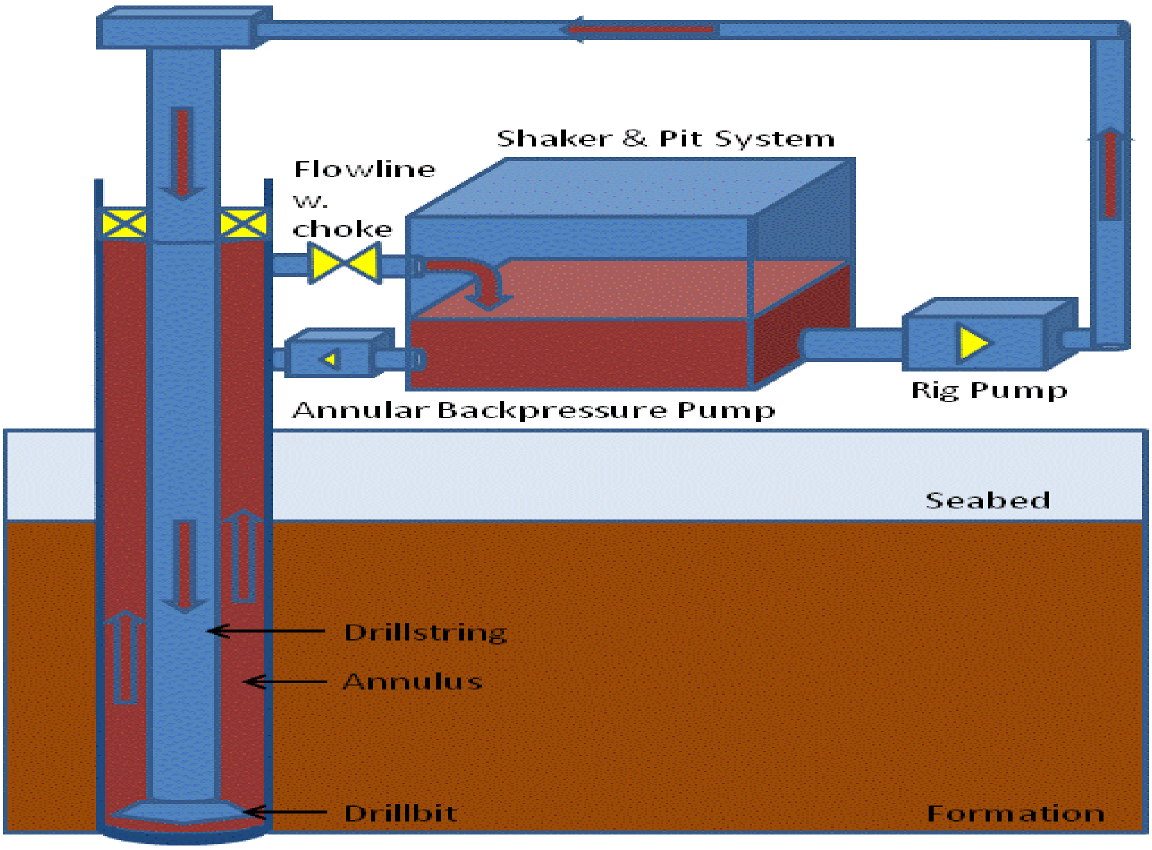

Figure 2.1.2: The basic parts of a MPD system. Pressure can be applied to the annulus by the annular backpressure pump and can be adjusted by opening or closing the choke valve.

MPD allows wells with narrower windows between pore pressure and fracture pressure to be drilled safely, wells that would be difficult or even impossible to drill with a conventional system. MPD requires specialized equipment such as a Rotating Control Device (RCD), making it more costly and requiring more training than conventional drilling. In an annular backpressure system, the bottomhole pressure during circulation will be given by the following equation:

$$BHP_{circ.,MPD} = MW_{static} + AFP + BP_{circ} \qquad \text{(Eq. 2.1.3)}$$

During a connection with the pumps shut off, there will not be any frictional pressure in the annulus, but the backpressure may be increased in order to achieve the same bottomhole pressure:

$$BHP_{static,MPD} = MW_{static} + BP_{static} \qquad \text{(Eq. 2.1.4)}$$

BP: Back Pressure (additional pressure provided by the MPD system)

2.1.3 - DG – Dual Gradient Drilling

Dual gradient drilling involves the use of two different mud systems in the same well. A typical approach is to have the riser filled with a light fluid (seawater in many cases), and the well below the seabed filled with a heavier drilling mud. DG drilling requires the use of a mud lift system in order to move mud and cuttings from the seabed to the rig. A sketch of a DG setup is shown in figure 2.1.3.

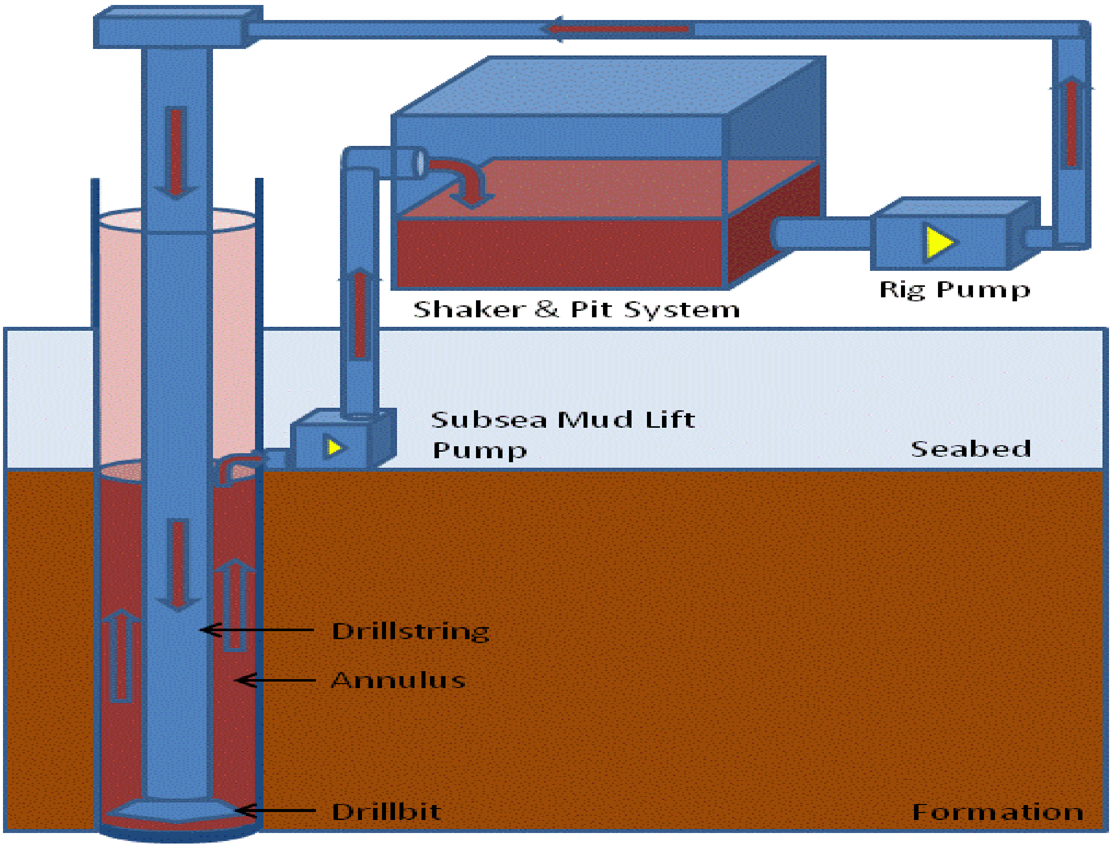

Figure 2.1.3: A dual gradient system. The marine riser is filled with a lighter fluid, giving a wellbore pressure closer to the formation pressure in the shallower sections.

The advantage of DG is the way the downhole pressure behaves as a result of the two different hydrostatic columns. The pressure will be a better fit to the way the pore and fracture pressures are behaving, allowing longer sections to be drilled with the same mud weight without having to run casing. In a deepwater situation, having mud in the entire riser would in many cases give downhole pressures above the fracture pressure. This may lead to a fractured formation and lost circulation, making the wells impossible to drill with a conventional system. As more equipment is involved, the cost of running a DG operation is higher than with a conventional system.

In a dual gradient system, the bottomhole pressure during circulation will be given by the following equation:

$$BHP_{circ.,DG} = MW_{1,static} + MW_{2,static} + AFP \qquad \text{(Eq. 2.1.5)}$$

During a connection the bottomhole pressure will consist of the sum of the static mudweights:

$$BHP_{static,DG} = MW_{1,static} + MW_{2,static} \qquad \text{(Eq. 2.1.6)}$$

The mud weights will be given in pressure units, and will be adjusted according to the corresponding height of the hydrostatic column.

Depending on the setup it will also be possible to apply back pressure in a dual gradient system, in the same manner as with MPD. In such a case, a term for this back pressure (BP) will have to be added to the right side of equations 2.1.5 and 2.1.6.

Figure 2.1.4 below shows two comparisons between a single gradient and dual gradient system. The curve shows the amount of pressure exerted by the hydrostatic column of mud at different depths.

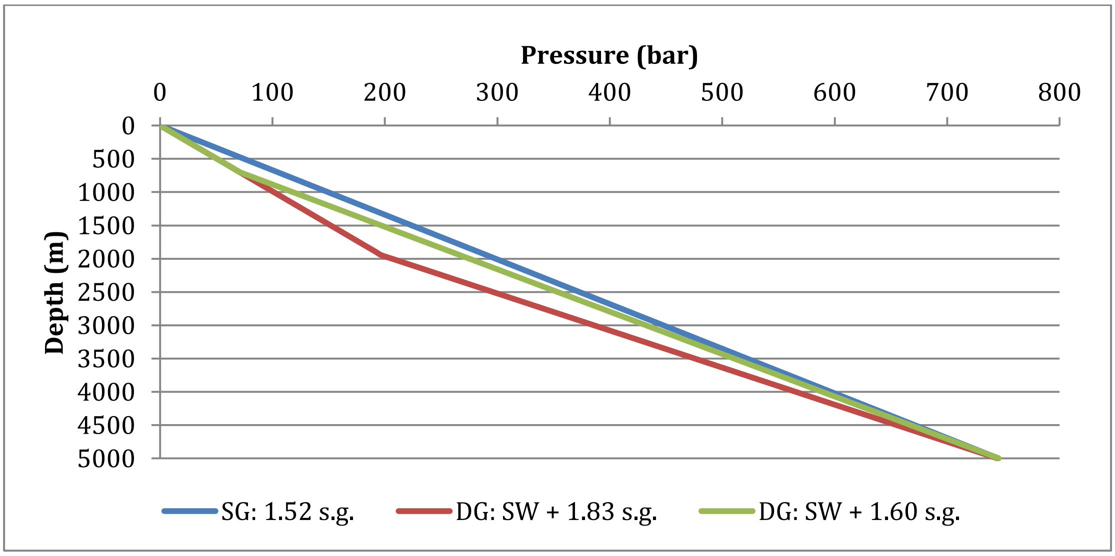

Figure 2.1.4: The relationship between downhole pressure and depth for one single gradient and two dual gradient systems giving the same bottomhole pressure. The two dual gradient systems have the fluid interfaces at 750 and 2000 m.

We see that throughout the well, the exerted pressure from the mud column is lower with a dual gradient system than a single gradient system, while the same bottomhole pressure is achieved (although with different mud weights). This reduces the risk of lost circulation and fractures, especially in the shallowest sections. Having the riser filled with seawater will also remove the need for a riser margin in the mud weight calculations. By shutting in the subsea mud lift system while pumping, it is also possible to adjust the height of the interface between the two fluids in the riser, allowing for precise control of the down hole pressures.

We can also see that the benefit of a dual gradient system will be larger with an increased sea depth, as the difference in exerted pressure will be larger with a larger column of lighter fluid. The weakest formations with respect to fracture pressure will be located just below the sea bed, and the formation pressure here will follow the seawater gradient. Applying a 70-80 bar overpressure will in many cases damage the formation, and in some cases using a dual gradient system may be the only option at 2000 m water depth.

A larger riser section will also allow for a greater freedom in adjusting the height of the interface between the two fluids.

2.2 - Overview of Causes of Reservoir Influx

In order to understand how to detect kicks, we need to understand why they happen. This understanding can also help us from preventing them in the first place, as almost any kick can be avoided either by proper planning or by acting according to procedures and the warning signs the well will give you.

Reservoir influx or influx of formation fluids into the wellbore is caused by the wellbore pressure being lower than the pore pressure of the formation. When this happens in a porous and permeable zone, the fluids in the formation will start seeping into the wellbore. When the amount of reservoir fluids in the wellbore exceeds a certain level it is called a kick. If not treated correctly and within a certain amount of time, a kick situation may lead to a blowout. Proper and timely detection and handling of such a situation is essential to prevent dangerous situations that may in the worst case lead to loss of life, damage to the environment as well as large economic consequences.

Although conventionally drilling is always planned with a wellbore pressure greater than the pore pressure, there are several reasons why the opposite may occur. According to the Schlumberger Oilfield Glossary (Schlumberger 2012) causes of kicks may be split into two groups:

- Underbalanced kicks
- Induced kicks.

An underbalanced kick will be caused by the fluid column being insufficient to hold back the formation fluid. An induced kick will in most cases be caused by the movement of pipe or casing, resulting in a temporary underpressure that allows fluid to flow from the formation into the wellbore.

In the following section, the causes will be presented by the major contributing factor. However, as discussed later, a combination of factors will in many cases contribute to the end result.

2.2.1 - Kick due to Swabbing

Pulling the bit and BHA out of hole will create a piston effect resulting in a pressure drop before the displaced steel volume is replaced with mud. If the tripping speed is too large, the pressure drop may be large enough to cause reservoir influx. This effect is called swabbing.

Apart from the pressures in the formation and the wellbore, there are two main factors affecting swabbing, the difference between the inside diameter of the open hole and the outside diameter of the pipe being moved, and the speed at which the pipe is being pulled. A smaller difference between the hole size and the pipe size will increase the risk of swabbing, as the piston effect is larger. Similarly, pulling the pipe faster will also create a larger piston effect. Given the correct inputs, such as mud parameters, the pulling speed can be calculated, and depending on the pressure difference, the minimum time allowed to use per stand may be smaller or larger than the capability of the equipment use. In cases with very small size differences, pulling the pipe may be close to impossible (i.e. in cases where you have to pull casing due to a collapsed wellbore).

2.2.2 - Kick due to Lost Circulation

Lost circulation can result from many different events. Tripping in too fast and causing surge pressures may fracture the formation and give losses. Having a too high ECD or even static mud weight may cause the same effect. In the event of lost circulation, failure to keep the hole full will result in a smaller hydrostatic column, giving a lower bottomhole pressure that may in turn result in a kick.

With surge, as with swabbing, the difference between the ID of the hole and the OD of the pipe, as well as the movement speed of the pipe are key factors. With known fracture pressures and mud parameters, these limitations can be calculated. Knowing the fracture pressure of the formation is therefore key, not only to avoid lost circulation (which by itself is a rather expensive affair), but also to avoid potential kicks as a result of this. The possibility of taking a kick as a result of lost circulation also sets requirements to the amount of mud onboard the rig, as well as LCM material.

The same type of pressure spike effect as with swab pressures can be seen in viscous mud when circulation is broken after a connection. These spikes can also result in fractures and lost circulation. How severe this effect will be is largely dependent on the properties of the mud (such as gel strength). Because of this, it is important to bring the pumps up slowly whenever circulation has been stopped.

2.2.3 - Kick due to Abnormal Pressure

Drilling into a high-pressure zone can also induce kicks. If an isolated zone is over pressured, the increase in pore pressure may be large enough to exceed the static and/or circulating mud pressure. Drilling into a under pressured (i.e. depleted) formation may result in lost circulation, which as mentioned above also can induce kicks.

The geological understanding of the prospect is key to prediction of abnormally pressured zones, and the mitigation of the risk by having sufficient mud weight to overcome the overpressure. As the geological understanding will increase with every well drilled in the area, the risk of running into unexpected zones of abnormal pressure is larger in a wildcat well situation, than when drilling production wells in a field that has been produced for several years.

2.2.4 - Kick due to Improperly Maintained Mud or Mud Column

"Simple" causes, such as forgetting to refill the well with mud when removing steel or forgetting to check that the mud weight is within the specified ranges may be serious enough to cause kicks. This should of course not happen, and is seen to by the use of procedures and reporting, but may still be a contributing factor to kicks.

2.2.5 - Combined Causes

Drilling a well is a complex operation, and because of this the underlying causes of taking a kick will in many cases be a combination of different factors. For instance, if drilling into an overpressured formation, but still having a sufficient mud weight, a kick will not be taken while drilling and circulating. However, the previous pipe movement limitations to avoid swabbing may no longer be sufficient to avoid influx when tripping out, resulting in a flowing well even when the driller is following procedures.

Understanding and getting to know the well being drilled is key to understanding how all the factors will come into play, and how to avoid the multitude of factors resulting in trouble. In this aspect, proper communication between the involved personnel is of major importance.

2.2.6 - Kick Size

The size of the kick taken will be determined by the change in volume at surface. If the reservoir fluid is incompressible and insoluble in the drilling mud, the volume seen at surface will be the same as the actual kick volume downhole.

However, the compressibility of the reservoir fluid will in fact play an important part, and most importantly when the reservoir fluid is gas. The size of the kick at surface will depend not only on the volume increase that is seen, but also on the downhole pore pressure. A simplified version of the ideal gas law displays this relationship.

$$P_1V_1 = P_2V_2 \qquad \text{(Eq. 2.2.1)}$$

Where P_1 is the pressure and V_1 the volume downhole, while P_2 and V_2 are the pressure and volume at surface. We see that a 1 m3 kick taken with a downhole pressure of 200 bars (that is, a 1 m^3 increase seen in the active volume at surface) will correspond to 200 m^3 at a surface pressure of 1 bar. This may challenge the capacity of the gas handling system when circulating out the kick. If the kick is not allowed to expand, the 200 bar pressure may be large enough to fracture the formation in weak sections. (Vik 2001). This shows the importance of early kick detection.

Oil-based mud adds increased complexity to the reservoir fluid behaviour, as hydrocarbon gas is soluble in the mud. This allows for larger amounts of fluid to enter the wellbore without visible volume changes at the surface compared to water-based mud. (Vik 2001). As the dissolved kick is circulated to the surface, it will eventually reach the bubble point and boil out. In addition to the dangers of the gas expansion itself, the situation may also lead to an improperly filled hole, and the possibility of another kick being taken.

2.3 - The Rig Circulation System

Proper understanding of how the rig circulation system works is essential in order to understand the information given to you by the well. It also serves as a basis for developing a model that describes the relationship between the circulation rates and the volumes seen at surface. The following section will give a brief overview of the different elements of the circulation system on a rig, and how they influence the circulation and measured volumes. The overview is divided into the following sections:

- The rig pumps
- The surface piping
- Rig floor equipment
- Downhole
- The flowline
- The shaker system
- The mud tank system

A drawing of a rig circulation system with its individual components and circulation path is shown in figure 2.3 below:

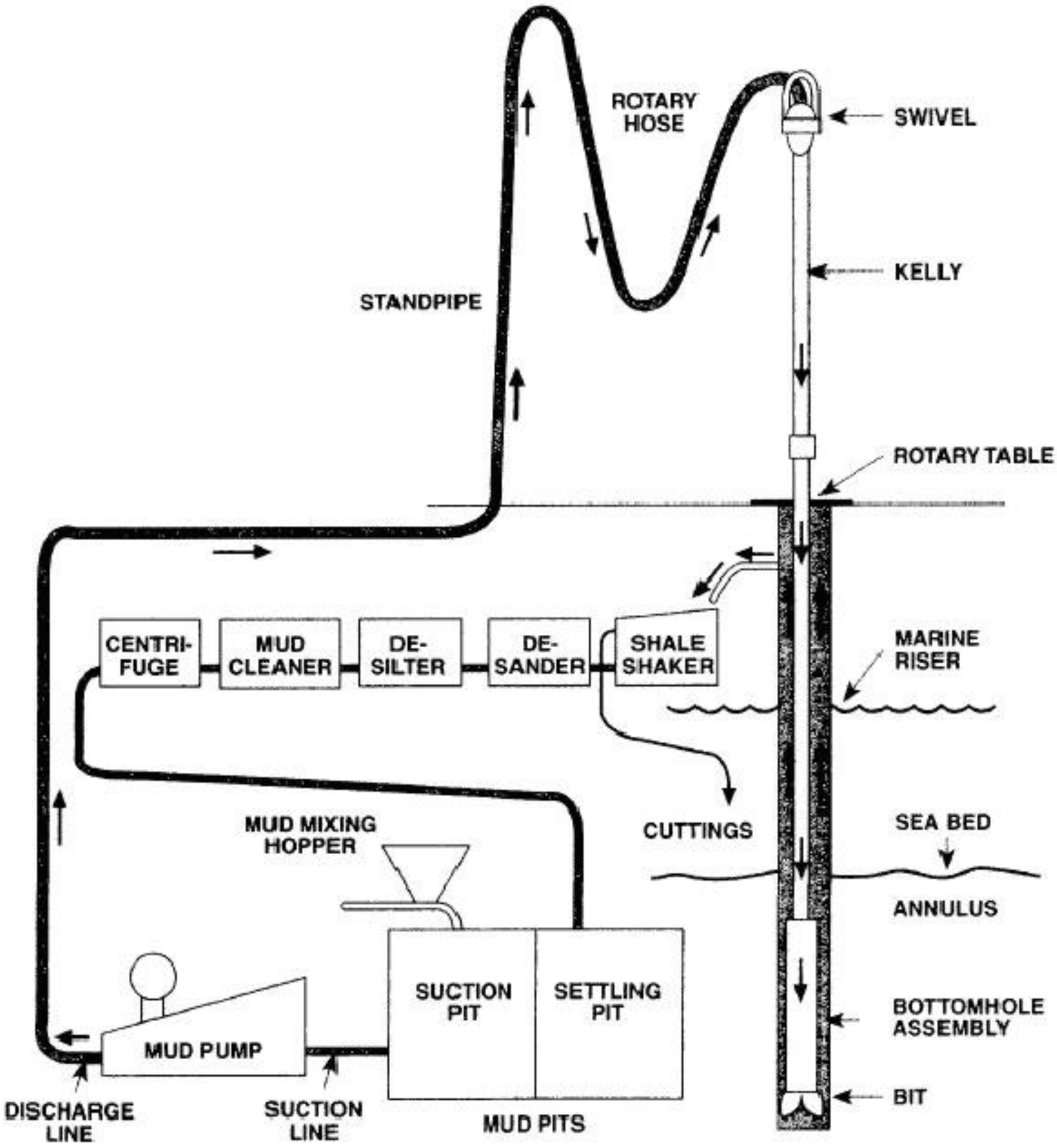

Figure 2.3: Circulation path and components in a rig circulation system. (Drillingcontractor.org 2011)

When everything is as it should be, the total volume of mud in the circulation system should remain the same. The same volume of mud that is pumped out of the selected mud pits (the active pits) will return through the flowline, flow over the shakers and return to the active pits. However, there are several mechanisms that will affect this balance throughout the system.

The amount of fluid in the system, and thereby also the gains or losses will be measured by the volume of mud in the active pits, and any changes to this volume, will appear as an unstable system. In most cases the active system will include some of the mud pits in the mud tank system, as well as the shaker pits. As the measurement uncertainty is related to the volume being measured, the volume in the active system should be kept as small as possible. However, in a larger (longer) wellbore, a larger volume of mud will be needed in the active system in order to fill the hole, resulting in a larger measurement uncertainty.

The Rig Pumps

The positive displacement rig pumps are the driving mechanism of the circulation system. Provided with mud from the active pits, they will displace the mud through the system at the rate set by the driller. Increasing the pump rate will increase the rate at which the mud is flowing out of the active pits, and until the same amount of fluid is flowing into the active pits from the shakers, this will give a decreasing trend in the active system, appearing as a loss.

The time delay depends on the flowrate, as the flow out of the active pits is directly related to the pump rate (at least as long as the pumps are not pumping any air in addition to the mud). However, care should be taken to observe that the system stabilizes within the appropriate time, as a failure to do so will be an indication of losses, either downhole, or somewhere else (in the surface system). This is also why it is common to have someone looking for returns on the flowline and shakers whenever starting circulation. This relationship is one of the main aspects being studied in this thesis.

The Surface Piping

The lineup of the surface piping will affect the responses to changes in the flowrate through the circulation system. The effect that is easiest to observe is the connection flowbacks. As the pumps are shut off, the needed pressure to hold the fluid in the surface piping will be lost, and the mud flows back into the mud pits located below due to gravity. The volumes will be largely dependent on the piping lineup of the rig, and may be in the scale of several cubic meters. Depending on the piping lineup, this effect may also be observed when the flowrate is changed. The initial flowrate may not fill up the entire volume of the surface piping during circulation. If the flowrate is increased, and the new flowrate fills up a larger volume of the surface piping, this will appear as a loss in the active system as there will be less volume left to fill up the tank. After the system has stabilized, the active volume will be stable, but at a lower level than with the previous flowrate.

On other rigs this effect may not be observed when changing the flowrate. That is, the surface system is already filled with mud at the initial flowrate, so no more mud will be "lost" in the surface piping when the flowrate is increased. When the flowrate is increased, the measured active volume will return to the same value as with the previous flowrate, after a time of instability related to the other components of the circulation system.

Rig Floor Equipment

When reaching the rig floor, the mud will pass through different pieces of equipment before going down the drillstring. During a connection, with pumps off, the standpipe will be bled of to the active system. If this is not done, the volume increase (connection flowback) will be different from a case where it is bled of. Also the trapped pressure will represent a risk when opening the system to atmospheric pressure during the connection.

Another piece of equipment that will affect the volumes during circulation on some rigs is MWD communications equipment. Baker Hughes uses a device called BPA (By-Pass Actuator) to communicate with downhole tools. The BPA will divert up to 15% of the flow in order to create pulses that is read by the tool downhole. The diverted flow will flow back to the active system quicker than the flow through the well and may appear as a gain before being leveled out by the lesser amount of fluid returning through the flowline.

Downhole

Various downhole effects such as ballooning, as well as real losses and gains may be observed downhole. Any changes in the volumes that is related to the well should be spotted at surface as quickly as possible, and are the reasons why we want to have full control over everything else going on in the circulation system. An aspect that should not be forgotten is the fact that making new hole will require the removed volume of rock to be displaced by mud, resulting in the surface volumes decreasing.

The Flowline

The piping at the flowline will in the same way as the piping between the mud pumps and the rig floor contribute to the connection flowback volume. It is also where the gas trap system used for monitoring the amount of gas in the mud will be installed, as well as a flow out sensor. The header box is located here, where the mud is slowed down and the flow rate is no longer directly driven by the pump rate. It is however indirectly driven, as the flow from the header box will increase when the volume increases.

The Shaker System

The solids control system or shaker system consists of the shale shakers as well as other equipment installed in order to treat the mud and prepare it for reuse. Solids are removed at the shakers, desanders and desilters, as well as at the centrifuge. Gas is removed by the degasser.

If the flowrate is larger than the shakers and/or screens installed on the shakers can handle, mud will be lost together with the cuttings going over the shaker. Even at low flowrates, some mud will be lost as it is sticking to the cuttings. The amount of mud lost can be approximated by weighing skips and comparing to the theoretical amount of cuttings being drilled, but this will rarely be accurate. In addition, it is far from being a real-time measurement, and will in the best case help in indicating what has already happened. Attempts have been made at real-time cuttings monitoring, however it is not common practice.

Mud from the shakers will enter the shaker pits prior to entering the desander, desilter and centrifuge. Any indication of increased flow from the well will first be seen in the shaker pits (unless using flowmeters or other indicators), and the shaker pits will be included in the active system that is monitored by the mudlogger and driller.

If a centrifuge is employed to remove low gravity solids, it may also be a source of continous losses that will affect the measured volumes in the active system.

The Mud Pit System

The mud pit system will consist of several mud pits of different volumes. Some of these pits will be the active pits that are directly connected to the well as suction and return pits, and some will be used as mixing pits or reserve pits. In mixing pits, new volumes of mud will be mixed to the appropriate specifications before being added to the active circulation system. The reserve pits may contain other needed fluids such as slugs, high viscosity pills or pre-weighted kill mud.

If mud is continuously lost over the shakers and at the centrifuge (and possibly also downhole), new volumes of mud will have to be added to the active system in order to maintain the needed volume for the circulation. New mud will also have to be added as new hole is drilled. A common way of doing this is adding the whole pit to the monitored system and bleeding in new mud from this pit to the suction and returns pit. From a monitoring point of view this will only appear as an instantaneous gain when the pit is added to the system, making it easier to monitor trends and changes while the mud is being bled in to the system. While this mud is added, new mud will be prepared in another pit, and this will be added to the active system as the previous pit is removed.

In some cases the personnel working in the mud pit room may want to add chemicals directly to the active system, for instance if it is discovered that the mud is outside the specifications. These added chemicals will appear as gaining in the active system, and in order to separate it from a simultaneous downhole gain, care will have to be taken to make sure that the exact volumes being added are reported correctly. One challenge in this aspect is making sure that the right volume change is observed when adding dry chemicals.

2.4 - Detecting Reservoir Influx

During drilling operations, there are several parameters that can provide indications of reservoir influx, such as:

- Positive drill breaks
- Mud pit increases
- Stand pipe pressure decreases
- Return flow rate increase
- Expected vs. actual mud volumes needed when tripping
- Increased pump rate in a subsea mud lift system, if applicable

2.4.1 Traditional Approach – Mudlogging

The traditional approach to monitoring the well and detecting reservoir influxes is mudlogging, a service commonly offered by service companies. In order to provide redundancy, a third-party service hand is collecting and monitoring data in real-time, and assisting the driller in monitoring the well. Usually, the on-site position also involves daily reporting of drilling performance and parameters.

Mudlogging involves monitoring and evaluation of several different parameters that indicate what is happening downhole. Understanding the well is key to early detection of downhole problems, including influx of formation fluid. Some of the parameters monitored by the mudlogger include:

Gas

By employing a system that monitors the amount of gas in the mud returning from the well, valuable information about the well may be collected. An increased amount of gas in the mud is an indication of changes downhole. This may be increased porosity or increased pore pressure. Increasing amounts of gas after connections indicate a decreasing overbalance in the well, and provides a indication of possible reservoir influx. Typically, a gas system will measure both the total amount of gas, as well as a breakdown of the different components in the gas, providing valuable insight into the properties of the downhole fluid. It should be noted that the gas needs to be circulated from the bottom of the well, meaning that the measurements are not instantaneous.

Mud Pit (Active) Volumes

During drilling, some of the mud pits are employed as the “active” system. These pits are directly connected to the well, one providing suction for the rig pumps and the other taking return flow from the well. They will also be connected directly to each other. Theoretically, the volume of mud in the active system should stay constant when corrected for the amount of hole drilled and displaced by steel. An unexpected increase in the active system may be influx from the reservoir and an unexpected decrease may be loss of circulation. An example of a plot of active pit volume is shown in figure 2.4.1.

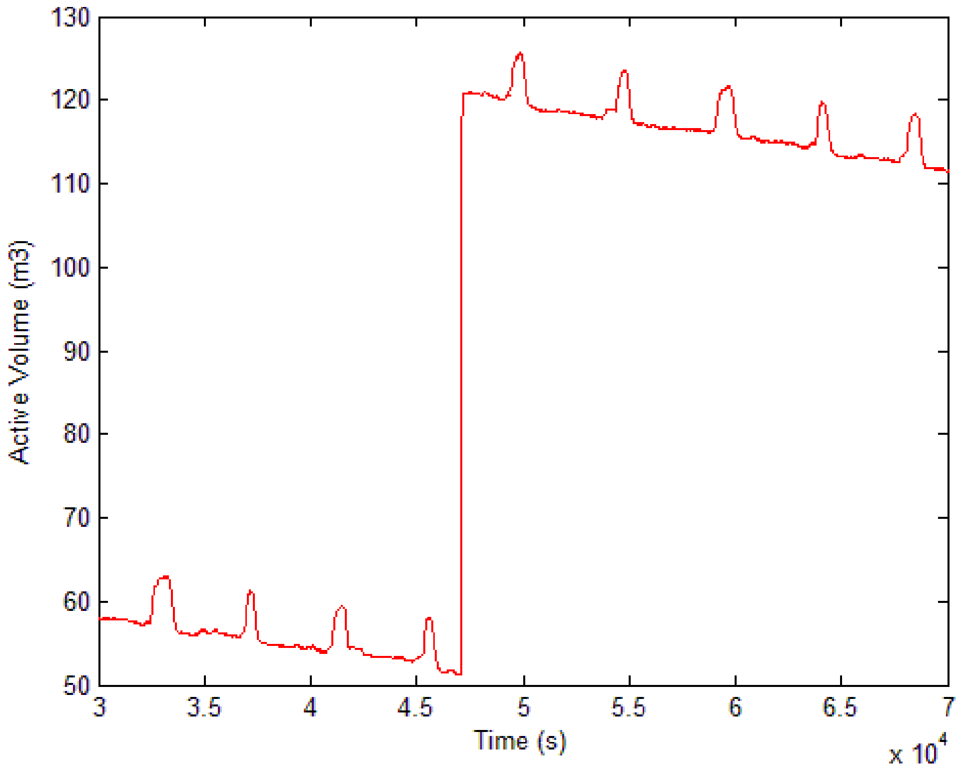

Figure 2.4.1: Active pit volume over a span of 11 hours. A total of 9 connection flowbacks are seen. After approximately half the time a pit of some 60 m3 is added to the active system.

However, there are certain limitations. Even with an effective mud treatment system, some of the mud will be lost together with the cuttings going over the shakers. This appears as loss of circulation, however it is not related to the wellbore itself. On floating rigs, the movement of the rig will affect the sensor readings, as may the movement of the on-board cranes. The accuracy of the volume readings will be limited by the size of the pits being used. Having larger pit volumes will increase uncertainty, but may at the same time be needed in order to maintain proper circulation while drilling.

During tripping, a smaller trip tank is employed in order to make it easier to detect changes in the well. This is mainly because kicks are often taken during tripping operations, and is also practically possible because of the smaller volumes needed to maintain an efficient operation.

Connection Flowbacks

Connected to the mud pit volumes are the flowbacks experienced during connections. During circulation, a certain amount of mud will be occupying the surface circulation system. When the pumps are shut off during a connection, this mud will flow back into the pits, making them appear to increase. Depending on the flow rate, the amount of flowback should be more or less the same at each connection, and any changes may indicate changes downhole.

Pump Pressure

The pump pressure (or standpipe pressure, depending on where it is being measured) provides an indication of the pressures being imposed on the wellbore, as well as the frictional pressure drop through the well. Peaks in pump pressure may indicate downhole problems and possible fracturing of the formation with lost circulation as a result. A decrease in pump pressure may indicate that a lighter fluid is flowing in the annulus, causing the mud in the drill string to u-tube. In cases with MWD service, downhole pressures will also be monitored, although usually not with the same data frequency.

Drill-breaks

Positive drill-breaks (sudden increases in the rate of penetration) may in some cases be an indication of an increased pore pressure. The pressure differential between the wellbore and formation will create a “hold down” effect, making the chips cut by the drilling bit harder to remove. An increase in pore pressure will reduce this effect, making the formation easier to drill, resulting in a higher ROP. A drilling break may also in many cases simply be an indication of a change in formation properties, without a change in the pore pressure, or it may be an indication of a change in both.

The same reduction in the hold down effect that gives the increase in ROP will also show as an increase in the hook load at surface. The reduced upward pressure on the bit means that a larger amount of the drill string weight will have to be carried by the travelling block. This may also be seen as a decrease in the torque.

Return Flow

Monitoring the return flow out of the well may also provide indications of both reservoir influx and lost circulation. In a stable well, the flow in and out of the well will be the same, and a change from this will indicate unstable conditions. An example of data from a flow sensor is shown in figure 2.4.2 below.

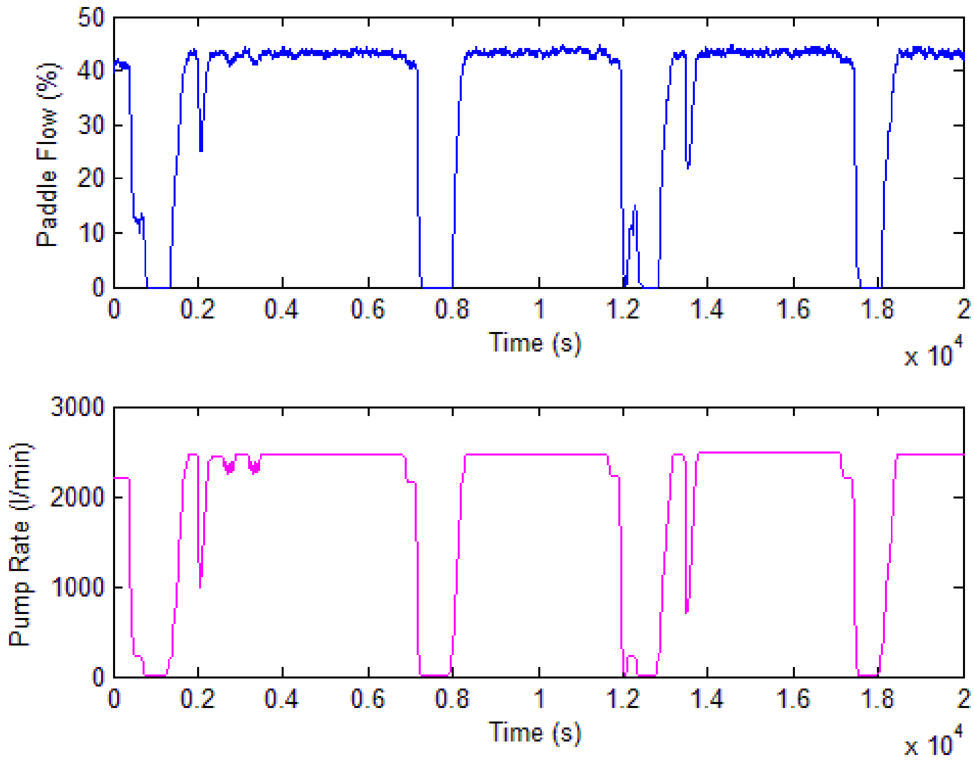

Figure 2.4.2: Return flow from a paddle sensor (top), compared with pump rate (bottom). This return flow sensor does not give a numerical value for the flowrate, but the trend can be monitored and compared to changes in the pump rate.

On some rigs, due to practical or economical reasons, low quality flow meters have been installed, resulting in the flow out not being a trustworthy parameter for monitoring. Some types of flow meters are also prone to plugging by the formation cuttings. Even a "good" flow meter may not show the correct numerical value, but showing consistent values and indicating trend changes will be a good aid in monitoring the well.

Incorrect Volumes during Tripping

When tripping out of the well, the volume of steel that is removed will have to be replaced by mud. In the same way during tripping in, a certain volume of mud is expected to flow back from the well as it is being displaced by steel. In order to keep track of these volumes, a trip sheet is filled out during the tripping operation, and a comparison is done between the actual volume changes seen and the calculated values from the pipe data. Deviations from the expected volumes are indications of either influx from, or loss to the formation. These calculations can also be done automatically.

In order to keep track of the rather small volumes involved in the tripping operation, the well is under normal circumstances connected to a trip tank system rather than the active system during tripping operations. Monitoring a volume of 5-10 m^3 gives a higher accuracy than monitoring an active volume of 50-100 m^3.

Interpretation of Parameters

Although all the mentioned parameters may be used as indicators of reservoir influx, they will rarely provide a definitive answer by themselves. Because of this, the different inputs will have to be interpreted together in order to understand what is actually happening with the well. In the traditional approach this interpretation is done by both the driller and mudlogger. Experience from training and previous work, as well as knowledge about the specific drilling rig and well will help them understand how the well is behaving.

In order to understand and "feel" the well, fingerprinting may be performed. The extent of this will be varying from well to well. One such fingerprint will be the amount of flowback or gain in the active system during pumps off and connections. In an HPHT setting, fingerprinting will be a lot more extensive, i.e. the behaviour of the pits with the on-board cranes in different positions.

Transferring experience and the ability to interpret to an automated system will no doubt prove challenging, and will require a lot of tuning in order to be applied in a rig setting. Some proposed methods are presented in the following section.

2.5 - Proposed Methods for Automated Detection of Reservoir Influx

Conventionally, monitoring of the well is not aided by more than linear alarm systems and experience. Developing a system than understands the rig and the well can be a great aid during the drilling operation, and if successful also help in streamlining the drilling procedure. A literature study has been performed to investigate proposed methods for detecting kicks automatically.

2.5.1 - Conventional Drilling

Automated Monitoring of Traditional Parameters

Perhaps one of the simplest approaches to automated detection of kicks is making the monitoring of the parameters already being monitored automatic. Close monitoring of parameters such as pit levels and flow out would be able to spot reservoir influx in the same way as today. One of the challenges, however, would be the fact that the active circulation system is a dynamic and complex system, and having alarms on every increase or decrease would not make an automated system very helpful. Basically, the system needs to be able to understand what is going on and adapt to this information.

An automated system based on already measured parameters was presented in the early nineties. (McCann, White et al. 1991) This system monitored delta flow (difference between flow in and flow out), as well as active system volume and expected tripping volume. The system appears to give promising results, also on field tests, but does not seem to have been adopted in the industry so far. An interesting aspect of this system is that it incorporates a model that gives theoretical behaviour of the active volumes during transient periods (shutting off or starting up pumps) that can be compared to actual measurements. Little information is given about how the model works, except that there is one model for steady state and one for transient periods, and that statistical analysis is employed in order to avoid false alarms.

An alternative to having an accurate model of the volume behaviour during transient periods is fingerprinting. This involves noting the behaviour of the system at different flow rates for later reference, so that any anomalies can be spotted later on. It is employed in HPHT and other settings, but is rather time consuming.

Detection of Wellbore Anomalies through Pressures

Another proposed method of detection of kick and loss, as well as other wellbore anomalies, is the use of standpipe pressure (SPP) and annulus discharge pressure (ADP). (Reitsma 2011) The behaviour of these pressures by themselves and in comparison to each other can help identify downhole problems. Pressure sensors are smaller and easier to install than Coriolis flow meters. For kicks and losses, the alarms are based on pressure change equivalents for total flow or continuous total change in volume. Washout and plugging are detected based on changes in pressure. To reduce noise and make interpretation easier, variance is normalized.

The method seems to compare well with the use of a Coriolis flow meter, with comparable results for the time used for detection, as well as the flow and volumes. The method also allows for detection of anomalies with a shut in well, which is not possible with a flow meter. In addition, the method is not prone to problems due to plugging or proximity to vibration sources in the same way as the flow meters. Using this system for MPD is also proposed, with choke opening as input instead of ADP. No published results of field trials of this method have been found.

Downhole Pressure Measurements

Measurements of downhole pressures may also be used for kick detection. These measurements can be transmitted to surface by traditional mud pulse telemetry, but measurements would then be limited to whenever the pumps are running, and at best a stored measurement from when the pumps were off. Data rate capabilities are limited, both by mud pulse telemetry itself, but mostly by all the other data measurements being transmitted in the same way.

A faster alternative would be wired pipe, which would also give measurements when not circulating. It is however also a lot more expensive.

2.5.2 - Managed Pressure Drilling

Influx Detection in MPD with the Micro-Flux Control Method

The Micro-Flux Control (MFC) method is a closed loop system with the capability of detecting reservoir influxes. (Santos, Catak et al. 2007) In addition to a conventional circulation system, the MFC system consists of a rotating control device (RCD), a manifold with two drilling chokes and a hydraulic power unit to control the chokes. The two chokes provide redundancy, and have the capability of measuring flow out as well as fluid density by the use of a mass flow meter. Other parameters used by this system include flow in (from stroke counters on the pumps) and stand pipe pressure. The system provides the opportunity of using several remote monitors to display trend lines of the observed parameters.

The system allows for real-time influx detection through the continuous monitoring of flow out and standpipe pressure. According to (Santos, Catak et al. 2007) the system provides the capability of going from detecting 5 bbl kicks down to 0,5 bbl kicks, even allowing for the detection of gas kicks in OBM prior to the gas dissolving in the mud. Observing trends and fingerprinting the well allows for differentiation between different causes of influx, such as swabbed gas, ballooning and connection gas. Trending of the density from the flow meter also allows for identification of the fluids when they are circulated to surface.

Field tests of the system proved the capabilities also in a real oilfield environment (Santos, Catak et al. 2007), being accurate even during dynamic rig conditions. Even with large flow rates and cuttings volumes (flowrate of 3000 l/min and ROP of 90 m/hr), the chokes did not plug. Rig crew also noted the small footprint and simplicity of the system, allowing for easy implementation without extensive training. The system also has the capability of drilling underbalanced, however this will require changes to procedures and well plans from an early stage.

MPD Kick Detection and Management with Pressures While Drilling

In a shallow well drilled offshore Myanmar, another method of kick detection and management during MPD drilling was employed. (Fredericks, Reitsma et al. 2008) This method involved a Dynamic Annular Pressure Control. This DAPC allowed for continuous management of downhole pressure by the use of a Integrated Pressure Manager. The IPM employed a real-time hydraulics model to control a choke manifold and an automated backpressure pump. In addition the flow was measured downstream of the choke by the use of a Coriolis flow meter, allowing for detection of kicks during connections that would otherwise have been masked by the annular backpressure pump running. The system allowed for continuous management of the pressure at the casing shoe, a critical point in this well due to a narrow pressure window.

During drilling, downhole pressures (PWD) were measured and transmitted by the use of MWD tools and wired pipe, allowing for 2-4 second latency and continuous management of downhole pressures by the integrated pressure manager. During drilling, the model was self-calibrating to the downhole pressure measurements. If a kick was taken, the system was switched over to running purely on the pressure measurements to avoid losing accuracy as a consequence of introducing a two-phase system of gas and mud.

The method for management of kicks was a modified volumetric kill method using the dynamic annular pressure control and downhole pressures to bleed and lubricate the gas influx. This simplified the well control process because the driller only had to line up according to the procedure, without having to engage the rig pumps and running a risk of introducing pressure spikes to the wellbore.

2.5.3 - Dual Gradient Drilling

Monitoring subsea mud lift system pump rate

In a dual gradient setting, cuttings transport from sea bottom to the rig will in many cases be done by a subsea mud lift system. With a drillstring filled with mud, the subsea pump rate and pressure at the subsea pump will be kick indicators (Choe, Schubert et al. 2007). Also for a drillstring not filled with mud, the subsea pump rate can be used as a kick indicator. A limitation of this system is that the well will be flowing due to u-tubing for some time after pumps are shut off, even when not taking a kick. This means that it will take some time to determine whether the well is actually flowing or not, and makes it important not to start with the next operation before the u-tubing has stabilized.

2.6 - Limitations on the Automated Detection of Reservoir Influx

Amount of Received Data

As with any other aspect of the industry, economics will always play its part. Although late detection of kicks, possibly resulting in a blowout will have very large consequences (not only economically), there will be a limit to how much money is spent on kick detection systems. A system that works with data already being collected will be preferred over a system that requires installation of new sensors and equipment. Not only because of the cost of the equipment itself, but also because of the possible non-productive time spent rigging it up.

As mentioned, in the case of downhole data, there will also be a limit to the data rate. In the case of surface sensors, or other sensors connected by wire, this will rarely be a problem. There may also be cases of sensor failure. In cases where there is only one sensor and no redundancy, the operation may either be halted in order to replace the sensor, or it may be decided to carry on without the sensor if it is non-essential. As an example, being fully dependent on downhole MWD pressure measurements for kick detection may result in a lot of tripping time, as there are many reasons why communication with this sensor may be lost.

Quality of the Received Data

Detection of reservoir influx is not only limited by the amount of data, but also the quality of the data. As an example, a paddle-type flow out sensor is cheaper, but also less accurate than a coriolis flowmeter. At the same time, the coriolis sensor will be more affected by nearby vibrations that may be present on the rig.

One source of error in the sensor measurement is the rig movement. This may be related to heave, or on some rigs, to crane movement. This rig movement may affect readings in several ways. For a pit volume measurement, movement on the rig may make the fluid in the tank move around, which will appear as volume changes to the sensor, even if the volume itself is not changing. Up and down movement of the rig may affect the flow at the flowline, making the well appear to flow at varying flowrates, even if it is actually flowing steadily. Both of these effects will result in a noisy signal, where interpretation will be more based on trends than the actual measurements at each point in time.

2.7 - Well Control Methods

Traditionally, whenever a kick is detected, through increased flow, pit gain or by other means, the rig pumps will be shut off, and the well checked for flow. If a kick is confirmed, the well will be shut in by the use of the BOP. This can be done the "hard" way, by simply shutting in the BOP, or the "soft" way, by opening the choke line, closing the BOP, then closing the choke line. (Grace 2003) (Carlsen, Nygaard et al. 2008). Closing in the well by using the choke line will create less pressure peaks in the annulus, reducing the risk of fracturing the formation. However, the increased use of time will allow the influx to grow larger before the well is shut in.

Some time after the well is shut in, the combined pressure of the kick and the hydrostatic column will exceed the reservoir pressure, stopping the influx. In order to maintain a well pressure above this bottomhole pressure while drilling further, a new mud weight will have to be used.

If a kick is taken during MPD operations, the flow rate through the choke will increase as the total volume of flowing fluid has increased. (Carlsen, Nygaard et al. 2008) This increased flow rate will result in an increased pressure drop through the choke, leading to a larger bottomhole pressure (BHP). In order to maintain a constant BHP, the control system will respond by opening the choke valve, and the resulting increase in fluid flow can be detected. When the kick has been detected, the choke is reset to the opening it had prior to taking the kick in order to evaluate the flow rate from the well. If necessary, the BHP can be further increased by applying more pressure with an annulus pump or by closing the choke valve even more. When the well stops flowing, the BHP is recorded and the new mud weight needed can be calculated.

During dual gradient (DG) drilling, and also during some applications of MPD, a subsea mud lift system is used in order to transport mud and cuttings from the seabed and up to the rig. This system contains a subsea pump that may be controlled to run at a certain speed to keep the inlet pressure constant. Slowing the pump down will increase the annulus backpressure in the well. If a kick is taken with such a setup, the subsea pump rate will increase due to the increased flow, allowing for detection of the kick. After the well is shut in, drill pipe and subsea pump inlet pressure is recorded. The flow is bypassed to the subsea pump, and both the subsea pump and surface pump are run at their pre-kick rate. When the pump speeds are adjusted, drill pipe pressure is observed until stable (in the same manner as with a shut-in well in conventional drilling). Comparison of the new drill pipe and subsea pump inlet pressures to the previous measurements allow for calculation of the pore pressure and new mud weight.

2.8 - Automated Data Analysis

2.8.1 - Methods for Automated Interpretation of Signals

In order for a system to be able to give proper warnings of indications of kicks, it will need some way of understanding what is going on. As mentioned previously, noisy signals will need to be analysed according to their trends, and not by each individual measurement.

A statistical method has been presented that allows interpretation of selected parameters and provide warning signals if the parameters indicate downhole problems. (Gulsrud, Nybø et al. 2009) The presented application of the method is detection of stuck pipe. The third order moment (skew) of standpipe pressure (or downhole pressure) multiplied by the normalized standard deviation of torque can, if the result is a positive number, represent an indication of poor hole cleaning and potential stuck pipe. To avoid getting false alarms due to signal spikes or other "false data", a threshold is set where a certain number of samples need to be positive within a moving time window before an alarm is activated. This threshold can be fine-tuned by selecting both the size of the time window, as well as the amount of samples/calculations within the window. Tuning the system to a specific environment (i.e. a specific rig drilling a specific hole size) in a similar way as the decoding of mud pulse telemetry, will most probably prove quite beneficial.

2.8.2 - Adaptive Observer Technology

An automated system will not only have to understand how to monitor trends instead of individual measurements, it will also have to understand which trend to follow. It should be able to represent what we know is true. Even with a very sophisticated model, it may be very hard to tune it so that it represents reality, especially if this tuning has to be done manually.

A better solution would be if the system was able to learn the trends from good data, and apply this tuning to predictions later on. One way of doing this is by using adaptive observer technology. The basics this technology were introduced in the 1960s (Luenberger 1964). Previously, control designs were based on all inputs of the controller being known at any time, but this technology allowed for control of systems also where the controlling inputs (state vector) is not measured. On a rig, there are several factors influencing flow and volumes that cannot or are not measured.

The idea is that by introducing an observer function similar to the function that governs the process, the properties of the influencing factors can be found and used as input for the control system. Consider a system governed by the following function:

$$\frac{dx}{dt} = \dot{x} = a \cdot x(t) + b \cdot u(t) \qquad \text{(Eq. 2.8.1)}$$

Here x is the state, the value that controls the process, and u is the input, a time-dependent variable that will affect the state. The parameters a and b both influence the process, but are unknown, for instance because they are not measured. The values can be found by introducing an observer function similar to the process function:

$$\frac{d\hat{x}}{dt} = \dot{\hat{x}} = \hat{a} \cdot \hat{x}(t) + \hat{b} \cdot u(t) \qquad \text{(Eq. 2.8.2)}$$

Here, we have introduced $\hat{x}$ as the state of the observer function, and $\hat{a}$ and $\hat{b}$ as influencing parameters. Note that this function also contains the same input, u(t). The goal is to have the observer function giving the same output as the state function by adjusting $\hat{a}$ and $\hat{b}$. This tuning, or learning, is performed by observing the error through the variable ε:

$$\varepsilon = x(t) - \hat{x}(t) \qquad \text{(Eq. 2.8.3)}$$

As a measurement of the error, ε will influence how $\hat{a}$ and $\hat{b}$ change.

$$\frac{d\hat{a}}{dt} = \dot{\hat{a}} = \gamma_1 \cdot \varepsilon \cdot \hat{x}(t) \qquad \text{(Eq. 2.8.4)}$$
$$\frac{d\hat{b}}{dt} = \dot{\hat{b}} = \gamma_2 \cdot \varepsilon \cdot u(t) \qquad \text{(Eq. 2.8.5)}$$

This results in a larger error giving a larger change per time unit. Note that we have also introduced the learning factors γ_1 and γ_2, which are used to influence the dependence on the error. A too large γ will give an unstable system, while a too small value will result in the system taking a very long time to adjust to changes. With the changes in $\hat{a}$ and $\hat{b}$ determined, the change in $\hat{x}$ can be calculated as per equation 2.8.2, and the new values for $\hat{a}$, $\hat{b}$ and $\hat{x}$ can be determined:

$$\hat{x}(t) = \hat{x}(t - dt) + dt \cdot \dot{\hat{x}} \qquad \text{(Eq. 2.8.6)}$$
$$\hat{a}(t) = \hat{a}(t - dt) + dt \cdot \dot{\hat{a}} \qquad \text{(Eq. 2.8.7)}$$
$$\hat{b}(t) = \hat{b}(t - dt) + dt \cdot \dot{\hat{b}} \qquad \text{(Eq. 2.8.8)}$$

With a properly adjusted gamma this observer system will based on the error measurement tune in to the same output values as the real system. As the two systems are governed by the same functions, the values of $\hat{a}$ and $\hat{b}$ can then be used as input for a and b in the state function. Note that large changes in the system may require a new learning process to be run.

2.8.3 - Low Pass Filters

As has already been mentioned, sensor inputs may not always provide perfect data. Depending on the sensor quality and setup, as well as the environment it is installed in, spiking of the sensor output may greatly affect the data quality. 'Noisy' data is problematic if it is going to be used for any calculations, as the error will be carried through the calculations. Another important aspect is the ability to set alarms on the parameter. Clean data allows for setting the alarms much closer than noisy data, so that changes can be spotted at an earlier stage.

Noisy data can be dealt with through filtering, and one way of doing this is by applying a low pass filter. A low pass filter essentially applies a limit to the difference between two data points, resulting in a smoothened curve. Such a filter can easily be implemented in a data program and is governed by the following equation (Wikipedia 2012)

$$y[i] = y[i-1] + \propto * \; (x[i] - y[i-1]) \qquad \text{(Eq. 2.8.9)}$$

Basically, the difference between the data output y[i] and the previous data output y[i-1] is proportional to the difference between the input x[i] and the previous data output. α is a proportionality or smoothing factor, and determines the dependency on the previous value versus the new input The results of applying a low pass filter to data from a paddle flow out sensor is shown in figure 2.8.

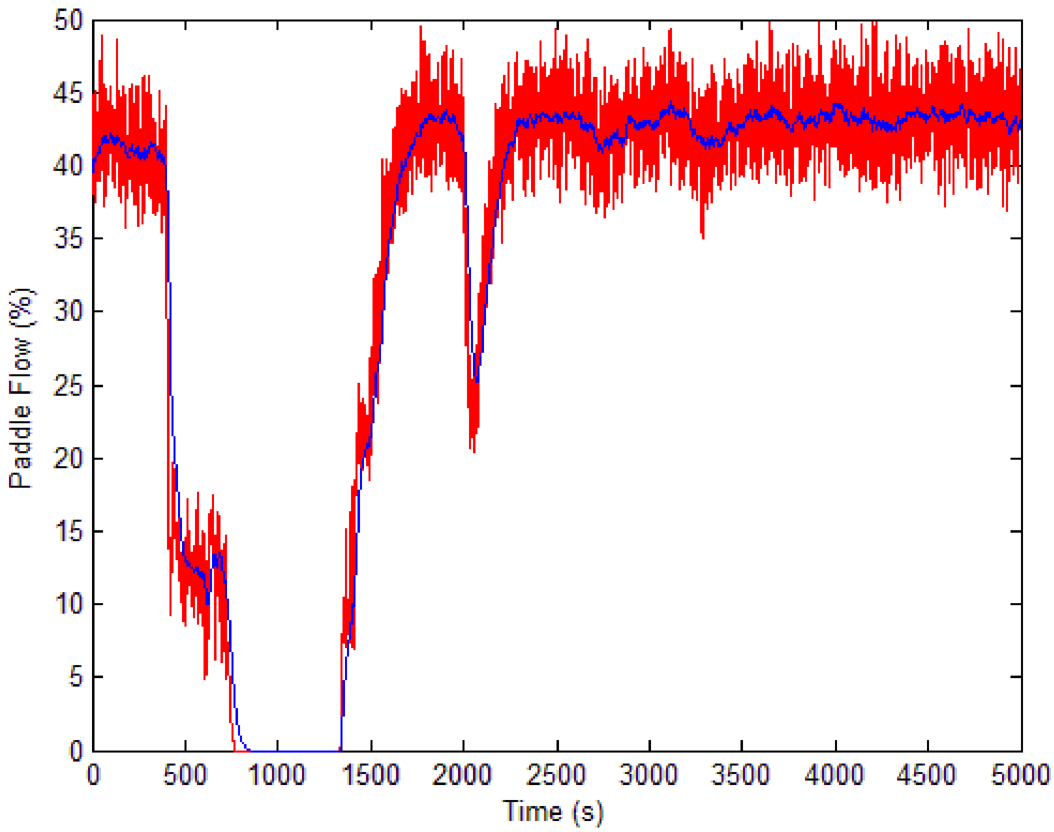

Figure 2.8: Comparison of raw (red) and filtered (blue) data from a paddle flow out sensor. We see that the noise is greatly reduced. It should be noted that the response is also affected, an example of this can be seen after approximately 750 s.

As can be seen in the figure, the low-pass filter has greatly reduced the noise. While alarms without filtering would have to be set with a range of 15 %, they could be set to a 5% range after filtering.

Care should however be taken not to apply a too strong smoothing factor, as it will increase the time it takes for the data to show a response to abrupt changes.

2.8.4 - High Pass Filters

Another aspect of data modelling and simulations is that even a small error will cumulatively grow larger and larger over time. One way of handling this is to reset the calculations frequently, removing the cumulative error. Another method is to apply a high pass filter, where only a certain amount of data points are considered.

A high pass filter can be described by the following equation (Wikipedia 2012):

$$y[i] = \propto * \ (y[i-1] + x[i] - x[i-1]) \qquad \text{(Eq. 2.8.10)}$$

We see that the new output y[i] is proportional to the sum of the previous output y[i-1] and the change in input (x[i] – x[i-1]). α determines the impact strength of changes in input and the previous value, and is given by:

$$\propto = \frac{RC}{RC + \Delta t} \qquad \text{(Eq. 2.8.11)}$$

Where RC is a time constant and Δt the sample time. When looking at the last hour of data from a sensor with a 1-second sample interval, RC will be 3600 and Δt will be 1.

The effect of applying this filter is that when considering only some data points, only the cumulative error associated with those points will be included. In many cases this error will be smaller than the cumulative error over the whole time period. It is however important to consider the choice of α, as you want to keep the error to a minimum while still considering enough points to pick up changes in trends.

3 - Developing a Circulation Model

On the basis of the literature study, it was decided to pursue the creation of a model of the transient volumes in the rig circulation system during conventional drilling. This has the benefit of being sufficiently simple to be modeled through rather simple programming, while at the same time having the possibilities of providing a simple, but good enough solution, resulting in large benefits. It is also based on data already being monitored on more or less every rig, making it easy to implement also in MPD and DG if found successful.

However, even if the modeling surface volumes at first glance may seem simple, there are several things to be aware of. As described in section 2.3 there exist a variety of different effects related to the different parts of the circulation system that will affect the measured volumes. In order to develop a model that will successfully detect and provide an appropriate warning about changes in volume related to a downhole gain, all of these effects will have to be accounted for.

With a traditional setup, the mudlogger and driller will set their alarms as close as practically possible and within the guidelines and procedures supplied by the operating company and/or drilling contractor. Depending on the sensors, as well as other conditions on the rig (heave, crane operations), the lines will contain a certain amount of noise. The main aspect will be monitoring the trends.
With such a setup, alarms will not be uncommon. The mudloggers job is to understand what is happening, and if there is a deviation from a previous trend, why this deviation is happening. Although it is better to raise too many alarms than too few, a mudlogger that calls the drillfloor with false alarms 10 times an hour will soon be disregarded. In the same way, an automated kick detection system will have to take into account and rule out the most common (and well known) reasons for gains in the active system in order for people to actually want to use it. At the same time, it will have to detect all indications of a real reservoir influx.

The challenge will then be to implement the dynamics of the rig circulation system into a model, while ensuring that it gives proper warnings. As mentioned, many of the effects that influence the measured active volume will be dependent on the rig, and a proper circulation model will have to be tuned to the rig where it is going to be used.

The main "instability" or difference between the flow in and out of the active system when starting up or changing the flowrate is related to the flow from the flowline through the shakers and back to the pits. From the pumps to the flowline, where the closed circulation system ends and the flow is exposed to atmospheric pressure, the change in flowrate will travel through the system at a speed equal to the speed of sound through the mud. This will vary with the type of mud used, but will be in the scale of 10^3 m/s.

At the flowline, or more specifically at the header box (diverter or possum belly), the flow from the well will be slowed down before entering the shakers. The flow from the header box back to the pits will be largely driven by gravity, and the time it takes the mud to flow through may be in the scale of several minutes. The decrease in flowrate is needed in order for the shaker and solids removal equipment to work properly, allowing the mud to be reused.

3.1 - Creating a Basic Circulation Model to Simulate Volume Changes

A basic circulation model had been created in Matlab in order to simulate volume changes at different places in the circulation system as the pump rate is changed. In this basic model, the circulation system is divided into 3 main parts, as shown in figure 3.1. The model only considers volumes and volumetric flowrate, and no friction or other pressure losses in the pressurized system are considered.

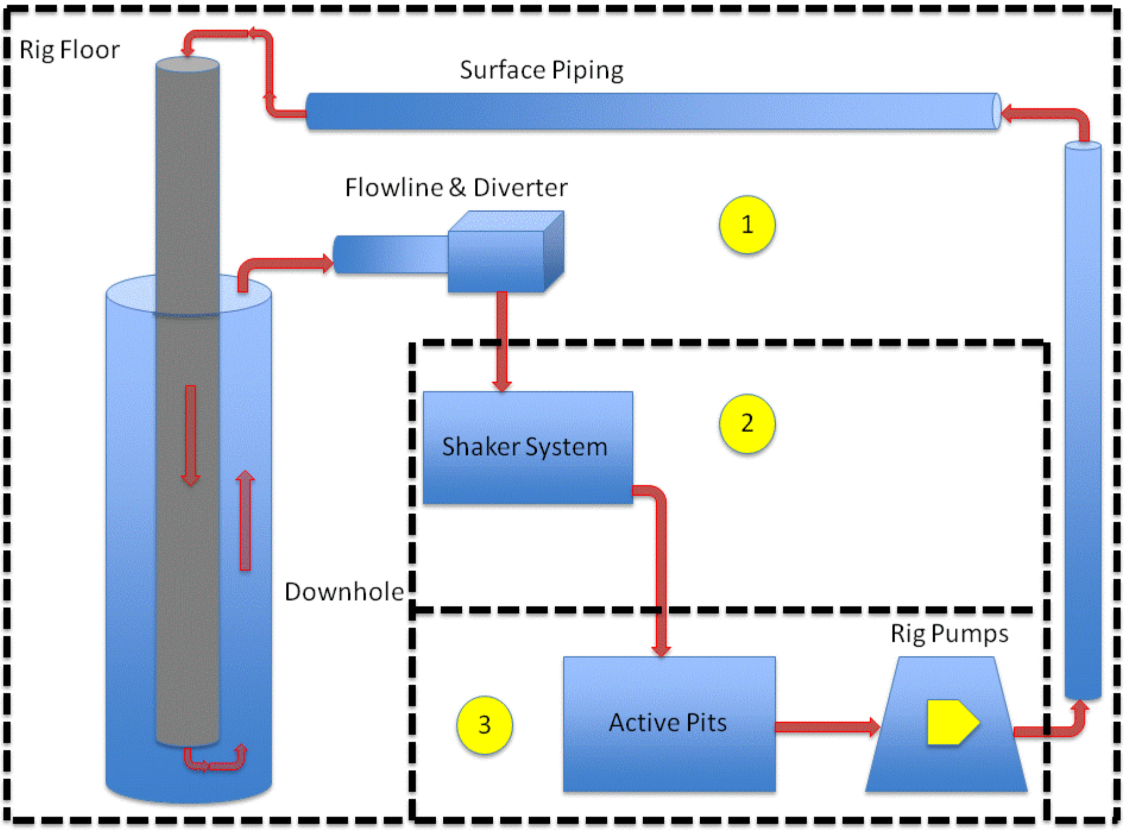

Figure 3.1: The division of the circulation system in the basic matlab model. (1) Contains all surface piping as well as downhole (the pressurized system). (2) Contains the shaker system including the shaker pit. (3) Contains the active pits as well as the pumps/flow control.

In order to create a working model for the flow and volume changes in the circulation system, we need to define the governing equations. Volume change per time unit can be described by the following equation:

$$\frac{dV}{dt} = q_{in} - q_{out} \qquad \text{(Eq. 3.1.1)}$$

Where V is volume in m3, t is time in seconds, and q_{in} and q_{out} are volumetric flowrates in m3/s.

Gravity driven flow is the basis for the simulations, and is given by the equation for volumetric discharge from a tank with varying head:

$$Q = CA\sqrt{2gh} \quad \text{(Eq. 3.1.2)}$$

Here, C is a unitless discharge coefficient dependant on the type of opening as well as other factors. Tuning of the model is possible by altering C. A is the opening area of the discharge (orifice) in m^2. Under the root sign g is the acceleration of gravity in m/s^2, and h is the hydrostatic head (height above zero level) of the fluid column.

The relation between the volume in the tank and the hydrostatic head is given by:

$$V = a * h \quad \text{(Eq. 3.1.3)}$$

Where a is the area of the tank in m2. (Not to be confused with the orifice area A from equation (3.1.2))

The relation between the discharge equation and the given equation for volume change per time will be that:

$$q_{out} = Q \quad \text{(Eq. 3.1.4)}$$

The other flowrate, q_{in}, will be governed by q_{out} from the previous tank in the system, given either by equation (3.1.2) or by the pump flowrate in case of the active. The simulation also includes a possibility of having a time delay from the flow goes out of one tank until it enters the next one.

With small variations in level height, we can set:

$$Q = k * h \quad \text{(Eq. 3.1.5)}$$

Where k is a combination of the different factors going into equation (3.1.2), essentially $CA\sqrt{2g}$, allowing for tuning of the model and a simplified equation that can be used as input for a adaptive observer model. This will allow the simulation model to “learn” from the real system and adjust accordingly.

Combining the equations we get the following relationship:

$$a * \frac{dh}{dt} = q_{in} - k * h \quad \text{(Eq. 3.1.6)}$$

This can be rearranged to:

$$\frac{dh}{dt} = \frac{-k}{a} * h + \frac{q_{in}}{a} = K' * h + \frac{q_{in}}{a} \quad \text{(Eq. 3.1.7)}$$

Where: $K' = \frac{-k}{a}$

This can be written as:

$$y = \frac{dx}{dt} = K' * x + b \qquad \text{(Eq. 3.1.8)}$$

Where: $b = \frac{q_{in}}{a}$

With equation 3.1.8 we have described the system in such a way that we can employ learning capabilities through the use of adaptive observer technology.

3.2 - How the Model Works

The basic idea of the model is that in a steady state with no flow, the head in the tanks will be zero. When pumping, the level in the tanks will increase, and with this increase in head, fluid will also start flowing out of the drain according to equation 3.1.2. At a steady flowrate the level in the tank will increase until one of two things happen. Either the flow out will balance the flow in, leaving the system in a steady state at a specific level until the flow is changed again. The other possibility is that the level in the tank reaches the maximum level specified for the tank, and the excess flow will continue directly to the next part of the system. See figure 3.2.1

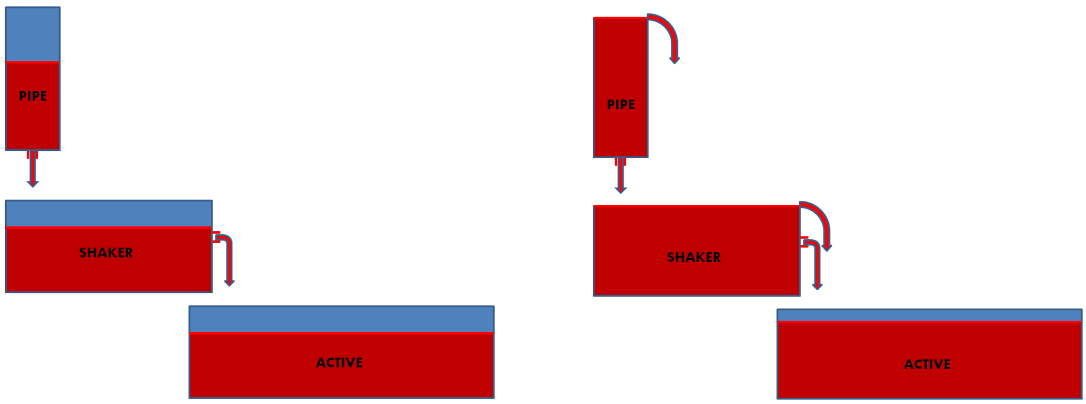

Figure 3.2: The basic principle of the flow model. To the left the system is in a low level with no overflow. All flow out goes through the drains, and this flow is high enough to keep the head below the maximum head. To the right the system is in a high level with overflow. The flow through the drain is not large enough to keep the head below maximum.

The driving mechanism of this circulation simulation is the user-defined flowrates. A set of flowrates is used as input together with the time when changes between flowrates occur, as well as the time it takes to change (ramp up or down) between two flowrates. Other inputs include the draining areas of the tanks, as well as volumes.

For the calculations, the flow out of the active (pump rate) enters the pipe after one timestep. The flow out through the drain is calculated with the previous head, and from this an apparent change in volume. This volume is compared to the maximum volume, and it is determined whether or not overflow will occur, and what the flow out will be. A time delay is applied before this flow out enters the shaker system. The same kind of calculation is performed for the shaker system, and another time delay is applied prior to the flow from the shakers entering the active system.

The model was developed using MatLab software. Printouts of the actual programs are given as attachments to this thesis.

As a further development used in a real-time environment, the model would be running continuously, and performing calculations at regular intervals, such as once every second. The model would then provide a simulated response to any changes in the input values, which could be compared to actual data. The system could then be set up to give alarms whenever the simulated and actual values differ by more than a certain value.

3.3 - Assumptions Made in the Modeling

Volume in the piping is dependent on the flowrate

This assumption is based on the paper (McCann, White et al. 1991). The delta volume when shutting off the pumps from 3700 and 1700 l/min is different, showing that the volume of fluid "lost" in the surface lines during circulation is dependent on the flowrate.

With zero flow, the volume in surface piping is zero. When flowing, the volume in surface piping will depend on the relationship between the drainage area and the flowrate. A maximum volume in the pipe is specified. If the flow out through the drain with the head at maximum volume, the volume will stabilize at some level lower than maximum. In the opposite case, where the flow out through the drain is lower than the pump flowrate, even at maximum volume, the volume will stabilize at maximum volume, and we will have overflow.

The equations are valid for all heads

According to the LMNO engineering webpage (LMNO 2012), the equation used is only valid for heads above a certain level. As the head approaches zero, other effects will start playing a larger part, and the resulting calculations may start to differ from reality. In the simulation calculations, the same equation is used for all heads. In a learning setting, these variations will be introduced into the C-value of equation 3.1.2. Flexibility can be increased by allowing for different C-values in different settings, i.e. pumps on and pumps off.

The delay time is independent on the flowrate

In the input section, delay times from the pumps to the pipe "tank" and from exiting the shaker until it enters the active are specified. In reality, the time to flow though the desander, desilter and degasser equipment would be dependent on the flowrate. In the model, these times are used independently of the specified flowrates. The times will also affect the delta volume in the active pit, as there will be more or less time with fluid only flowing out of the tank before return flow starts increasing.

The head cannot exceed the specified level

For both the pipe and shaker, a maximum volume is specified. As mentioned, whenever this volume is exceeded, overflow will occur, and the overflowing volume will continue directly to the next part of the circulation system.

For the pipe system the basis for this assumption is that there is a limit to how much fluid can be caught up in this part of the circulation system. Whenever this volume is filled up, the excess volume will have to go somewhere, which will be continuing through the system. If this limitation was not implemented into the model, the calculated results could in some cases that extremely large volumes of fluid got caught up in the surface piping, which would definitively not represent reality.

The shaker system is admittedly more complex, and overflow would in some cases end up outside the circulation system, resulting in drops in volumes and fluid levels. There are also numerous possibilities for adjustments at the shakers, such as how many shakers that are used and how the flow is diverted. These adjustments will affect how the volumes behave over time. However, for the sake of creating a simple model that could show the basics of the fluid behavior, including all these adjustments would add too much complexity.

The head cannot be lower than zero

The head also has to be limited at zero. Having a head lower than zero does not make sense, as it would mean a negative volume. The equation will still calculate if not limited, and output imaginary numbers. This problem is removed as the lower limit for the head is set to zero.

The change in flowrate is linear

In the input section, a time is specified for the time it takes to change from one flowrate to another. The simulation will assume a linear change between the two flowrates, distributing the change over the specified time.

No cuttings or gas in the system

No volume changes are calculated to take into account cuttings or gas in the system. The volume of fluid pumped out of the active will have the same volume at all stages through the system before returning to the active. When simulating an influx, this is only modeled as an increase in flow and volume. No calculations are done on density change or gas expansion.

All surface lines will drain to the shaker

In the simulation it is assumed that the entire volume of surface lines draining as the flowrate is decreased will go through the shaker pit before entering the active. In reality, some of this volume would probably drain directly into the active pit.

Losses or gains happen at constant rates

The model incorporates the possibilities of having static losses at the shakers (i.e. from mud being lost together with the cuttings or from the use of a centrifuge), where a rate for the losses is input to the system. This is done by removing the lossrate from the flow out of the shakers, making the active volume decrease during steady circulation and transient periods. The losses are assumed steady and independent of the flowrate. Losses only occur as long as there is flow out of the shakers.

The model also incorporates the possibilities of gaining from the well. The input is the rate of influx as well as the time the influx starts. This makes it possible to simulate kicks being taken both during steady circulation and during transient periods (i.e. when changing pump rates). The influx is added to the calculations as an increased flow out of the pipe system. In this simple model, the influx will continue until the simulation is finished, independent of whether the pumps are on or off.

4 - Simulated Cases

4.1 - Case 1 - The Base Case

In the first simulated case, the model was tested by trying to recreate the results shown in figure 3 in the paper by (McCann, White et al. 1991). The input data for the rig and circulation system is not presented, but it is mentioned that the flowrates are 3700 l/min and 1700 l/min for the two cases presented. There is no information about how much time is spent ramping the pumps down and up again, or when they are stopped and started. We can, however, see that in both cases, the pumps are turned on before the active stabilizes, meaning that the flowback is not completed (surface system not fully drained) during the connection.

The authors do not present the basis for their modeling software, but looking at the graphs suggests similarities with the model presented in this thesis, making it a natural starting point for comparison. The authors also mention the use of technology that enables the tank monitoring software to “learn” the characteristics during the transient periods when the pump rates are changed. The specific technology used for this is not mentioned.

As a first test of the MATLAB model, the input variables in the model were altered in order to have the resulting simulated volumes during the transients follow the curves from McCann et al. as close as possible. Three different cases were simulated, with several adjustments being made throughout the simulations.

4.1.1 - Run 1: Active Pit Volumes with No Influx

This run shows the response from a connection scenario with the flowrates presented previously. The active pit response to turning the pumps off and then on again before the active pit has stabilized is simulated. It will serve as comparison for the next two runs.

High Flowrate

In the target data, as the pumps are shut off, the flowback gives a gain in the active of approx 8.9 m3 over 400 seconds, when the pumps are turned on. With the pumps are turned on again, the active drops 7.7 m3 over the first 520 seconds. The input data for the simulation is presented in Table 4.1.1 below:

Table 4.1.1: Data Input 3-Tank High Flow					
Data	**Value**	**Unit**	**Data**	**Value**	**Unit**
Low Flowrate	0	l/min	Decrease Flow Start	1040	s
High Flowrate	3700	l/min	Increase Flow Start	1430	s
Co Pipe	2		Flow Ramping Time	120	s
Co Shaker	8		Delay Through Pipes	20	s
Pipe Drain Area	$8.5 \cdot 10^{-4}$	m^2	Delay Through Shaker	35	s
Shaker Drain Area	$2.8 \cdot 10^{-3}$	m^2	Shaker Base Volume	20	m^3
Shaker Area	4	m^2	Shaker Max Volume	40	m^3
Pipe Max Volume	8	m^3	Active Base Volume	100.2	m^3

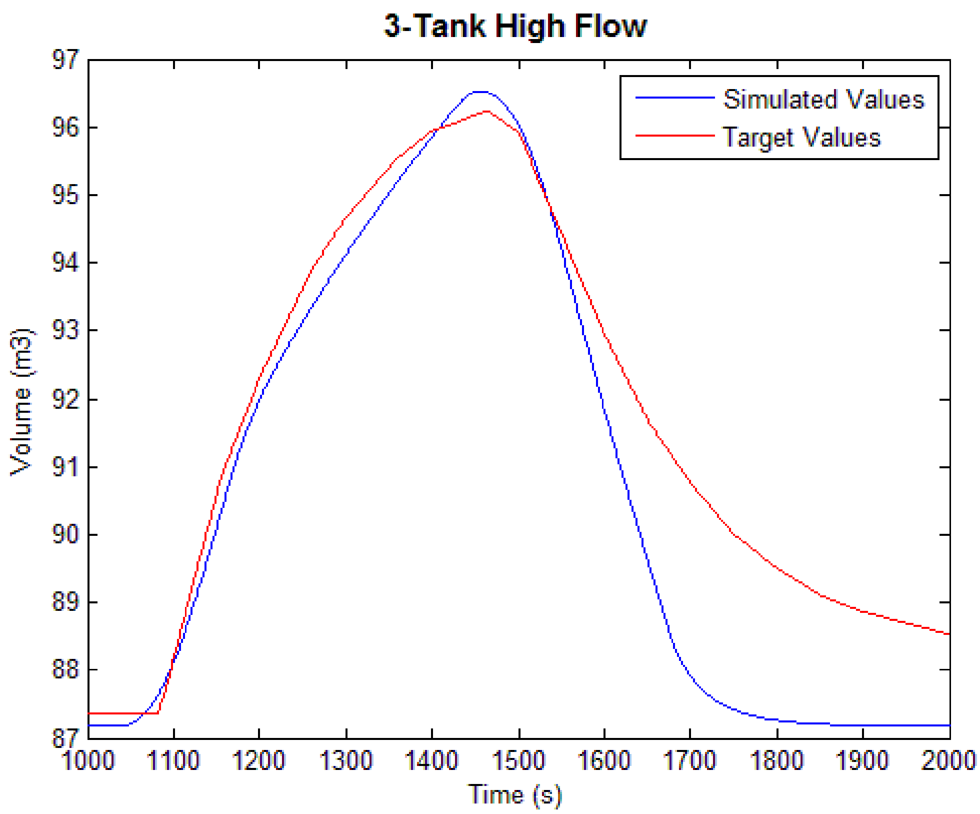

Figure 4.1.1: Comparison of target values (from the McCann, White et al. paper) and the results of the tuned 3-tank model when turning off the pumps from 3700 l/min. The simulation gives acceptable results for the flowback scenario, but does not fit well when the pump starts up again.

The main problem proved to be the drop in the active, or filling of the pipes, as the pumps are turned on again. The simulation results show a steeper drop than the compared data. This means that even if the flow from the shakers into the active start more or less at the same time, the flowrate is lower in the simulated case than the compared data. However, the results show the simulated case stabilizing at an earlier time. The simulated curves indicate slow flowrates into the active when starting up, and then a rapid increase before stabilizing. The compared data indicate a higher initial flowrate, but not the same rapid increase. The figure from McCann et al. does not show the active stabilizing as it is still decreasing at time 1000. The flowback is leveling out at a much earlier stage in the simulated results.

Using very high values for the Co constants provided pump on responses more similar to the compared case, with the pit not stabilizing before time 1000, however the curves did not fit well for the flowback scenario in these cases, and the volume changes were larger as well.

Low Flowrate Data Input

Target data for the low flowrate case shows a gain of 2.4 m3 over 340 seconds as the pumps are shut off, and then a drop of 2.1 m3 over the first 390 seconds after the pumps are turned on again. Input data for the simulation are presented in table 4.1.2 below:

Table 4.1.2 Data Input 3-Tank Low Flow					
Data	**Value**	**Unit**	**Data**	**Value**	**Unit**
Low Flowrate	0	l/min	Decrease Flow Start	70	s
High Flowrate	1700	l/min	Increase Flow Start	420	s
Co Pipe	1.1		Flow Ramping Time	30	s
Co Shaker	2.7		Delay Through Pipes	10	s
Pipe Drain Area	$3.0 \cdot 10^{-4}$	m^2	Delay Through Shaker	20	s
Shaker Drain Area	$8.0 \cdot 10^{-3}$	m^2	Shaker Base Volume	20	m^3
Shaker Area	6	m^2	Shaker Max Volume	40	m^3
Pipe Max Volume	8	m^3	Active Base Volume	50	m^3

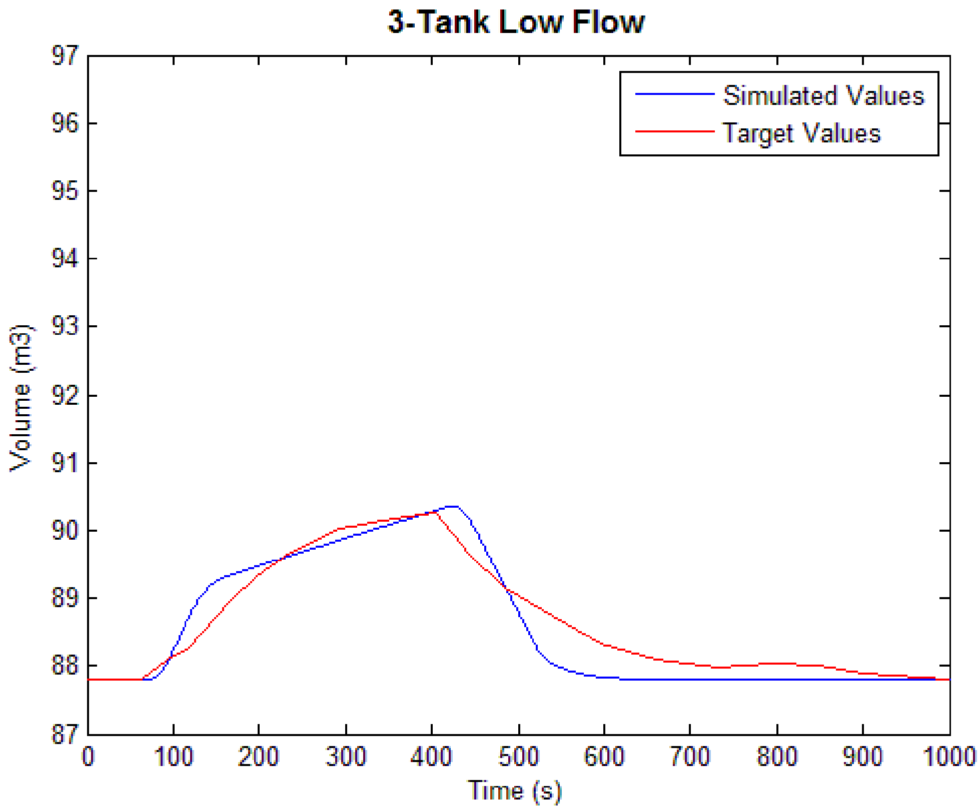

Figure 4.1.2: Comparison of target values and the results of the tuned 3-tank model when turning off the pumps from 1700 l/min. Although the flowback volume and times are acceptable, the general fit of the curve is not very good.

Achieving similar curves for the low flow case also proved challenging. As can be seen in figure 4.1.2 above, the results same kind of difference in the volumes when starting the pumps again, with the simulated active volume decreasing faster than the target values. In this case, there is also a difference in the shape of the flowback curve. This shape is governed by the Co values for pipe and shaker, but altering them also affects the flowback volume. Using the same inputs as for high flow did not give well fitting curves, and trying the low-flow input with the high flowrate case resulted in the flowback decreasing at a much earlier stage than shown in figure 4.1.2 above.

Comparison of Simulated Values with Data from McCann et al

As can be seen above, in order to make the curves fit well, different inputs had to be used with the high and low flowrate. This may have to do with the fact that the McCann et al. model is "learning" while running, whilst the basic simulation does not.

The curves fit pretty well for the flowback after the pumps are turned on, with both the rate of increase, time and volume fitting reasonably well. The fit is best in the high flow case. In the low flow case the interaction between the Co factors for pipe and shaker makes it harder to recreate a curve with the same trajectory while still keeping the volume at the same level as in the target data.

Simulations with number of tanks reduced from 3 to 2

In order to achieve a better fit, it was attempted to simplify the simulation model to a one-tank system, and focusing on achieving the correct curve with no limitations on the flowback volume. The modeling setup of this 2-tank system is presented in figure 4.1.3 below, for comparison with the 3-tank system presented in figure 3.1 and 3.2.

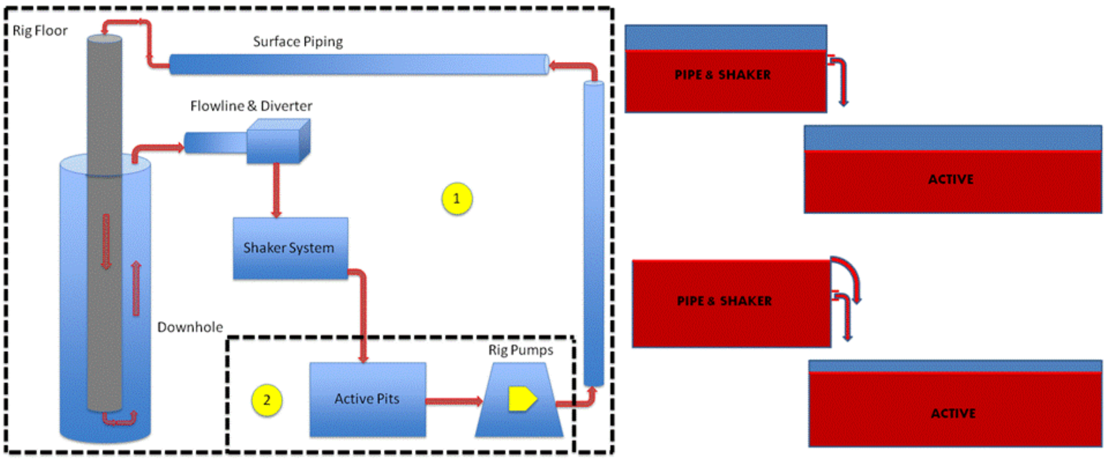

Figure 4.1.3: Setup of the modeling as the number of tanks is reduced from 3 to 2. The pipe and shaker systems are now combined into one system.

The input data and result of a high flow simulation with the 2-tank system and different flowback volume is shown in table 4.1.3 and figure 4.1.4 below:

Table 4.1.3: Data Input 2-Tank High Flow (Different Flowback Volume)					
Data	**Value**	**Unit**	**Data**	**Value**	**Unit**
Low Flowrate	0	l/min	Decrease Flow Start	2070	s
High Flowrate	3700	l/min	Increase Flow Start	2475	s
Co Shaker	5.70		Flow Ramping Time	30	s
Shaker Drain Area	$1.5 \cdot 10^{-3}$	m^2	Delay Through Shaker	20	s
Shaker Area	4	m^2	Shaker Base Volume	20	m^3
Active Base Volume	50	m^3	Shaker Max Volume	45	m^3

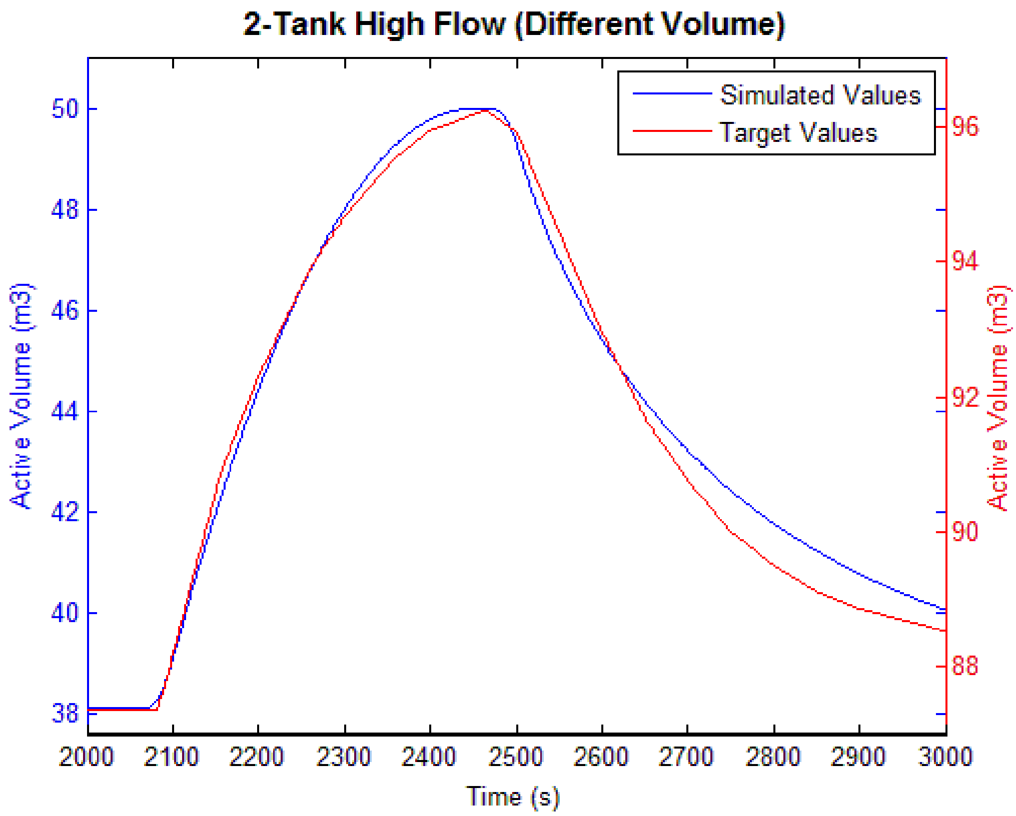

Figure 4.1.4: Comparison of target values and the results of the tuned 2-tank model with different flowback volume. The initial flowrate is 3700 l/min. The general curve fit is better than with the 3-tank model, although there is still some difference when starting up the pumps.

Even in this case, the simulation results do not fit as well to the target values as the model in the McCann paper. Note that the delta volume in the target values is 8.9 m3 while it is 14.2 m3 in the simulated results in figure 4.1.4.

We see that the fit during the flowback period is even better than in the high flow case presented earlier, and that the filling up of the pipes represents the target data a lot closer than previously, even if not fitting perfectly. This indicates at least some similarity between the models. It should be noted that the simulated curve levels out (i.e. flowback stops), while the target values appear not to do this.

As positive results were achieved with a simpler model, attempts were also made to achieve similar flowback volumes as the target data. Input values and results are presented in table 4.1.4 and figure 4.1.5 below.

Table 4.1.4: Data Input 2-Tank High Flow					
Data	**Value**	**Unit**	**Data**	**Value**	**Unit**
Low Flowrate	0	l/min	Decrease Flow Start	2030	s
High Flowrate	3700	l/min	Increase Flow Start	2435	s
Co Shaker	6.55		Flow Ramping Time	180	s
Shaker Drain Area	$1.5 \cdot 10^{-3}$	m^2	Delay Through Shaker	10	s
Shaker Area	4	m^2	Shaker Base Volume	20	m^3
Active Base Volume	96	m^3	Shaker Max Volume	45	m^3

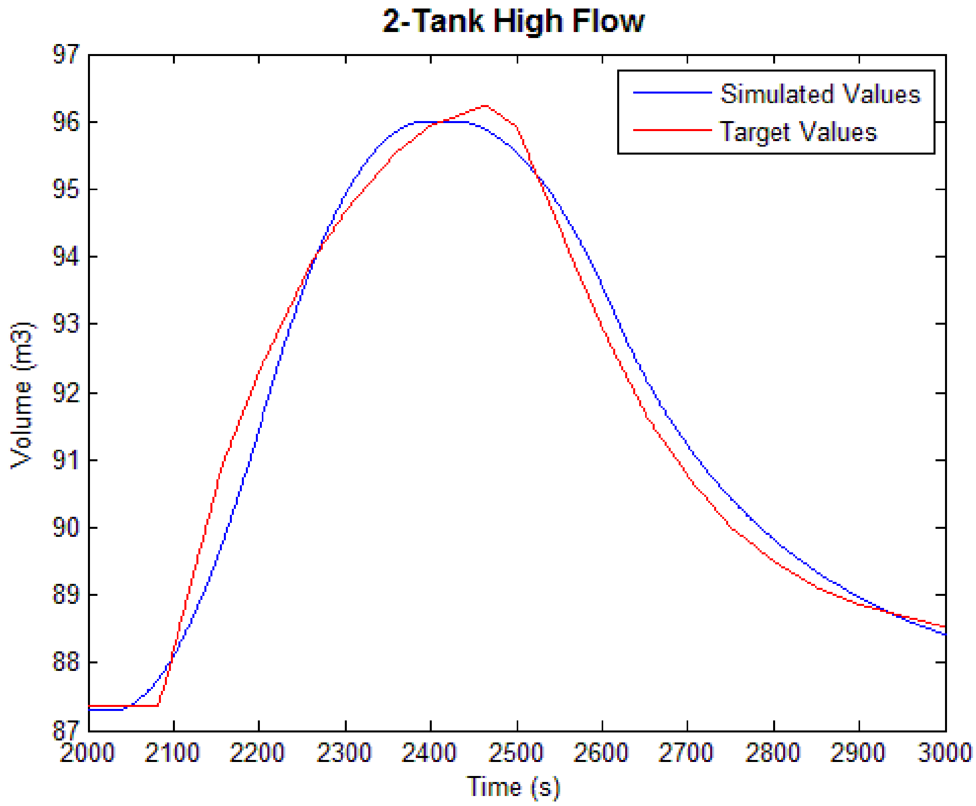

Figure 4.1.5: Comparison of target values and the results of the tuned 2-tank model with correct flowback volume. The initial flowrate is 3700 l/min.

By using the 2-tank model, it's possible to generate curves that seem to fit better than the 3-tank model, although it is still not a perfect fit. The fit for flowback is not as good as for the more complex model, but the results for filling up the pipes appear closer. One drawback is that achieving this involves using very long ramping times, up to 180 seconds/3 minutes.

The simpler model was also applied to the low-flow case, the input data and results of this are presented in table 4.1.5 and figure 4.1.6 below.

Table 4.1.5: Data Input 2-Tank Low Flow					
Data	**Value**	**Unit**	**Data**	**Value**	**Unit**
Low Flowrate	0	l/min	Decrease Flow Start	2040	s
High Flowrate	1700	l/min	Increase Flow Start	2330	s
Co Shaker	6.57		Flow Ramping Time	200	s
Shaker Drain Area	$1.5 \cdot 10^{-3}$	m^2	Delay Through Shaker	10	s
Shaker Area	5	m^2	Shaker Base Volume	20	m^3
Active Base Volume	90.2	m^3	Shaker Max Volume	45	m^3

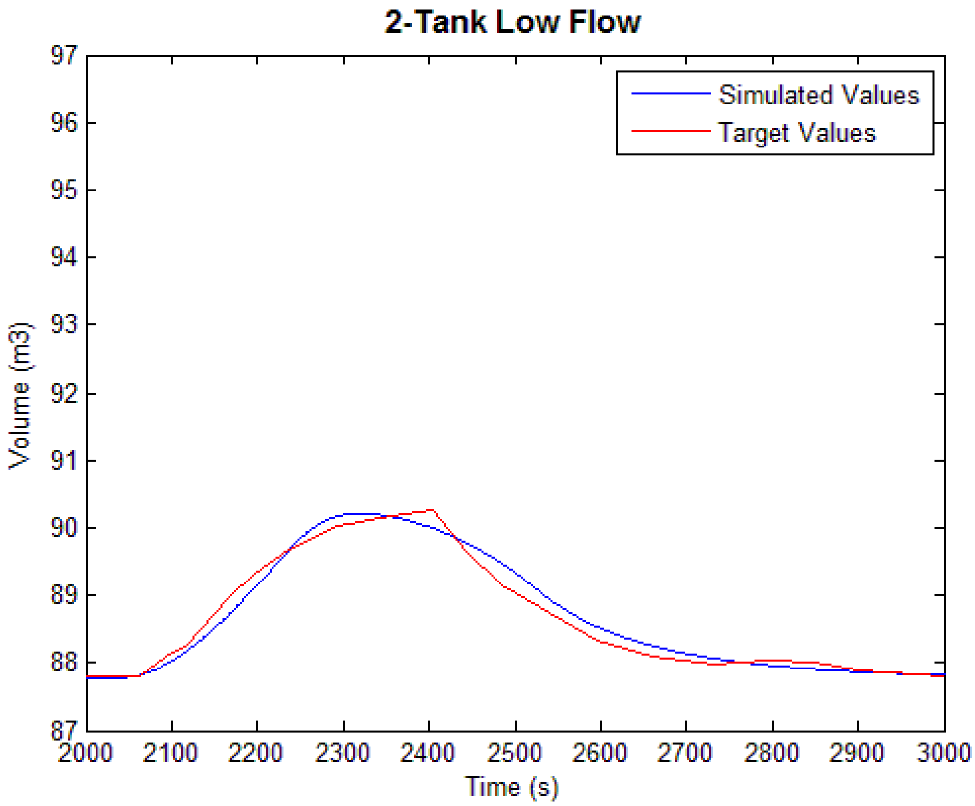

Figure 4.1.6: Comparison of target values and the results of the tuned 2-tank model with low flowrate (1700 l/min) and correct flowback volume.

In this case the results of the simulation were a lot better for the simple (2-tank model) than for the more complex (3-tank model). The curve fit is fairly good both for the flowback and the filling up of the pipes. Note that also in this case, the simulated results level of at their maximum level, while the target values appear not to.

In general, the results of the initial simulations show similarities between the simulations and the target values, although extensive tuning is required in order to get a good fit in the different scenarios. The simpler model appears to give better overall results than the more complex model.

4.1.2 - Run 2: Active Pit Volumes with Influx during Steady Conditions

During this run, a simulated influx was set to start at time 2200. The influx is simulated by adding a flow of 3 m^3/hr extra into the shakers. The response in the active volume is shown together with the active volume results for high flow from Run 1 for comparison. Input data and simulation results are presented in table 4.1.6 and figure 4.1.7 below.

Table 4.1.6: Data Input High Flow With Influx During Steady Conditions					
Data	**Value**	**Unit**	**Data**	**Value**	**Unit**
Low Flowrate	0	l/min	Decrease Flow Start	2030	s
High Flowrate	3700	l/min	Increase Flow Start	2435	s
Co Shaker	6.55		Flow Ramping Time	180	s
Shaker Drain Area	$1.5 \cdot 10^{-3}$	m^2	Delay Through Shaker	10	s
Shaker Area	4	m^2	Shaker Base Volume	20	m^3
Active Base Volume	96	m^3	Shaker Max Volume	45	m^3
Influx Start Time	1600	s	Influx Rate	3	m^3/hr

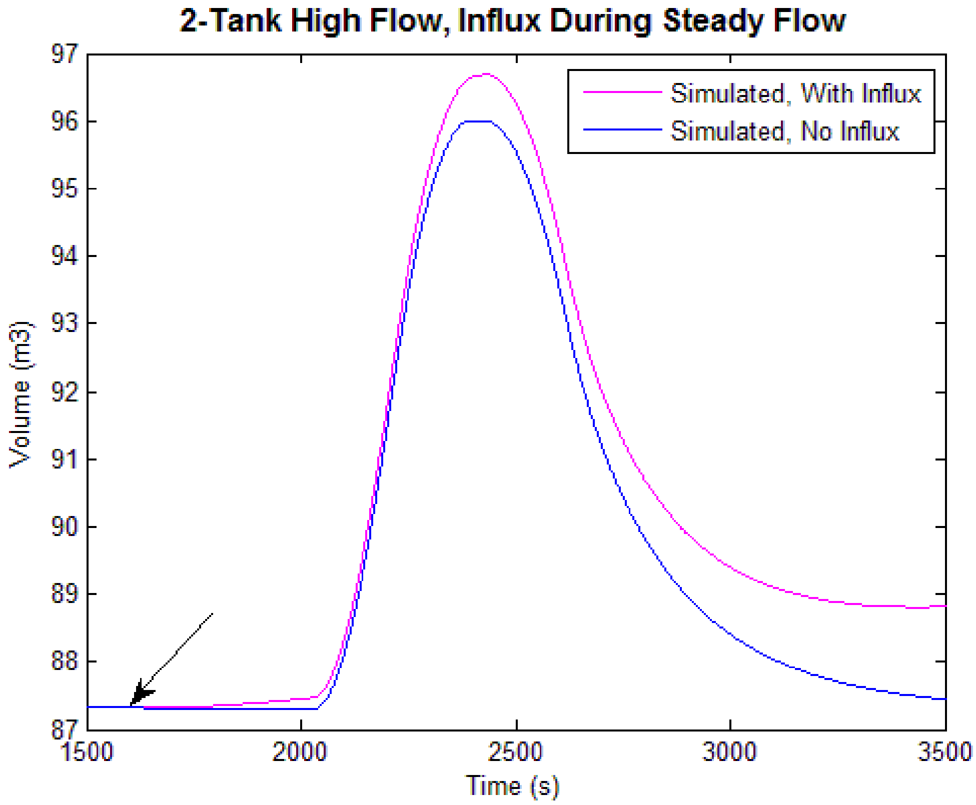

Figure 4.1.7: Comparison of simulation results of an influx scenario and a no influx scenario. The influx of 3 m3/hr starts during the steady period at time 1600 s. The arrow indicates the start of the influx.

At time 3500, the difference in the active volume is approx 1.45 m3. We see that it takes between 100 and 200 seconds from the additional flow starts flowing into the shaker before the volume difference is visible in the active pit. We also see that the gradient of increase and decrease in the active pit is more or less similar during large parts of the connection, making it harder to spot the influx if looking only at this interval. Keep in mind that rig crew might only be looking at the flowback with influx, without the no-influx flowback for direct comparison.

4.1.3 - Run 3: Active Pit Volumes with Influx during Transient Conditions

This run is similar to the previous run, except the influx is now set to appear during a transient period (i.e. while making a connection). The results are presented together with the results from Run 1 for comparison. Input data and results are presented in table 4.1.7 and figure 4.1.8 below.

Table 4.1.7: Data Input High Flow With Influx During Transient Conditions					
Data	**Value**	**Unit**	**Data**	**Value**	**Unit**
Low Flowrate	0	l/min	Decrease Flow Start	2030	s
High Flowrate	3700	l/min	Increase Flow Start	2435	s
Co Shaker	6.55		Flow Ramping Time	180	s
Shaker Drain Area	$1.5 \cdot 10^{-3}$	m^2	Delay Through Shaker	10	s
Shaker Area	4	m^2	Shaker Base Volume	20	m^3
Active Base Volume	96	m^3	Shaker Max Volume	45	m^3
Influx Start Time	2200	s	Influx Rate	3	m^3/hr

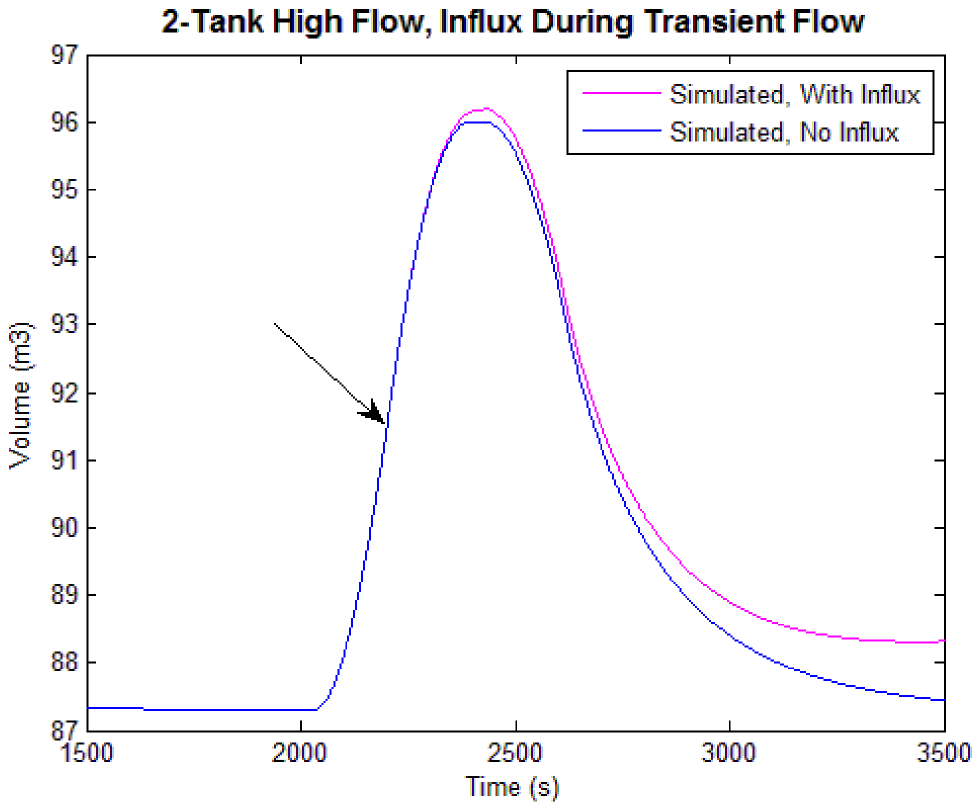

Figure 4.1.8: Comparison of simulation results of an influx scenario and a no influx scenario. The influx of 3 m3/hr starts during the transient period at time 2200 s. The start of the influx is indicated by an arrow in the figure.

Volume difference at simulation time 3500 is 0.95 m3. In this case we also see that it takes some time before the active pit shows a visual response to the increased flowrate. The volume difference is not visible at this scale before the volume increase starts leveling off in the no-influx case.

4.1.4 - Including Adaptive Observer Technology

Although, the simulation results in general show the tendency to recreate the actual volumes, a perfect fit was not achieved by manual tuning. A natural next step was therefore to include learning abilities in the form of adaptive observer technology, so that the model could tune itself to real data. Because of the limited amount of data given in the McCann paper (basically only the volume per time and the flowrate used initially), quite a few assumptions would have to be made in order to apply the adaptive observer technology to this dataset.

Initial tests were made, with assumptions being made on when the pumps where turned off and on, and how long time was spent on ramping between the flowrates, but this mostly resulted in illogical results. Instead, a more complete dataset from a rig in the North Sea was used. The results of this are presented as Case 2.

4.2 - Case 2 – A North Sea Dataset

This dataset was provided by an operator in the North Sea. The data has been made anonymous, so there is no information about which operator, rig or field it belongs to. This is however not important at this stage in the process.

The dataset includes three parameters: active volume (in m^3), pump rate (in m^3/min) and flow out from a paddle sensor (in %). The data points are at 1 second intervals spanning close to 28 hours (10^4 data points). The raw sensor data included some noise, especially the data from the paddle flow out sensor. Because of this, all the data was run through a low-pass filter prior to any calculations being made. Plots of the dataset are presented in figure 4.2.1 below.

In the plots, a slightly decreasing trend in the active volume can be seen, indicating new hole being drilled and cuttings being lost over the shakers. Some of the decrease in volume may also be related to losses to the formation. This could be determined by comparing with ROP data and calculating the volume of new hole drilled.

Several instances where pits are added to or removed from the active system are also shown, indicated by large, instantaneous changes in the active volume. Some smaller changes in the active volume can also be found, showing that the rig circulation system is indeed a dynamic system. This will of course affect the simulations to some degree.

The zoomed data show the active response to changing the pumprate during one of the connections. The low flowrate seen during the connection could be the drilling crew performing an SCR.

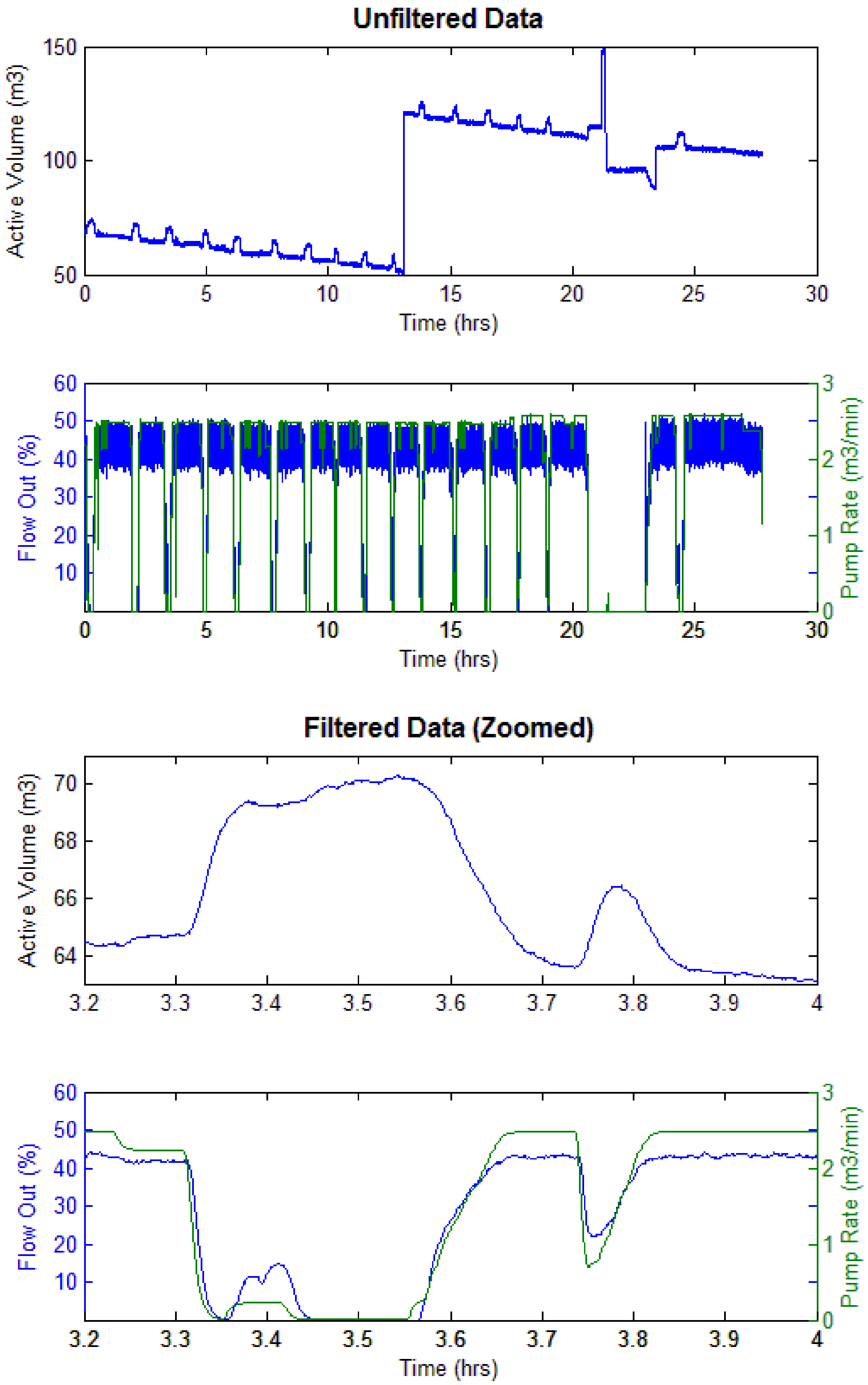

Figure 4.2.1: Plots of the dataset from the North Sea. The two top plots show the unfiltered data, and the two bottom plots show a zoomed connection after the data has been run through a low-pass filter. The filtering has especially made an impact on the paddle flow data, but to some degree also on the active volume. The active volume is in m^3, pump rate in m^3/min and flow out in %.

The simulations were done with a rewritten program, as some structural changes were needed in order to incorporate the use of an adaptive observer as well as filters. The basic concept is still the same as the previous 2-tank model, where the well and shakers are considered as one tank, and the active pit as the other. The flow out of the well is calculated based on pit volume and pump rate, data from the paddle sensor is not used in the following simulations.

4.2.1 – Run 1: Running the Model with No Influx

The first simulation run was performed without influx in order to show how the model works under normal circumstances. During the first period, the estimator is learning the behavior of the system by applying an adaptive observer. After a certain amount of time, the estimator set to run with the input found during the learning period. Figure 4.2.2 below shows the cumulative volumes in a no-influx case along with the estimator volumes for the same case.

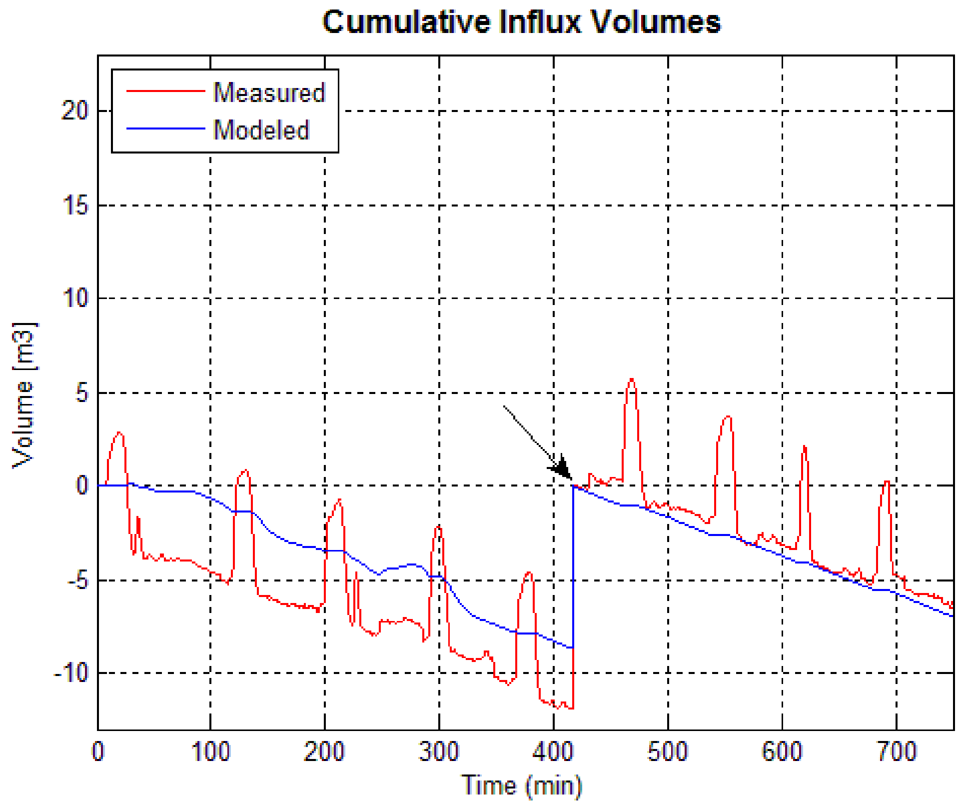

Figure 4.2.2: The red curve shows the measured cumulative influx volume, while the influx volume from the estimator is shown as blue. The measured volume shows the decreasing trend in volume as new hole is drilled, as well as the connections. Simulation starts after 8 minutes.

The estimator is in learning mode up to 333 minutes, after this point the input values for the estimator are fixed. The volumes are reset after 417 minutes, as indicated by the arrow. The estimator removes the effect of the connection flowbacks, while the cumulative decrease over time is similar (with this specific estimator input). The dynamics of pumps on/pumps off are incorporated in the model, the drilling of new hole is not.

The program will choose the data point when the learning period is stopped for the continued calculations. Because of this, the results are somewhat dependent on when the learning period is stopped. A better approach could be to use a weighted or filtered average.

As the model rarely will give a perfect fit, the cumulative difference between the measurements and the model will grow larger and larger over long time periods. In order to avoid frequent resetting of the model, a high pass filter is applied, where only the last 3600 data points (1 hr) are considered. This is a long enough time period that a change in trend will be visible, while still keeping smaller errors in the model from dominating too much. Plots of the high-pass filtered volumes are shown in figure 4.2.3 below.

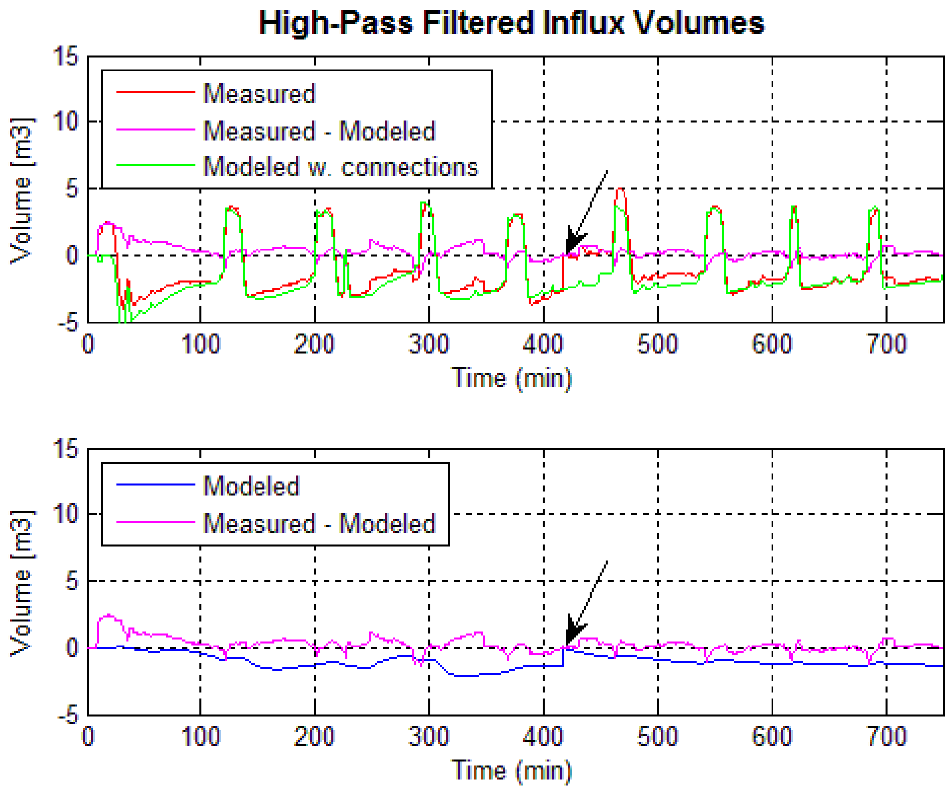

Figure 4.2.3: High-pass filtered volumes. The top plot shows the measured volume, the modelled volume and the difference between the measured and modelled volume with connection dynamics removed. The modelled volume with connections is also shown for comparison with the measured data. The bottom plot also shows the modelled volume with connections removed.

The long-term decreasing trend in volume is removed by the high-pass filter, as only the last 3600 data points are considered. We see that after the model input is fixed and the volumes reset, the difference between the measured and modelled volumes is steady, although with some variations during the connections. The arrows indicate that the volume calculations are reset.

Table 4.2.1: Data Input Adaptive Observer Model					
Data	**Value**	**Unit**	**Data**	**Value**	**Unit**
Start Learning	500	s	RC Low Pass	15	
Stop Learning	20000	s	RC High Pass	3600	
Reset Volumes	25000	s	Gamma 1	0.8	

Basic inputs for the adaptive observer program are presented in table 4.2.1 above. A printout of the program code is included as an attachment.

4.2.2 – Run 2: Influx during Steady Conditions

The next simulation run was performed in order to show the response to a kick during steady condition. The kick is set at a rate of 100 l/min and starts after 30000 seconds (333 minutes). Figure 4.2.4 shows the cumulative volume response to this influx, where the change is quickly seen in the measured volume, while the estimator is unaffected. Monitoring of the active volume by setting linear alarms would quickly pick up this change, provided that the alarms had been reset properly after the connection.

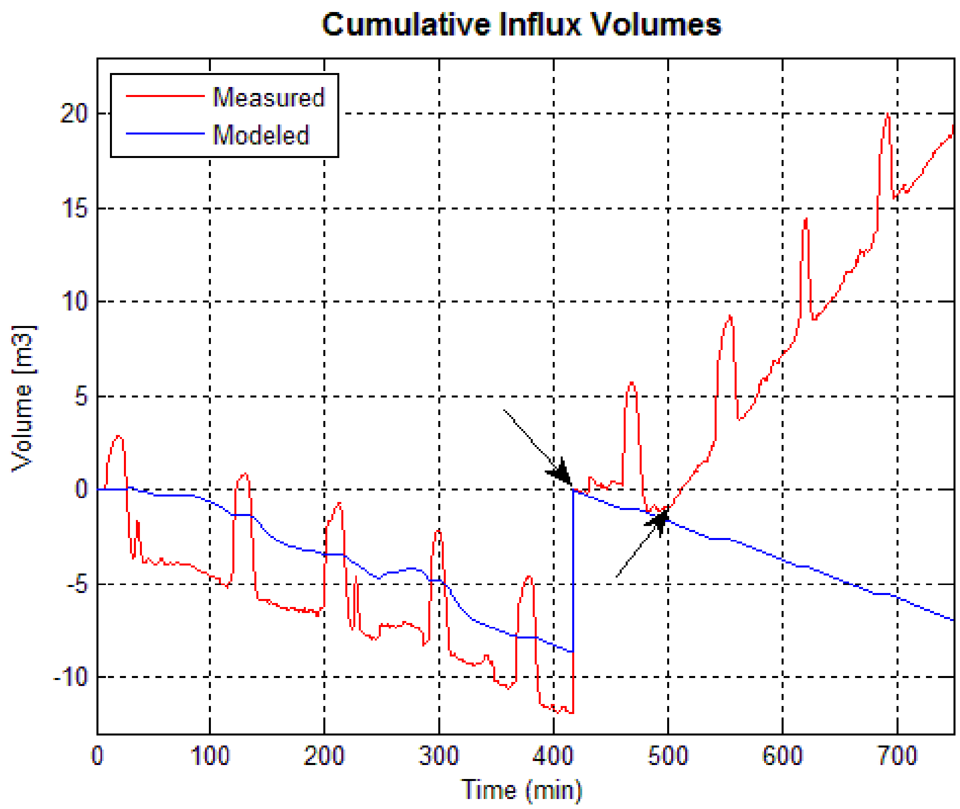

Figure 4.2.4: Measured and estimated cumulative volumes with an influx of 100 l/min taken after 500 minutes, as indicated by the upwards pointing arrow. As in the no influx case, the estimator is in learning mode until 333 minutes, and the volumes are reset after 417 minutes. This is indicated by the downwards pointing arrow. The influx is visible in the measured volume shortly after it starts. The estimator is calculating based on pump rate and is unaffected by the influx.

Plots of the filtered volumes are shown in figure 4.2.5 below. The increase in volume is visible shortly after the influx started, and we can also see that the difference between the measured and modeled volumes no longer continues steadily, but that we have separation between the curves. Setting a linear alarm on this parameter instead of the volume itself would spot the kick in the same way as an alarm on the measured volume, but without the drawback of having to reset the alarm during every connection.

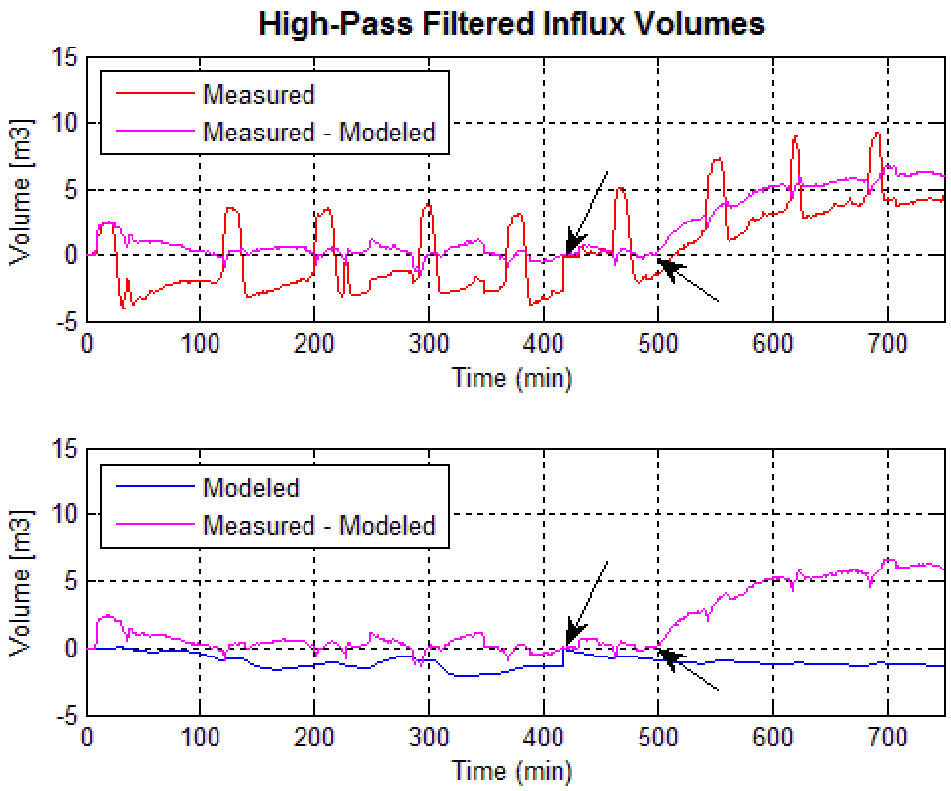

Figure 4.2.5: Plots of the high-pass filtered volumes. The influx is visible shortly after it is initiated. We see that the measured (red) and model difference (magenta) plots follow the same trend, except for the connections. We also see that the model difference curve quickly separates from the blue curve showing the estimated volume. The downward pointing arrows indicate that the volume calculations are reset, the upward pointing arrows indicate the start of the influx.

4.2.3 – Run 3: Influx during Transient Conditions

The third simulation run was done to show the response to taking a kick during transient conditions, i.e. during a connection. The influx is set to start at 27650 seconds (461 minutes), just as the connection flowback is starting. This could as an example be related to swabbing when pulling off bottom to perform the connection. As in the previous simulation run, the rate of the influx is 100 l/min.

The response in the cumulative volumes is shown in figure 4.2.6 below. As in the previous run, the estimator is unaffected by the influx. The measured volume does show an increase, but by watching the trends alone, this is not clearly visible until the connection is visible and the pumps are started up again. A direct comparison of the flowback volumes from previous connections could possibly have revealed something going on, but as can be seen from the plots, the connection flowbacks are not similar at every connection

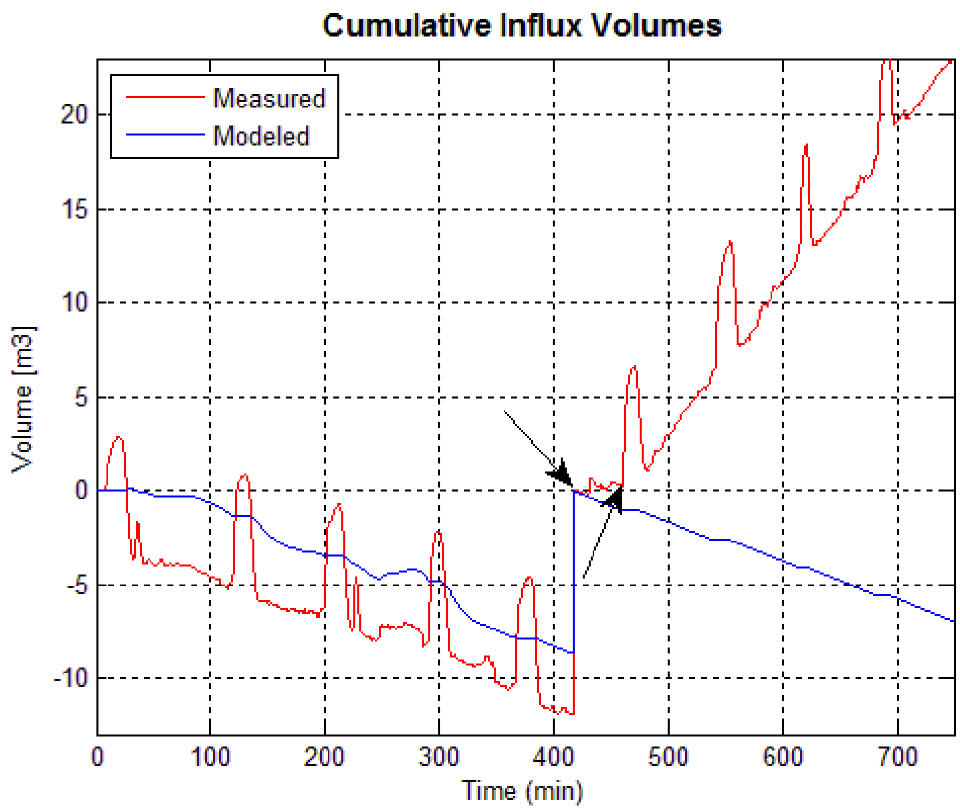

Figure 4.2.6: Cumulative volume response to taking a kick while performing a connection at approximately 461 minutes. The connection flowback looks similar to previous flowbacks, and by looking at volume trends alone, the influx could in a worst case scenario not have been spotted until steady circulation is re-established, half an hour after the kick was initiated. The downwards pointing arrow indicates the volume calculations being reset; the upwards pointing arrow indicates the start of the influx.

Looking at the high-pass filtered volumes in figure 4.2.7 we see that the influx is visible shortly after it is initiated, as the model difference trend starts separating from the model. This would make it possible to easily spot and confirm the kick during the connection, several minutes earlier than what can easily be seen by watching the volume alone.

A zoomed view of the results compared with the cumulative measured volume is shown in figure 4.2.8. The time difference between when the kicks are spotted may be as large as 15 minutes. For comparison, the measured volume from the same connection without the influx is included. We can see that the volume curve behaves quite similar, and while the difference is visible when comparing directly, the rig crew will be comparing to different connection flowbacks, that may not have the same shape after all.

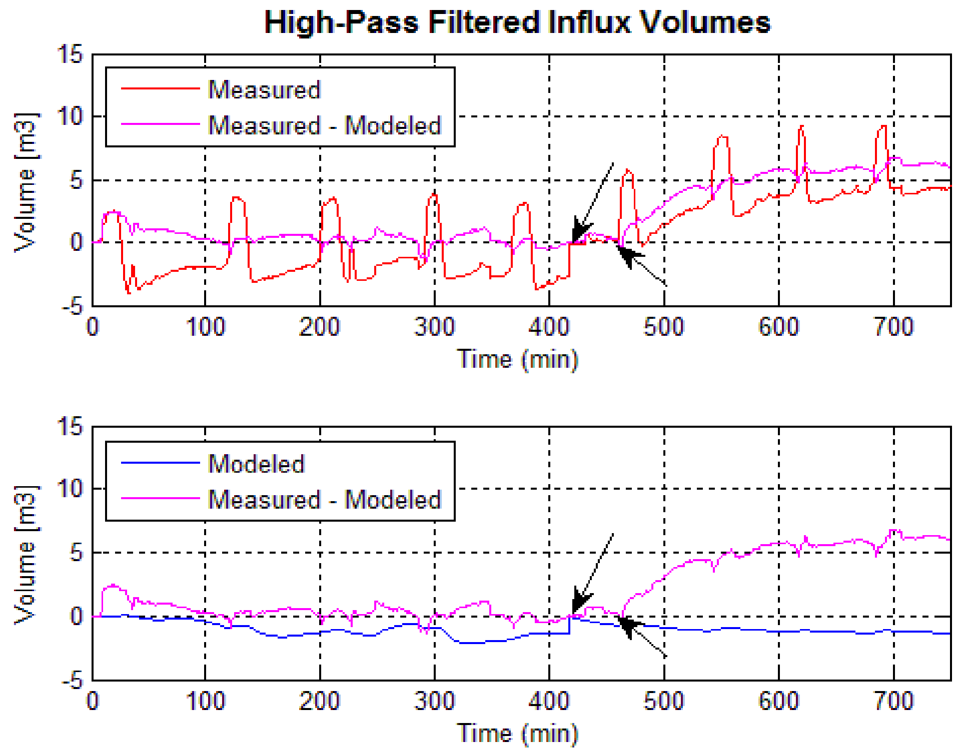

Figure 4.2.7: This plot of the filtered volumes shows that the model difference trend (magenta) starts separating from the estimated volume (blue) shortly after the kick is initiated. This makes it possible to spot the kick during the connection a lot easier than by watching the volume alone. As earlier, the upwards pointing arrow indicate the volumes being reset, the downwards pointing arrow indicate the start of the influx.

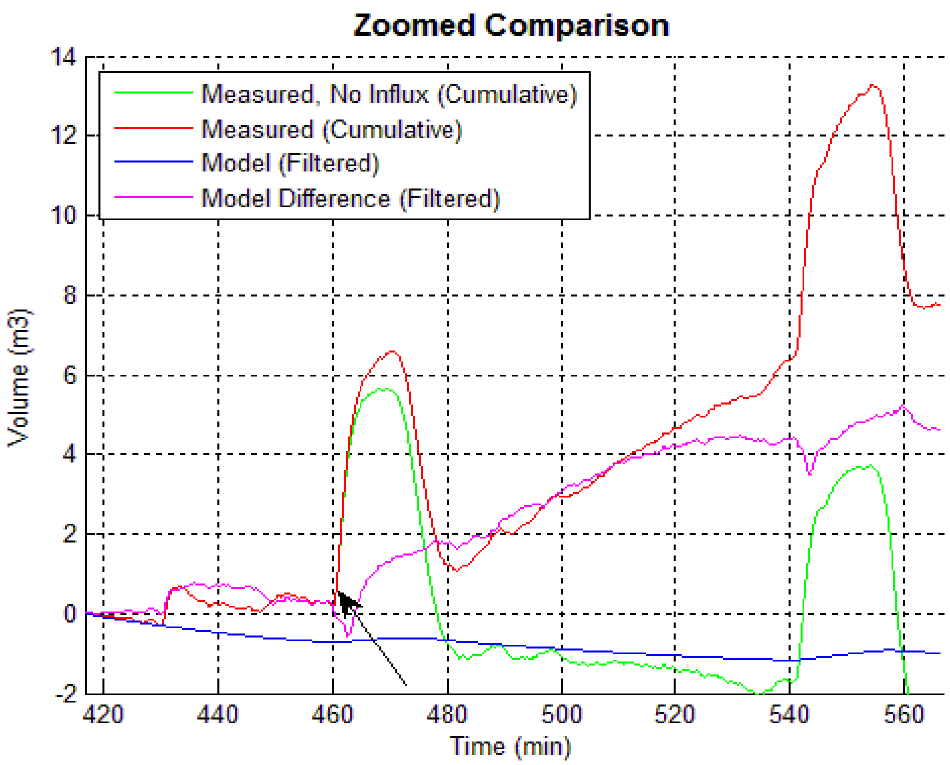

Figure 4.2.8: From this zoomed comparison of the volumes we see that the model difference curve (magenta) quickly reaches a larger separation than has been seen previously, while increasing trend in the measured volume is not clearly visible until after steady-state circulation is re-established. The green plot shows how the connection would have looked without an influx, and is what the driller would be comparing to (although possibly only by memory) if looking at the volume alone.

5 - Simulations Summary

Initial simulations showed that using the proposed drainage equation allowed for reproduction of volume curves similar to the real volume data presented in the McCann, White et al. paper. Manual tuning of the inputs made it possible to achieve quite close results, however exactly similar results were not achieved. Some error could possibly be explained by lack of information about the given data (such as how fast the pumps were ramped up and down). A large part of it is probably related to the model itself, to be able to describe all the complexity of a rigs circulation system by the use of just one drainage equation is perhaps a little much to ask for.

Simulations were also run to demonstrate the effect of an influx on the active flowback. The results showed that even when comparing directly to an exactly similar flowback curve an influx can be hard to spot before some time has passed, especially if the influx is taken during a transient period. Also if the influx is taken just prior to the connection and not spotted before the pumps are shut off, the shape and size of the flowback curve may not be changed more than what may be considered normal variations. Real well data shows that no two connections are exactly alike.

Being able to achieve OK results for a single connection flowback doesn't provide much more than a starting point. In order for the method to have value, it will have to be able to predict the volume behavior over longer time periods, and be able to adapt to changes to the system.

Simulation runs based on well data from the North Sea demonstrated that the program was able to adapt to the given information by the use of adaptive observer technology. Noise from the sensor data itself as well as noise that was magnified through the calculations were treated with low-pass filters. In order to avoid accumulating large errors over long time periods, high-pass filters were employed, so that only data from the last hour were considered in the model.

Results showed that an influx taken during a period of steady state, i.e. when circulating at a constant pump rate, the influx can be spotted just as easily by use of the demonstrated method as by traditional observation of the active volume. In addition, a benefit of this method is that monitoring the deviation between the model and the measurements allows for fewer adjustments of alarms than if watching only the measurements, because the effects of connection flowbacks were removed by the model.

An important finding that was demonstrated was that monitoring the deviation between the model and the measurements allows for earlier detection of the influx than monitoring of the volume itself, as the trend change is visible at an earlier point in time. Earlier detection is a key factor in reducing the risks connected to having a reservoir influx situation.

6 – Conclusions

Influx of fluid from the reservoir may have large consequences during drilling operations. An important factor in limiting the severity of such a situation is spotting the influx as quickly as possible. By watching volume and flow alone, reservoir influx can be spotted during periods of steady flow, but can be a lot harder to spot during transient periods such as a connection. This may result in larger kicks and larger consequences from taking the kicks.

This thesis presents a method for predicting active volume behavior as a function of the pump rate. Being able to predict volume changes during transient periods such as pump rate changes during a connection makes it possible to detect wellbore anomalies such as a reservoir influx also during these periods.

Simulation results show that a model of the drilling rigs circulation system can be developed even with simple techniques and programming tools. The presented programming scripts are able to reproduce real active volume data from the literature as well as from a drilling rig in the North Sea. Having an accurate model for the active volume provides the possibility of detecting reservoir influx by comparing the prediction to the actual data being measured.

Kick detection is an essential part of the drilling operation. If field tests of the presented method are performed and show an increased ability to detect reservoir influx, the method should be implemented both into today's monitoring of the well, but also into a possible future automated drilling setup.

The main benefit of the method as demonstrated in the simulations is the ability to detect influx during transient periods at an earlier stage. The trends observed when looking only at a limited amount of data provide the earliest indication, and the main benefit of the method is on a short time scale (30-min to 1 hour). On a longer time scale (such as 24 hours), losses and gains can be just as easily observed by observation of the volume itself. An important benefit is also that the method does not need any additional input data compared to what is already being monitored on a rig. The only difference is the real-time calculations being performed on the data.

Although the main focus of this thesis has been on conventional drilling, some considerations have also been made concerning automated kick detection in managed pressure drilling and dual gradient drilling.

In MPD, the Micro-Flux Control system works well even in dynamic conditions (such as on a semi-submersible rig), and is able to detect small kicks. Continuous monitoring of pressure and flow allows for real-time detection, and employs equipment already in use in a MPD setting.

For dual gradient drilling, monitoring of the subsea mud lift pump rate has been found effective for kick detection. As with MFC for MPD, it is based on equipment already in use. It is somewhat limited by the u-tube effect, however this could be counteracted by the use of non-return valves in the drillstring.

A more developed version of the kick detection method for conventional drilling presented in this paper also has the potential to be employed in MPD and DG settings. The fact that volumes going in and out of the well should be the same is independent of the drilling technology, and as long as the circulation system can be described to provide correct expected volume changes, any variation from these is an indication of changes downhole. The hardware and data input needed is already in place, the challenge is developing a model than incorporates the dynamics of the circulation system.

7 - Proposals for Further Work

Although the model and simulations have been tested on real data and show positive results, further testing is definitively needed. Testing with data from different rigs will also be beneficial, as it will not only test and show the capabilities of model itself, but also of the adaptive observer technology.

Rewriting the model to run continuously parallel to a real-time environment will be a natural next step. If alarm capability is incorporated, the model could be compared to playback of real drilling data, and within a longer timeframe also tested during drilling operations on a rig.

Although initial results indicated better curve fits with the simplified model, a more complex model than presented here will probably be needed. As mentioned earlier, there are a lot of factors that influence the measured volumes and flow, many of which are the result of human interaction. In order to create a system that works as seamlessly as possible, these effects will either have to be included in such a way that the system spots and understands them, or it should be simple to input the expected changes to the system (i.e. adding 500 liters of chemicals to the active pit.)

A fully developed version of this model would prove beneficial to the industry as a whole. Given high quality data and proper tuning, it has the power to detect reservoir influx quickly and at small scales. It would also be a very important part in the process of developing fully automated drilling systems. As mentioned, one of the main benefits is that the system doesn't rely on any other data than what is already being monitored on the rig, something that will make it easier to implement on a large scale throughout the industry if such a decision is made.

Automated systems will, if made properly, improve safety by reducing the dependency on human judgment and response. An automated system doesn't have a bad day at work or get tired from working nightshifts, and doesn't get distracted by phone calls or reporting duties. Such a system will improve safety, and be a benefit to rig crew safety and the safety of the environment, as well as economically. Reduced cost and increased accuracy might make it possible to develop low-margin prospects that might have been disregarded without this technology.

It is however important to remember that even automated systems will have their flaws, mostly related to the programming setup and how the logics work. If a long term goal is to make kick detection fully automated, such a system would have to be tested and tested again for every imaginable and unimaginable scenario that may occur. Increased detail in the model will improve accuracy, but at the same time increase the possibility of errors.

It's interesting to observe that even when similar approaches were proposed 20 years ago, they seem not to have caught on in the industry. The challenges in developing fully automated drilling systems will not only be related to the technology itself, but also to convince it's users and the industry as a whole that such a development is worth pursuing. Although many new developments have been made in all the fields of the industry, there still seems to be a certain resistance towards change, especially when what is being used today is considered "good enough". However, with the reserves decreasing and the drilling challenges increasing in difficulty as every year goes by, a time will come where today's technology is no longer "good enough". The companies that have planned ahead, and are prepared for the challenges ahead will no doubt benefit from the preparations made. Or, to put it in the words of Roald Amundsen:

Victory awaits him who has everything in order — luck, people call it.

8 - References

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9 - List of Figures and Tables

Figures

Tables

10 – List of Attachments

1. Printout of the 2-tank model (4 pages)
2. Printout of the 3-tank model (4 pages)
3. Printout of adaptive observer program (7 pages)
4. Printout of low pass filter (2 pages)

```
%% 2 TANK MODEL PROGRAM

%% INPUT

% The different circulation rates in [l/min]. Because the input volumes are 0, it is
% recommended to have rate1liter = 0. In order to get the same cumulative volume
% through all parts of the system, it is recommended to have the last rate = 0 as well.

rate1liter = 0;
rate2liter = 3700;
rate3liter = 0;
rate4liter = 3700;
rate5liter = 0;

tstop = 5000;     % Length of the simulation in [s]
tchange1 = 150;   % At which time the changes between the rates will take place [s]
tchange2 = 2030;
tchange3 = 2435;
tchange4 = 4000;
ttochange = 180;  % The time it will take to ramp from one flowrate to the next [s]
shakerdelay = 10;
% The time it takes from the fluid flows out of the shaker to it enters the active. [s]
pipedelay = 1;
% Changing this will increase the volume difference in the active when circulating

influxstatus = 1;
% Whether to start influx or not. 1 = [ on ], anything else = [ off ]
influxrate = 3;
% Rate of influx (from well) in m3/hr. Will be added as increased flow into shaker
influxtime = 2200;   % Time of influx start

shakerlossstatus = 0;
% If there are losses at shakers. 1 = [ on ], everything else = [ off ]
shakerlossrate = 0.5; % [m3/hr]
% Rate of loss at the shakers. Will be removed as lost flow from shaker to active.
% These losses will only appear when there is flow out from the shaker.

Coshaker =6.55;
G = 9.81;    % Acceleration of gravity [m/s2]

shakerdrain = 0.0015;     % Drain area in the shaker tank [m2]
shakermaxvolume = 45;     % Maximum total volume in the shaker tank [m3]
shakerbasevolume = 20;    % Volume in the shaker tank when the head is zero [m3]
shakerarea = 4;           % Area of the shaker tank [m2]
activebasevolume = 96;    % Base volume in the active

t = 1;

%% CALCULATIONS
rate1 = rate1liter/60000;  % Conversion of the flowrates from [l/min] to [m3/s]
rate2 = rate2liter/60000;
rate3 = rate3liter/60000;
rate4 = rate4liter/60000;
rate5 = rate5liter/60000;
```

```
shakerlosses = shakerlossrate/3600;  % Convert losses from m3/hr to m3/s
influx = influxrate/3600;

%% GENERATE MATRIX FOR DATA STORAGE
pumpcumulativevolume = 0;   % Sets initial values and populates the first
                            % line in the matrixes used
                            % in the calculation loop.
shakercumulativevolume = 0;
activecumulativevolume = 0;
pipevolume = 0;
shakerflowin = 0;
shaker = [shakerflowin,shakerbasevolume,0,0,0];
active = [0,0,activebasevolume,0,0];

%% THE LOOP
while t<tstop
    tcount = t+1;      % Increase time counter, to create new line in matrixes
    time = tcount;     % Input for time coloumns
                       % This section determines the flow out of the active
                       % (the pumprate). The limits are based on the input times
                       % for changes as well as the input time used to change from
                       % one flowrate to another. The ramping up or down between
                       % two flowrates is asssumed linear, distributed evenly over
                       % the specified ramping time
    if tcount < tchange1
        pumpflow = rate1;
    elseif tcount < tchange1 + ttochange
        pumpflow = rate1 + ((rate2-rate1)/ttochange)*(tcount-tchange1);
    elseif tcount < tchange2
        pumpflow = rate2;
    elseif tcount < tchange2 + ttochange
        pumpflow = rate2 + ((rate3-rate2)/ttochange)*(tcount-tchange2);
    elseif tcount < tchange3
        pumpflow = rate3;
    elseif tcount < tchange3 + ttochange
        pumpflow = rate3 + ((rate4-rate3)/ttochange)*(tcount-tchange3);
    elseif tcount < tchange4
        pumpflow = rate4;
    elseif tcount < tchange4 + ttochange
        pumpflow = rate4 + ((rate5-rate4)/ttochange)*(tcount-tchange4);
    else
        pumpflow = rate5;
    end


      if tcount < tchange1
        shakerflowin = 0;
        else
        shakerflowin = active(tcount-pipedelay,2);
      end

      if influxstatus == 1
        if tcount > influxtime
            shakerflowin = shakerflowin + influx;
        end
```

```
        end

    shakervolume = shaker(tcount-1,2);
    shakerpotentialflowout = Coshaker*shakerdrain*sqrt(2*G*((shakervolume-↙
shakerbasevolume)/shakerarea));
    shakervolumechange = shakerflowin - shakerpotentialflowout;
    shakerpotentialvolume = shakervolume - shakerpotentialflowout + shakervolumechange;
    if shakerpotentialvolume > shakermaxvolume
        shakeroverflow = shakerpotentialvolume - shakermaxvolume;
    else
        shakeroverflow = 0;
    end
    shakervolume = shakervolume + shakervolumechange - shakeroverflow;
    if shakervolume < shakerbasevolume
        shakervolume = shakerbasevolume;
    end
    shakerflowout = shakerpotentialflowout + shakeroverflow;

    if shakerlossstatus == 1
        if shakerflowout > shakerlosses
                 shakerflowout = shakerflowout - shakerlosses;
        end
    end

    if tcount < tchange1
        activeflowin = 0;
    else
        activeflowin = shaker(tcount-shakerdelay,3);
    end
    activevolumechange = activeflowin - pumpflow;
    activevolume = active(tcount-1,3) + activevolumechange;


    pumpcumulativevolume = pumpcumulativevolume + pumpflow;
    shakercumulativevolume = shakercumulativevolume + shakerflowout;
    activecumulativevolume = activecumulativevolume + activeflowin;

    active(tcount,1) = time;
    active(tcount,2) = pumpflow;
    shaker(tcount,1) = shakerflowin;
    shaker(tcount,2) = shakervolume;
    shaker(tcount,3) = shakerflowout;
    active(tcount,3) = activevolume;
    active(tcount,4) = activeflowin;
    t = tcount;
end

%% PLOTTING
% figure(1);
% plot(active(:,1),active(:,2),'r');
% hold on;

% plot(active(:,1),shaker(:,3),'b');
% plot(active(:,1),active(:,4),'g');
% xlabel('Time (s)')
```

```
% ylabel('Flowrate (m3/s)')
% figure(2);

% hold on;
% plot(active(:,1),shaker(:,2),'b');
% plot(active(:,1),active(:,3),'r');
% plot(active(:,1),active(:,3)+shaker(:,2),'g');
% xlabel('Time (s)')
% ylabel('Volume (m3)')
% axis([1000 2000 60.5 70.5])

figure(3);
hold on;
plot(active(:,1),active(:,3),'m');
plot(savedactivehigh(:,1),savedactivehigh(:,2),'b')

xlabel('Time (s)')
ylabel('Volume (m3)')
legend('Simulated, With Influx','Simulated, No Influx')
axis([1500 3500 87 97]);
title('2-Tank High Flow, Influx During Transient Flow','fontweight','b','fontsize',12)
annotation(figure(3),'arrow',[0.30 0.4],[0.60 0.48]);
box on
% grid on;
% subplot(2,1,2)
% plotyy(Array(:,1),Array(:,3)-10,Array(:,1),Array(:,11))
% ax = plotyy(Array(:,1),Array(:,3)-10,Array(:,1),Array(:,11));
% axes(ax(1)); axis([0 15000 0 60])
% axes(ax(2)); axis([0 15000 0 3.5])
% legend([ax(1);ax(2)],'Paddle Flow','Pump Rate');
```

```
%% 3 TANK MODEL

%% INPUT

% The different circulation rates in [l/min]. Because the input volumes are 0, it is
% recommended to have rate1liter = 0. In order to get the same cumulative volume
% through all parts of the system, it is recommended to have the last rate = 0 as well.
rate1liter = 0;
rate2liter = 3700;
rate3liter = 0;
rate4liter = 3700;
rate5liter = 0;

tstop = 5000;     % Length of the simulation in [s]
tchange1 = 150;   % At which time the changes between the rates will take place [s]
tchange2 = 1040;
tchange3 = 1430;
tchange4 = 3000;
ttochange = 120;  % The time it will take to ramp from one flowrate to the next [s]
% The time it takes from the fluid flows out of the shaker to it enters the active. [s]
shakerdelay = 35;
pipedelay = 20;
% Changing this will increase the volume difference in the active when circulating.

influxstatus = 0; % Whether to start influx or not. 1 = [ on ], anything else = [ off ]
% Rate of influx (from well) in m3/hr. Will be added as increased flow into shaker
influxrate = 1;
influxtime = 920; % Time of influx start

% If there are losses at shakers. 1 = [ on ], everything else = [ off ]
shakerlossstatus = 0;
shakerlossrate = 0.5;  % Rate of loss at the shakers.
             % Will be removed as lost flow from shaker to active. [m3/hr]
             % These losses will only appear when there is flow out from the shaker.

Copipe = 2;  % Orifice constant. 0.98 for circular drain. Use this to tune the flow.
Coshaker =8;
G = 9.81;    % Acceleration of gravity [m/s2]

pipedrain = 0.00085; % Area of the drain from the imaginary tank in the pipes [m2]
pipemaxvolume = 8;   % The maximum volume before the pipes "overflow" [m3]
shakerdrain = 0.0028; % Drain area in the shaker tank [m2]
shakermaxvolume = 40;   % Maximum total volume in the shaker tank [m3]
shakerbasevolume = 20;  % Volume in the shaker tank when the head is zero [m3]
shakerarea = 4;         % Area of the shaker tank [m2]
activebasevolume = 100.2;  % Base volume in the active

pipegain = 1;
shakergain =1;

t = 1;

%% CALCULATIONS
rate1 = rate1liter/60000;   % Conversion of the flowrates from [l/min] to [m3/s]
rate2 = rate2liter/60000;
```

```
rate3 = rate3liter/60000;
rate4 = rate4liter/60000;
rate5 = rate5liter/60000;

shakerlosses = shakerlossrate/3600;  % Convert losses from m3/hr to m3/s
influx = influxrate/3600;

%% GENERATE MATRIX FOR DATA STORAGE
% Sets initial values and populates the first line in the matrixes used
% in the calculation loop.
pumpcumulativevolume = 0;
pipecumulativevolume = 0;
shakercumulativevolume = 0;
activecumulativevolume = 0;
pipevolume = 0;
pipeflowin = 0;
shakerflowin = 0;
pipe = [pipeflowin,pipevolume,0,0,0];
shaker = [shakerflowin,shakerbasevolume,0,0,0];
active = [0,0,activebasevolume,0,0];

%% THE LOOP
while t<tstop
    tcount = t+1;      % Increase time counter, to create new line in matrixes
    time = tcount;     % Input for time coloumns
                       % This section determines the flow out of the active
                       % (the pumprate). The limits are based on the input times
                       % for changes as well as the input time used to change from
                       % one flowrate to another. The ramping up or down between
                       % two flowrates is asssumed linear, distributed evenly over
                       % the specified ramping time
    if tcount < tchange1
        pumpflow = rate1;
    elseif tcount < tchange1 + ttochange
        pumpflow = rate1 + ((rate2-rate1)/ttochange)*(tcount-tchange1);
    elseif tcount < tchange2
        pumpflow = rate2;
    elseif tcount < tchange2 + ttochange
        pumpflow = rate2 + ((rate3-rate2)/ttochange)*(tcount-tchange2);
    elseif tcount < tchange3
        pumpflow = rate3;
    elseif tcount < tchange3 + ttochange
        pumpflow = rate3 + ((rate4-rate3)/ttochange)*(tcount-tchange3);
    elseif tcount < tchange4
        pumpflow = rate4;
    elseif tcount < tchange4 + ttochange
        pumpflow = rate4 + ((rate5-rate4)/ttochange)*(tcount-tchange4);
    else
        pumpflow = rate5;
    end

    % Flow in to the pipe system = flow out of active in last timestep
    % Volume used for calculations set to volume from last timestep
    % Potential
```

```
    pipeflowin = active(tcount-1,2);
    pipevolume = pipe(tcount-1,2);
    pipepotentialflowout = Copipe*pipedrain*sqrt(2*G*pipevolume);
    pipevolumechange = pipeflowin - pipepotentialflowout;
    pipepotentialvolume = pipevolume - pipepotentialflowout + pipevolumechange;
    if pipepotentialvolume > pipemaxvolume
        pipeoverflow = pipepotentialvolume - pipemaxvolume;
    else
        pipeoverflow = 0;
    end
    pipevolume = pipevolume + pipevolumechange - pipeoverflow;
    if pipevolume < 0
        pipevolume = 0;
    end
    pipeflowout = pipepotentialflowout + pipeoverflow;


    if influxstatus == 1
        if tcount > influxtime
            pipeflowout = pipeflowout + influx;
        end
    end

      if tcount < tchange1
        shakerflowin = 0;
        else
        shakerflowin = pipe(tcount-pipedelay,3);
      end

%     shakerflowin = pipeflowout;
    shakervolume = shaker(tcount-1,2);
    shakerpotentialflowout = Coshaker*shakerdrain*sqrt(2*G*((shakervolume-↙
shakerbasevolume)/shakerarea));
    shakervolumechange = shakerflowin - shakerpotentialflowout;
    shakerpotentialvolume = shakervolume - shakerpotentialflowout + shakervolumechange;
    if shakerpotentialvolume > shakermaxvolume
        shakeroverflow = shakerpotentialvolume - shakermaxvolume;
    else
        shakeroverflow = 0;
    end
    shakervolume = shakervolume + shakervolumechange - shakeroverflow;
    if shakervolume < shakerbasevolume
        shakervolume = shakerbasevolume;
    end
    shakerflowout = shakerpotentialflowout + shakeroverflow;

    if shakerlossstatus == 1
        if shakerflowout > shakerlosses
                 shakerflowout = shakerflowout - shakerlosses;
        end
    end

    if tcount < tchange1
        activeflowin = 0;
    else
```

```
        activeflowin = shaker(tcount-shakerdelay,3);
    end
    activevolumechange = activeflowin - pumpflow;
    activevolume = active(tcount-1,3) + activevolumechange;

    pipecumulativevolume = pipecumulativevolume + pipeflowout;
    pumpcumulativevolume = pumpcumulativevolume + pumpflow;
    shakercumulativevolume = shakercumulativevolume + shakerflowout;
    activecumulativevolume = activecumulativevolume + activeflowin;

    active(tcount,1) = time;
    active(tcount,2) = pumpflow;
    pipe(tcount,1) = pipeflowin;
    pipe(tcount,2) = pipevolume;
    pipe(tcount,3) = pipeflowout;
    shaker(tcount,1) = shakerflowin;
    shaker(tcount,2) = shakervolume;
    shaker(tcount,3) = shakerflowout;
    active(tcount,3) = activevolume;
    active(tcount,4) = activeflowin;
    t = tcount;
end

%% PLOTTING
% figure(1);
% plot(active(:,1),active(:,2),'r');
% hold on;
% plot(active(:,1),pipe(:,3),'m');
% plot(active(:,1),shaker(:,3),'b');
% plot(active(:,1),active(:,4),'g');
% xlabel('Time (s)')
% ylabel('Flowrate (m3/s)')
% figure(2);
% plot(active(:,1),pipe(:,2),'m');
% hold on;
% plot(active(:,1),shaker(:,2),'b');
% plot(active(:,1),active(:,3),'r');
% plot(active(:,1),active(:,3)+shaker(:,2),'g');
% xlabel('Time (s)')
% ylabel('Volume (m3)')
% axis([1000 2000 60.5 70.5])
figure(3);
% plot(active(:,1),pipe(:,2),'m');
% plot(active(:,1),shaker(:,2),'b');
plot(active(:,1),active(:,3),'b');
% plot(active(:,1),active(:,3)+shaker(:,2),'g');
hold on;
plot(targetvalues(:,1)+1000,targetvalues(:,2),'r')
xlabel('Time (s)')
ylabel('Volume (m3)')
axis([1000 2000 87 97]);
legend('Simulated Values','Target Values')
title('3-Tank High Flow','fontsize',12,'fontweight','b')
% grid on;
```

```
%% INTRODUCTION AND PROGRAM STARTUP
% Adaptive Observer program
% The program simulates flow and volume based on pump rate
% Based on an adaptive observer and employs low-pass & high-pass filters

% Parameter estimation of first order system
% x_dot = -a*x + b*u
%
% u = input
% x = state

% Adaption to tank system
% xhat = Modeled flow out of well / flow into tank
% u = pump flow
% volume(t+1) = volume(t) + flow out of well(t) - pump flow(t)
%
% flow out of well(t) = [volume(t) - volume(t-1)] + pump flow(t)
% flow out of well(t) = volume diff + pump flow(t)
% x = vol_diff(t-(t-1)) + pump_flow_k
% Actual flow out of well / into tank

% clear all;
% close all;

% load low-pass filtered dataset
load wellA_filtered;
% Units:
% active_pit_filtered [m3]
% pump_rate_filtered [m3/min]

%% INPUTS

%Sample time (loaded data is sampled at 1-sec intervals)
dt = 1;
% max iterations
maxIterate  = 45000;

% system parameters
a  = 3;
b  = 1;

%INITIAL VALUES
x = 0;                              % Actual flow out of well
u = 0;                              % Pump rate
xhat = 0;                           % Modeled flow out of well
eps1 = 0;                           % Difference between model and measurement
ahat = 1;               %ahat = 0.5;
bhat = 1.0;             %bhat = 1.1;
gamma1 = 0.8;                       % Learning parameter (volume)
gamma2 = 0;                         % Learning parameter (flow)
est_influx_vol = 0;                 % Modeled cumulative volume change (t)
est_influx_vol_prev = 0;            % Modeled cumulative volume change (t-1)
meas_influx_vol = 0;                % Measured cumulative volume change (t)
meas_influx_vol_prev = 0;           % Measured cumulative volume change (t-1)
influx_vol = 0;                     % Measured - modeled volume change (t)
```

```
influx_vol_prev = 0;            % Measured - modeled volume change (t)

hp_est_influx_vol = 0;          % High-pass filtered meas-model vol ch (t)
hp_meas_influx_vol = 0;         % High-pass filtered meas vol ch (t)
hp_influx_vol = 0;              % High-pass filtered model vol ch (t)

influx_rate = 0;                %
tau = 15;                       % samples (how much the low-pass smoothes)
alpha = dt/(tau +dt);           % for low-pass filter
lowpass_vol_diff = 0;           %
xhat_delay = xhat;              %
% high pass filter
hp_tau = 3600;                  % Only consider last 3600 s. (1 hr.)
hp_alpha = hp_tau/(hp_tau + dt);% tau = RC = time constant

%% ITERATION LOOP
for i=500:maxIterate+1,        % Starts at 500 seconds
   time = (i-1)*dt;
   Array(i,:) = [time,x,u,a,ahat,b,bhat,xhat,est_influx_vol,meas_influx_vol,xhat_delay,↙
hp_est_influx_vol,hp_meas_influx_vol,eps1,influx_vol,hp_influx_vol];

   u = (pump_rate_filtered(i)/60);

   if i == 20000                % Stop learning at this point
       gamma1 = 0;
   end
   if i == 25000
       est_influx_vol = 0;      % reset influx volumes
       meas_influx_vol = 0;
       influx_vol = 0;
       hp_est_influx_vol = 0;
       hp_meas_influx_vol = 0;
       hp_influx_vol = 0;
       est_influx_vol_prev = 0;
       meas_influx_vol_prev = 0;
       influx_vol_prev = 0;
   end;
   if i == 27650                % Start influx at this point
       influx_rate = 0.00; % No influx
%         influx_rate = 0.0017; %[m3/s] equiv to 100 l/min
    %  influx_rate = 0.0083; %[m3/s] equiv to 500 l/min
   end
%    if i == 48000
%        est_influx_vol = 0;      % reset influx volumes
%        meas_influx_vol = 0;
%        influx_vol = 0;
%        hp_est_influx_vol = 0;
%        hp_meas_influx_vol = 0;
%        hp_influx_vol = 0;
%        est_influx_vol_prev = 0;
%        meas_influx_vol_prev = 0;
%        influx_vol_prev = 0;
%    end;
%
```

```
    % MEASURED VALUES
    % Calculate "measured" flow in by looking at volume change
    % x = vol_diff(k-k_1) + pump_flow_k
    % use low-pass filter due to noise active vol used as input
    % Add influx rate as it will show on measurements
    vol_diff = (active_pit_filtered(i+1)- active_pit_filtered(i));
    lowpass_vol_diff = alpha*vol_diff + (1-alpha)*lowpass_vol_diff;
    x = lowpass_vol_diff + u + influx_rate;

    % ESTIMATOR/MODEL, update values
    ahat_dot = -gamma1*eps1*xhat;
    bhat_dot = gamma2*eps1*u;
    xhat_dot = -ahat*xhat + bhat*u;

    xhat = xhat + dt*xhat_dot;
    ahat = ahat + dt*ahat_dot;
    bhat = bhat + dt*bhat_dot;
    % Add delay from pumps to flow into tank, (Array(:,8) = xhat
    xhat_delay = Array(i-145,8);
    % eps1 = x-xhat;
    % Compare measurement to corresponding model timestep
    eps1 = x-xhat_delay;

    % Cumulative volume calculations
    % MODEL
    % new volume = previous volume + modeled flow into tank - pump rate
    est_influx_vol = est_influx_vol + xhat-u;
    % MEASUREMENT
    % new volume = previous volume + "measured" flow into tank - pump rate
    meas_influx_vol = meas_influx_vol + x-u;
    % CALCULATED (MEASUREMENT - MODEL)
    influx_vol = influx_vol + eps1;


    % high pass filter ( looking only at last hour ( 3600 s)
    % for estimator / model
    hp_est_influx_vol = hp_alpha*hp_est_influx_vol + hp_alpha*( est_influx_vol-↙
est_influx_vol_prev);
    est_influx_vol_prev = est_influx_vol;
    % for measured
    hp_meas_influx_vol = hp_alpha*hp_meas_influx_vol + hp_alpha*( meas_influx_vol-↙
meas_influx_vol_prev);
    meas_influx_vol_prev = meas_influx_vol;
    % for calculated
    hp_influx_vol = hp_alpha*hp_influx_vol + hp_alpha*(influx_vol-influx_vol_prev);
    influx_vol_prev = influx_vol;

end

% Plotting

time_ar = Array(:,1);                % Time
x_ar   = Array(:,2);                 % Measured flow into tank
```

```
u_ar   = Array(:,3);                % Pump rate
a_ar   = Array(:,4);                % not in use
ahat_ar   = Array(:,5);             % Volume factor for modeled flowrate
b_ar   = Array(:,6);                % not in use
bhat_ar   = Array(:,7);             % Pump factor for modeled flowrate
xhat_ar   = Array(:,8);             % Modeled flow into tank
 % Delayed modeled flowrate (for comparison with pump rate)
xhat_delay_ar   = Array(:,11);
 % Difference between measured and modeled flowrate
eps1_ar   = Array(:,14);

est_influx_vol_ar   = Array(:,9);   % Modeled influx volume (cumulative)
meas_influx_vol_ar   = Array(:,10); % Measured influx volume (cumulative
hp_est_influx_vol_ar   = Array(:,12); % Filtered modeled influx volume
hp_meas_influx_vol_ar   = Array(:,13); % Filtered measured influx volume
% Difference between measured and modeled influx volume
influx_vol_ar   = Array(:,15);
hp_influx_vol_ar   = Array(:,16);  % Filtered difference in volume

% clf;
figure(1);
subplot(2,1,1)
plot(time_ar,x_ar*60000,'r',time_ar,xhat_ar*60000,'c',time_ar,xhat_delay_ar*60000,'g');
xlabel('tid (s)');
ylabel('Flow Rate (l/min)');
legend('Actual Flowrate','Modeled Flowrate','Time Delayed Mod. Flow.')
%title('x');
grid;

%figure(2);
subplot(2,1,2)
plot(time_ar,u_ar*60000);
xlabel('tid (s)');
ylabel('Pump Rate (l/min)');
%title('u');
grid;

% figure(2);
% subplot(2,1,1)
% plot(time_ar,a_ar);
% xlabel('tid (s)');
% ylabel('a');
% %title('x');
% grid;

figure(2);
% subplot(2,1,2)
plot(time_ar,ahat_ar);
xlabel('tid (s)');
ylabel('ahat');
%title('u');
grid;

figure(3);
```

```
% subplot(2,1,1)
plot(time_ar/60,meas_influx_vol_ar,'r',time_ar/60,est_influx_vol_ar,'b');
xlabel('Time (min)');
ylabel('Volume [m3]');
axis([0 750 -13 23])
annotation(figure(3),'arrow',[0.5 0.56],[0.5 0.41]);
% annotation(figure(3),'arrow',[0.57 0.605],[0.30 0.41]);
%title('u');
grid;
title('Cumulative Influx Volumes','fontweight','b','fontsize',12)
legend('Measured','Modeled','location','NorthWest')
% subplot(2,1,2)
% plot();
% xlabel('Time (s)');
% ylabel('Estimator [m3]');
% axis([0 45000 -13 23])
% %title('x');
% grid;




figure(4);
subplot(2,1,1)
plot(time_ar,x_ar-u_ar,'r',time_ar,eps1_ar,'b');
xlabel('tid (s)');
ylabel('measured influx rate (volume diff) [m3/s]');
legend('x - u','x - xhat_d_e_l_a_y')
%title('x');
grid;

%figure(2);
subplot(2,1,2)
plot(time_ar,xhat_ar-u_ar,'b');
xlabel('tid (s)');
ylabel('modeled influx rate [m3/s]');
legend('x_h_a_t - u')
%title('u');
grid;

figure(5)
hold on;
plot(time_ar(25001:34000)/60,comparisonvolume(25001:34000),'g')
plot(time_ar(25001:34000)/60,meas_influx_vol_ar(25001:34000),'r')
plot(time_ar(25001:34000)/60,hp_est_influx_vol_ar(25001:34000),'b')
plot(time_ar(25001:34000)/60,hp_influx_vol_ar(25001:34000),'m');
annotation(figure(5),'arrow',[0.42 0.36],[0.12 0.24]);
xlabel('Time (min)')
ylabel('Volume (m3)')
legend('Measured, No Influx (Cumulative)','Measured (Cumulative)','Model↙
(Filtered)','Model Difference (Filtered)','location','NorthWest')
title('Zoomed Comparison','fontweight','b','fontsize',12)
axis([25000/60 34000/60 -2 14])
grid;
```

```
% figure(5);
% subplot(3,1,1)
% plot(time_ar,(x_ar-u_ar)*60000,'r');
% xlabel('tid (s)');
% ylabel('measured influx rate (volume diff) [l/min]');
% %title('x');
% grid;

% %figure(2);
% subplot(3,1,2)
% plot(time_ar,(xhat_ar-u_ar)*60000,'r');
% xlabel('tid (s)');
% ylabel('estimated influx rate [l/min]');
% %title('u');
% grid;

% %figure(2);
% subplot(3,1,3)
% plot(time_ar,(eps1_ar)*60000,'r');
% xlabel('tid (s)');
% ylabel('estimated influx rate [l/min]');
% %title('u');
% grid;


%figure(2);
% subplot(3,1,3)
% plot(time_ar,influx_vol_ar,'r');
% xlabel('tid (s)');
% ylabel('influx volume [m3]');
% %title('u');
% grid;
accu(1) = 0;
hp_accu(1) = 0;
for j=2:length(time_ar)
    accu(j) = accu(j-1)+xhat_delay_ar(j)-u_ar(j);
    hp_accu(j) = hp_alpha*hp_accu(j-1) + hp_alpha*(accu(j)-accu(j-1));
end

figure(7);
% hold on;
subplot(2,1,2)
plot(time_ar/60,hp_est_influx_vol_ar,'b',time_ar/60,hp_influx_vol_ar,'m');
xlabel('Time (min)');
ylabel('Volume [m3]');
legend('Modeled','Measured - Modeled','Location','NorthWest')
axis([0 750 -5 15])
annotation(figure(7),'arrow',[0.6 0.565],[0.3 0.2]);
annotation(figure(7),'arrow',[0.6 0.565],[0.77 0.67]);
% annotation(figure(7),'arrow',[0.65 0.605],[0.145 0.195]);
% annotation(figure(7),'arrow',[0.65 0.605],[0.615 0.665]);
%title('x');
grid;
```

```
%figure(2);
subplot(2,1,1)
plot(time_ar/60,hp_meas_influx_vol_ar,'r',time_ar/60,hp_influx_vol_ar,'m',time_ar/60,↙
hp_accu,'g');
xlabel('Time (min)');
ylabel('Volume [m3]');
legend('Measured','Measured - Modeled','Modeled w. connections','Location','NorthWest')
title('High-Pass Filtered Influx Volumes','fontweight','b','fontsize',12)
axis([0 750 -5 15])
%title('u');
grid;
```

```
%% INTRODUCTION
% This program takes the data set from wellA and runs it through a Low-pass
% filter in order to improve the data quality for later calculations.
% Smoothing can be tuned by adjusting the alpha value.

%% THE PROGRAM

alpha = 0.04;
t = 0;
time = [0:100000];
time = time.';
maxIterate = 100000;

lowpass1 = active_pit(1,1);
unfiltered1 = zeros(100000,1);
active_pit_filtered = zeros(100000,1);

lowpass2 = paddle(1,1);
unfiltered2 = zeros(100000,1);
paddle_filtered = zeros(100000,1);

lowpass3 = pump_rate(1,1);
unfiltered3 = zeros(100000,1);
pump_rate_filtered = zeros(100000,1);

for i=1:maxIterate+1

   noise1 = active_pit(i,1);
   lowpass1 = lowpass1 + alpha * (noise1 - lowpass1);
   unfiltered1(i,1) = noise1;
   active_pit_filtered(i,1) = lowpass1;

   noise2 = paddle(i,1);
   lowpass2 = lowpass2 + alpha * (noise2 - lowpass2);
   unfiltered2(i,1) = noise2;
   paddle_filtered(i,1) = lowpass2;

   noise3 = pump_rate(i,1);
   lowpass3 = lowpass3 + alpha * (noise3 - lowpass3);
   unfiltered3(i,1) = noise3;
   pump_rate_filtered(i,1) = lowpass3;
end


figure(1)
plot(time,unfiltered1,'r')
hold on
plot(time,active_pit_filtered,'b')
axis([0,10000,64,75])

figure(2)
plot(time,active_pit_filtered,'b')

figure(3)
plot(time,unfiltered2,'r')
```

```
hold on
plot(time,paddle_filtered,'b')
% axis([0,10000,35,45])

figure(4)
plot(time,unfiltered3,'r')
hold on
plot(time,pump_rate_filtered,'b')
```