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Main Pump Start-up Pressure Limitation Control System
when using Thixotropic Drilling Fluids

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Executive summary

Everyday drilling operations in the Norwegian Continental Shelf become more challenged. They include drilling of highly inclined long wells in depleted reservoirs within narrow geo-pressure margins. In addition, drilling in unstable formations can cause serious problems which can increase non-productive time.

In order to solve these problems there is a need to develop an automated mud-pump management system with purpose to minimize the possibility of formation fracturing during start-up of the mud pump or fluid circulation.

Thixotropic drilling fluids enhance a hole cleaning in a wellbore during connections, avoiding cutting settings and packoffs. On the other hand, they bring challenges when starting the mud pump. Pressure peaks are typically seen when starting the pump manually after a connection.

The theoretical results found in this thesis where pressure peaks are significantly reduced during pump start-ups, indicate that automations of pump start-up should be implemented in real rig operation at the field in the near future.

Acknowledgements

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Abbreviations

BHA- bottom hole assembly

CFR – critical flow rate

ECD – equivalent circulation density

ERD – extended reach wells

HPHT – high pressure and high temperature

MD – measured depth

MWD – measurement while drilling

NCS – Norwegian Continental Shelf

PWD – pressure while drilling

SBM – synthetic based mud

SPP – stand pipe pressure

Nomenclature

p : pressure [Pa]

q : flow rate $[m^3/s]$

L : length [m]

V : volume [m3]

D : diameter [m]

ρ : density [kg/m3] , also used as (rho) in MATLAB code

ε : roughness [m] , also used as (eps) in MATLAB code

Re : Reynolds number [unit less quantity]

ϑ : velocity of fluid in the pipe $\left[\frac{m}{s}\right]$

μ : viscosity [Pas]

Subscripts:

_i : inlet

_o : outlet

_p : pipe

_f: friction

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1. Introduction

Drilling in the North Sea is facing ever more challenges due to the narrow geopressure windows in depleted reservoirs. In addition, unstable formations can cause potential pickoffs, which further lead to significant damages to the formation and non-productive time as well. In order to solve these problems there is a need to develop an automated mud-pump management system with aim to minimize the possibility of formation fracturing during start-up of the mud pump or fluid circulation. Since the downhole conditions are constantly changing (e.g. depth, temperature, flow rate, gel time, cuttings proportions), the necessary safeguards to operate the mud pump have to be updated continuously (Cayeux, Daireaux and Dvergsnes, 2011).

The first integrated system for real-time optimization of the drilling process was implemented in 2008 on the Statfjord C platform in the Norwegian part of the North Sea. Iversen, Cayeux, Devergsnes, Ervik, Welmer and Balov (2009) claimed that implementation of real-time calibrated process in drilling control can contribute to better control of the drilling process, make it more reliable, improve efficiency and ensure safer working conditions. The test they performed confirmed that it is possible to handle the mud pump during start-up, such that potential fracturing of the open hole formation was reduced. Furthermore, the drillers who had participated in the testing were interested in pump-start-up procedure improvements such as automatic pump shutdown and maximum flow rate control. The initial test indicated that rapidly shifting the configuration parameters could be a challenge for the real-time system to react as all the parameters must be calculated in less than a second. In order to try to solve this problem, a new system was reinstalled in 2009 and used for the drilling operations of three wells on the NCS (Cayeux *et al.* 2011).

1.1 Motivation and problem descriptions

Oil and Gas industry today drill long directional wells and extended reach wells with high angle of inclination in order to enrich oil recovery. Drilling of these wells affects effective flow rate of fluid circulation and cutting transport, especially in reservoirs with narrow geo pressure margins. Therefore mud pump rate should be highly controlled as high flow rate can lead to loss of circulation. On the other hand, sufficient hole cleaning is very important to reach those reservoirs. Furthermore industry uses drilling fluids which have gelation behaviour in order to prevent cuttings falling down and produce cutting beds in the wellbore. In addition, those gelatinous fluids affect pump start-up procedures and thus, high pressure peaks may occur and cause formation to fracture. Therefore, mud pump manual operation becomes very sensitive and a need for an automated mud pump management is prioritised.

1.2 Objectives and Scope of the Work

The objective of this thesis is to discuss the current use of drilling fluids and various drilling fluid properties, such as thixotropy , to enhance hole cleaning. In addition focus should be on developing of pump start-up procedure reducing the pressure peaks typically found when using manual procedures. The start-up procedures are evaluated by MATLAB software. Furthermore, by proposal of this dissertation, a small scale flow loop experiment in laboratory conditions was planned in order to make and circulate of thixotropic fluids with various levels of thixotropy based on silicon oil. Then the existence of a database of real measurements supposed help to make better assumptions.

1.3 Limitations

Automation of mud pump management is very new in the Oil and Gas industry. Published scientific journals on this topic are still in expansion. Furthermore, complexity of thixotropic drilling fluids behaviour and gel build-up/ breaking processes in terms of pressure limitations require implementation of correct assumptions in order to understand their behaviour.

The build-up of small scale flow loop experiment in the University laboratory and real data measuring was restricted due to long delivery period of necessary equipment and relatively short time assigned for Master Thesis reports.

1.4 Methodology

In order to collect rich data on a given topic and accomplish scope and objectives of this report, the most recent and previously published data were analysed. In the case of automation of mud pump management there are very few comprehensive publications. Therefore, collecting of various data from the library databases belong to the *University of Stavanger,* combined with online scientific journals, conference and other applicable papers helped to gather valuable insight on research topic. Furthermore, in order to acquire in-depth understanding of the drilling operations demands and constraints, interviews with industry experts working on the field were conducted in addition. Moreover, discussion with fellow students provided important hands-on perspective.

MATLAB® was used to simulate gel breaking procedures while starting the mud pump and using thixotropic drilling fluids. Modeling of conventional and automated methods was based on lectures with instructions given in the booklet “*Automated Drilling Operations*” published by Gerhard Nygaard and John-Morten Godhavn (2013). The aim was to produce a reliable model which can simulate thixotropic drilling fluid behavior.

1.5 Structure of the Report

The thesis is divided into six chapters. Following the Introduction chapter, various theories related to drilling fluid properties and pump management procedures are covered. Chapter three presents the analysis and results as well as a brief description of the basis for analysis. A discussion of the results is given in chapter four, identifying the limitations of the analysis and results. Suggestions for future work are provided in chapter five and finally the conclusions are given in chapter six. Furthermore, comments to the MATLAB® Source Code Implementation of both conventional and automated method are given in Appendices A.1 and A.2. The MATLAB code is presented in appendices B.1 and B.2.

2. Theory and Literature Review

This chapter presents outlines of the drilling fluid usage, requirement and operation. The drilling fluid is used for transporting the cuttings from the drilling process, but when the rig pumps are stopped for a connection, the cuttings may fall down in the well. To avoid this from occurring, the drilling fluid has often thixotropic behaviour. However this thixotropic behaviour cause challenges when the pumps are started.

To detail some of the operational challenges regarding the drilling fluid and pressure limitations, this chapter is divided in three sections. The first section presents some theory of cuttings transportation, the following section presents thixotropic drilling fluids theory, and the last chapter presents the rig pump procedures.

2.1. Cuttings Transportation

Well drilling operations is the process where a borehole is drilled from the surface to the target, such as an oil reservoir. In essence, the drill bit crashes the rock in its trajectory and produces cuttings which have to be instantly and efficiently removed from the hole in order to perform further drilling. For this purpose, there are two energies brought from the surface to the bottom hole. One is mechanical energy, in the form of weight on the bit, and the other is hydraulic, where the drilling fluid is circulated from the surface through the drill string, and bit nozzles out to the well annulus back to the surface. Primary function of drilling fluid is to pick up the cuttings and lift them up out of the hole. Secondary functions are to lubricate and cool the drill bit (Skalle, 2011).

The drilling fluids carrying out cuttings that are made while well drilling (U.S. Patent No. 4,595,343, 1986). According to U.S. Patent No. 4,595,343 (1986) “in normal drilling fluid or mud circulation, the drilling fluid is pumped down through the drill pipe, discharged through the bit and returns to the surface in the annular space outside the drill pipe and inside the drill hole and casing placed in the well” (p. 1). The flow rate of mud fluid circulation is regulated by the required upward flow velocity needed for circulations the drill cuttings and debris from the collapsed formation from the wellbore to the surface, as well as by the jetting requirements of the bit (U.S. Patent No. 4,595,343, 1986). The main advantages of the rotary drilling system is that it allows fluid circulation used to remove the cuttings, and maintains the hole in order to easily rotate and withdraw drilling string when needed (U.S. Patent No. 4,595,343, 1986).

Most of the drilled wells today are directionally drilled and provide an economical advantage compared to vertical wells. In case of offshore operations, mostly exploration wells are vertical as per today. While drilling directional wells, the cuttings are naturally building up at the bottom of the drilled section due to the gravity and the drilling fluid is intended to collect these cuttings and direct them back to the surface. The ability of mud to lift cuttings is reduced with increasing well inclination. In this sense, the cuttings have a tendency to separate from the fluid flow and therefore start to fall towards the well floor. Once they settle, the ability of the drilling fluid to transport the cutting up to the surface is significantly reduced since the fluid velocity near the wall is small and therefore inadequate for it. Thus, concentration of cuttings in the hole starts to increase and creates cutting beds (Skalle, 2011).

Furthermore, when this situation is unclear and not monitored appropriately, it can cause further challenges and implications. Common drilling problems caused by inadequate hole cleaning can occur, for instance, during tripping or reaming operations. Accelerated degradation of the drilling bit, slow rate of penetration, high torque and drag, loss of circulation, stuck pipe, possible hole pack-off, extreme equivalent circulation density (ECD), fracture of formation or serious interruptions while setting casing into the hole are all possible consequences of cuttings accumulation (Skalle, 2011). If these problems are not controlled appropriately, they can lead to side-tracking or even loss of the well (Ogunrinde, 2011). Nevertheless, cuttings can be removed by injecting fluids at high flow rate, but this will raise bottom hole pressure as well. Further, high flow rate's injection is only limited to 12 ¼" hole sections or smaller. This implies that mechanisms for transporting cuttings in inclined wells are complex (Skalle, 2011). Also, Ogunrinde (2011) noted that few filed studies conducted on cutting transport reported that hole cleaning is a repeatedly emerging problem that has to be managed carefully. Furthermore, real scale models and different experiments have shown that cutting transport in long and highly inclined wells is a complex problem. Such problems can be diminished "by a combination of training, better guidelines and better predictive tools" (p. 2). The main goal of cutting transport predictions is to avoid such operational problems and to implement the most favourable, safe and efficient cutting transport solution (Skalle, 2011).

There are many factors that influence the performance of efficient cutting transport which include:

1. Hole Angle
2. Fluid Velocity
3. Fluid Properties (rheological properties and density)
4. Cuttings Size, Shape, and Concentration
5. Cutting Transport Ratio
6. Rate of Penetration (ROP)
7. Fluid Flow Regime (laminar or turbulent) (Ogunrinde, 2012, p. 7).

These factors have an effect on taking away the cuttings from the wellbore and they are listed according to the level of importance for wellbore cleaning during drilling (Ogunrinde, 2012).

Oil industries worldwide are trying to reach the most difficult reservoirs by drilling ultra-deep wells and extended reach wells with highly deviated side-tracks for hydrocarbon recovery. In order to perform such extremely demanding drilling tasks, hole cleanliness is crucial (Ogunrinde, 2012). The author claimed that “the key to a successful hole cleaning relies upon integrating optimum drilling fluid properties with best drilling practices” (p. 1).

Skalle (2011) asserted that every oil/service company nowadays define their own Best Practice. He presented the summary of Best Practice guidelines to achieve efficient hole cleaning which is derived from field experience and laboratory research. The author suggests that in order to confirm that hole cleaning parameters are not well performed, it is suggested to inspect hole cleaning parameters by performing bottoms-up operation, wiper trip, off bottom drag measurement, drag & torque test whenever is suitable. Related best practice includes:

- Keep rate of penetration (ROP) to a maximum, without compromising hole cleaning. ROP should be maintained steady; peaks should be avoided.

- Circulate to clean the well until clean. Reciprocate drill string and rack back one stand/hour while circulating bottoms up at maximum flow rate and maximum RPM during circulation (Skalle, 2011, p. 80).

Additionally, rotation of the drill pipe in the wellbore applies centrifugal force to the cuttings which can affect their lifting by the drilling fluid (Ogunrinde, 2012). The author recognized that in the case of insufficient hole cleaning in real operation, the flow rate and effective viscosity are often increased. For that reason, raising the mud viscosity or flow rate can be harmful to the process of cleaning below the bit since it will lead to a decrease in ROP. Consequently, a sizable economic hit might result if a higher than needed flow rate or mud viscosity is used.

As estimated by Azar and Sanches (1997), one third of stuck pipe situations happen due to inadequate hole cleaning. Furthermore, Ogunrinde (2012) noted that “the common practice is to stop drilling occasionally, clean the borehole by using viscous pills, pipe rotation and drilling fluid circulation” (p.5). The author noticed that is very crucial to be able to estimate when drilling should be interrupted in order to perform additional cleaning of wellbore. Furthermore, the same author claimed that “it is reportedly known that time spent for the drilling of wells is composed by up to 30% “rotating time” of the total well construction time which can be reduced if there is proper hole cleaning”(p. 7).

Key variables that control cuttings transport are presented in Figure 2.1 below, including their level of importance with respect to control and influence on hole cleaning.

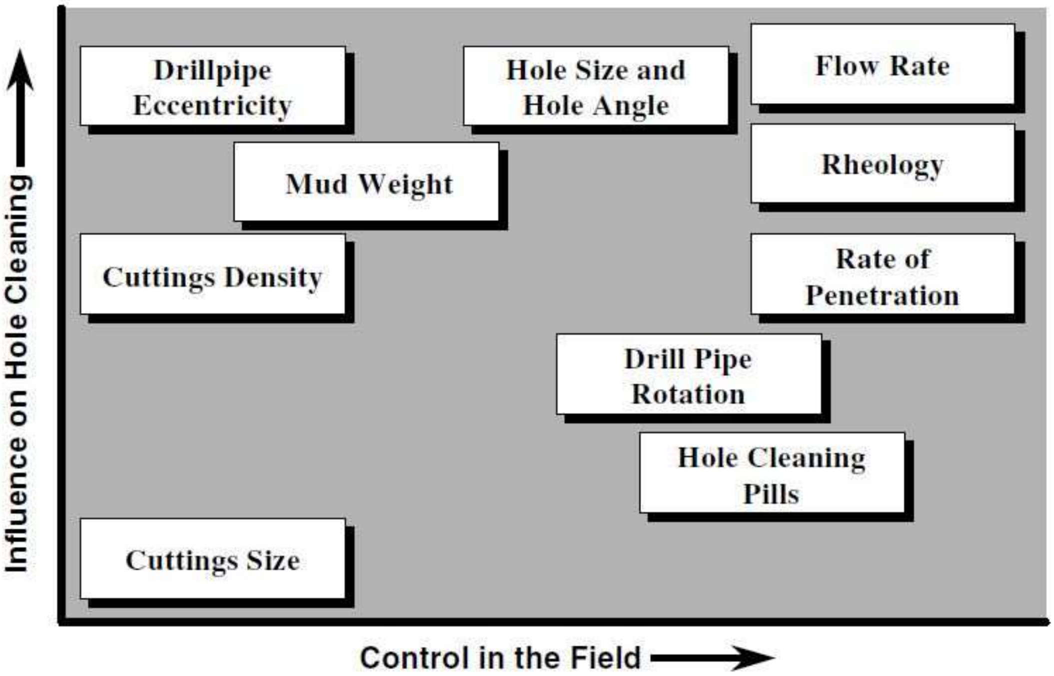

Figure 2.1: Key variables controlling cuttings transport (Adari, Miska, Kuru, Bern and Saasen, 2000)

Ogunrinde (2012) described the flow of cuttings in the annulus as “a dynamic process subject to gravity force, buoyancy force, drag, inertia and inter-particle contact” (p. 7). Furthermore there is a minimal flow rate required to pick the cuttings up and properly clean the hole. This flow rate is called critical flow rate (CFR). When actual flow rate is lower than CFR, the cuttings will start to remain in the wellbore and thus, beds of cuttings will start to form. The cuttings react when the drill string rotates and moving upwards in a spiral fashion. Figure 2.2 shows the effect of drill pipe movement on cuttings. Furthermore, when rotation speed is low or the drill pipe stops due to pipe connection for instance, the cuttings will again sink to the lower part of the well. Therefore, pipe rotation is important for cutting transport as well.

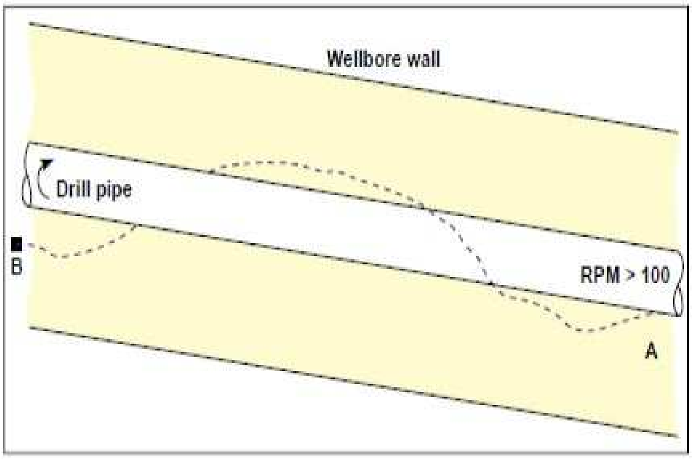

Figure 2.2: Effect of drill pipe movement on cuttings (Ogunrinde, 2012)

According to Adari *et al*. (2000) drilling operators, in order to avoid the common drilling problems, strive to incorporate such practices as “*washing and reaming*” when the drill string is tripping into the wellbore and the driller performs rotation of the string and circulates drilling fluid until the bit reaches the bottomhole. The other is “*back reaming*”- when the driller is withdrawing the string from the wellbore while performing fluid circulation and bit rotation. Other practices, such as "*wiper trips*" or "*pumping out of the hole*" are often carried out to try to control the quantity of cuttings gathered in the wellbore. All these operations are time consuming and can considerably increase the cost of drilling high-incline wells. Thus, it is very important to understand how different drilling variables affect cutting bed erosion in order to create models to better foresee the time needed to clean the cuttings from the wellbore.

In Figure 2.1, it can be concluded that flow rate and rheology of drilling fluids are two key parameters that significantly affect moving of cutting beds. In order to guarantee the most effective transport of cuttings, the optimum combination of these two parameters has to be used (Adari *et al.*, 2000). The same authors suggest that cuttings removal is easier with turbulent flow compared to laminar.

A lot of science projects of modelling, experimenting and testing were performed on the cutting transport challenges. Thus, this indicates that insufficient cutting transport is one of the biggest challenges that happens frequently while drilling highly inclined and horizontal wells.

2.2. Thixotropic Drilling Fluids

Drilling fluids used in the oil and gas industry are fluids with time dependent properties. This means that, when applying sufficiently high pressure to break a fluid structure, it is breaking continuously with time. When the fluid is at rest, the structure rebuilds itself again (Shah, Shanker and Ogugbue, 2010). This fluid structure is said to have gel behaviour and is characterized as thixotropic fluid. The thixotropic behaviour is shown in Figure 2.3 (MI SWACO, 2006). The change from gel (a solid condition) to liquid can be performed countless times (Reid, 1937).

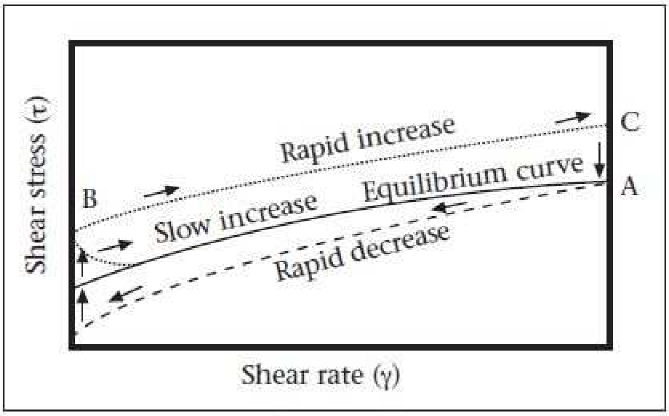

Figure 2.3: Txihotropic behaviour (MI SWACO, 2006)

Note that in the figure above the equilibrium curve is the solid line and in case of thixotropic fluid flow, when the flow is slowly reduced to zero, the gel solidification will follow the equilibrium curve from A to B. However, if the flow rate is reduced suddenly, then the gel solidification will follow the dashed curve titled “Rapid decrease”. Otherwise, if the pump is started and the flow increased gradually, then the fluid will follow the equilibrium curve, in this case from B to A. Moreover, in a case where the flow rate is increased suddenly, the thixotropic fluid will behave as per the top curve, the dotted line from B to C.

Degree of gelation and value of gel strength are essential as they can suspend the cuttings when the flow has stopped for any reason and prevent their fall towards the borehole floor (MI SWACO, 2006). However, the gelation should not be higher than required to hold the specific type of cuttings. Therefore, as MI-SWACO (2006, p. 5-7) propose that excessive gel strengths can cause complications, such as the following:

1. Entrapment of air or gas in the fluid.
2. Excessive pressures when breaking circulation after a trip.
3. Reduction in the efficiency of solids-removal equipment.
4. Excessive swabbing while tripping out of the hole.
5. Excessive pressure surges while tripping in the hole.
6. Inability to get logging tools to the bottom.

Cayeux, Mesagan, Tanripada, Zidan and Fjelde (2013) claimed that “drilling muds are non-Newtonian fluids, they are more precisely shear thinning fluids with a yield stress” (p.5). Furthermore, Herzhaft, Ragouillaux and Coussot (2006) described that “drilling muds like many pasty materials present shear thinning, yield stress and thixotropic effect” (p.6). Therefore according to Shah *et al.* (2010), “shear-thinning properties help lower the friction pressure loss in the drillpipe but in the drillpipe/wellbore annulus where shear rate is significantly lower, the fluid rebuilds its structure and exhibits yield stress” (p. 8).

The non-Newtonian fluids do not have single viscosity value. This value may differ at different value of shear rate, as shown in Figure 2.4 (MI SWACO, 2006).

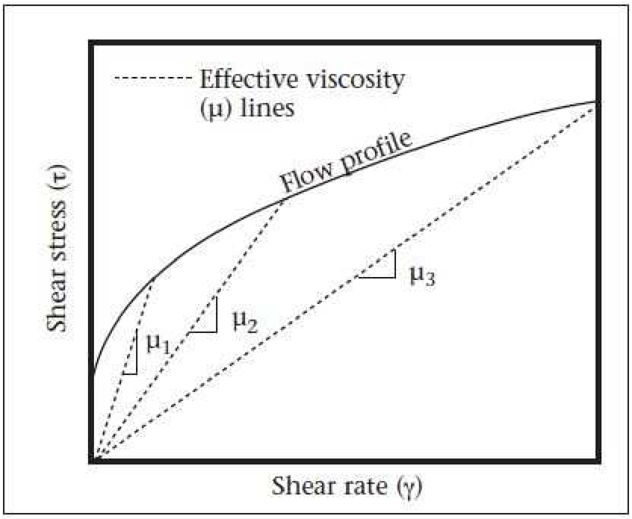

Figure 2.4: Effect of shear rate on effective viscosity of non-Newtonian fluid (MI SWACO, 2006)

Viscosity of non-Newtonian fluids is defined as an effective viscosity value relative to varying shear rate. This effective viscosity, also called apparent viscosity, is measured in certain shear rate, temperature and pressure accordingly. Thus, pressure and temperature affect viscosity of drilling fluids as well. Additionally, as it can be observed in Figure 2.5, effective viscosity decreases with increase of shear rate. This effect is called *shear thinning behaviour*. This behaviour is shown in Figure 2.5 (MI SWACO, 2006).

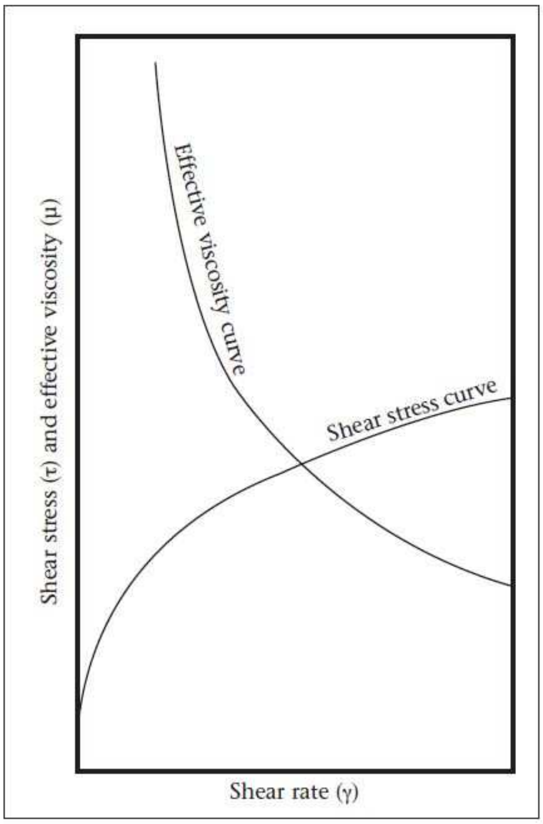

Figure 2.5: Shear-thinning effect in non-Newtonian fluids (MI SWACO, 2006)

According to MI SWACO (2006, p. 5.12), shear-thinning is very important parameter of drilling fluids as it provides the following:

1. At high velocities (high shear rates) in the drillstring and through the bit, the mud shear thins to low viscosities. This reduces the circulating pressure and pressure losses.

2. At the lower velocities (lower shear rates) in the annulus, the mud has a higher viscosity that aids in hole cleaning.

3. At ultra-low velocity the mud has its highest viscosity and when not circulating will develop gel strengths that aid in suspending weight material and cuttings.

In addition, the gel strength is measured with Fann VG rheometer which has two speeds, 300 and 600 revolutions per minute. Gel strength readings are measured at 10 seconds and 10 minute intervals and in crisis situations at 30 minute intervals as well, showing the degree of thixotropy in the fluid (MI SWACO, 2006).

During drilling operations when installing a new pipe in order to extend the drilling-string, the mud pump is always turned off and, in this case, flow rate reaches zero value. Installation of new pipe takes approximately 5 minutes and during that time gel strength is formed (Jachnik and Baker Huges INTEQ, 2005). Thus, when the pump starts up again, it has to break the gel inside the drill-string first and as well at the two surfaces within the well annulus. One is within wellbore and the other is at the surface of the drill-string (Skalle, 2011). High pressure peaks will show up as a consequence of the pump work, especially in long deviated horizontal wells.

Furthermore, when tripping drill-string out of the well to change the drill bit, or when installing casing for formation and pressure protection, there is a rest time for circulation fluids when the gel will form as well (Jachnik and Baker Huges INTEQ, 2005).

Transient gel breaking models complemented by field data for use in drilling critical wells is presented by Bjørkevoll, Rommetveit, Aas, Gjeraldstveit and Merlo (2003). The authors discussed a problem of pressure peaks during mud pump start-up procedure, when breaking the gel of thixotropic fluids. They used Fann viscometer and gel breaking model to foresee such peaks while running different fluids with similar properties through a flow loop. They started-up the pump with those fluids after some time of rest, performed measurements and observed pressure peaks. Later, they presented a local model of gel breaking pressures versus time prediction with rheometar measurements by integrating it into a transient drilling simulator for prediction of pressure peaks. Moreover, they measured data of two high pressures and high temperature (HPHT) well in the North Sea- one used oil based mud and the other water based mud. They concluded that the transient gel breaking model reproduced data with reasonable precision. They assert that this might help engineers identify if there is a need to be extra cautious during mud pump start-up procedures (Bjørkevoll *et al*., 2003).

Moore and Gillikin (2010) presented a project where they attempted to eliminate pressure peaks after pipe connections and pipe trips in order to improve control of equivalent circulating density and to minimize down-hole losses. They observed and analysed data of a deepwater well in Mississippi Canyon. High pressure peaks were observed when using conventional clay-based synthetic-based mud (SBM). It was later realized that they caused mini fracturing of the formation and loss of returns leading to the well collapsing at the end. Later on, operators carried out sidetracking of the same well, but by using different mud-clay-free SBM. Milling of existing 9 5/8" casing hole section and drilling of 9 7/8" hole section with an inclination angle of 40 degrees were performed with eliminated pressure peaks. The peaks were eliminated even when the pumps were run to 3000 [PSI] in less than 5 minutes after a connection. The operation was performed without circulation losses during tripping, running casing and cementing. The authors analysed post well drilling data for drilling performance and fluid hydraulics of two wells. They concluded that there are many factors that lead to pressure peaks, like rate of penetration, max speed of the pumps with full drilling rate, hole geometry, drilling practise and drilling fluid also. The same authors claimed that, in order to mitigate these problems "the easiest solution is to use a clay free fluid that has a robust, rapid building, but fragile gel strength" (p. 4).

Gokdemir, Ozbayoglu, Majidi, Miska, Takach and Mengjiao Yu (2011) analysed transient stress response and pressure of gel breaking of synthetic drilling fluids, especially how temperature and maturing time influence the progress of fluid structure. They evaluated data from the gelation process over a range of temperatures, from 4 to 50 Celsius degrees. Also, they used high accuracy rheometer with different shear rates to measure steady state conditions and non-equilibrium conditions of the synthetic based fluid. In addition, they tested fluids through a flow loop with an annular test section. Furthermore, the authors measured and simulated pressure peaks that emerged due to breaking gel procedure and surge that occurred when gelled fluid was changed to liquid. As a final point, they concluded that gel strength and pressure peaks increase over time. As well, they assert that gel strength increases with a decrease in temperature.

According to Zoellner, Thonhauser, Lueftenegger and Spoerker (2011), wellbore hydraulics is a vital component of real-time drilling monitoring with emphasis on fluid flow and pressure response. They presented the concept and several case studies of monitoring fluid flow with the aim of recognizing hydraulic problems early to allow them to take corrective actions before problems occur. The concept refers to analytic, static and knowledge based concepts and uses hybrid algorithms in order to recognise estimated variations in behaviour of rig sensors. By using automated operations recognition, the concept gathers numerous data from the real rig operation at a highly detailed level. They concluded that "analysis of routine drilling operations, like pump start-up, allow the optimisation of the drilling process to avoid hidden lost time" (p. 1).

The most recent study about gel strengths for horizontal and vertical drilling was conducted by Otell and Hathcox (2013). They performed several measurements in order to test properties of drilling fluids. They assert that physical and chemical characteristics of the fluid such as density, viscosity, pH, hardness, cuttings carrying capacity, hole cleaning ability and hole stabilization potential can give crucial information about the fluid. Also they claimed that gel strength is a vital property which can be measured and further evaluated in order to get full benefit. It is especially important for estimating the fluid to be used in horizontal drilling. According to the authors, it is particularly important to assess the gel strength in horizontal drilling which differs from the gel strength in vertical drilling, i.e. vertical drilling requires lower gel strength than horizontal drilling. In addition, in horizontal drilling the gel strength is very important to maintain the cuttings in a state where they can be transferred to the surface. In order to clean the hole systematically, cuttings must be taken away at a rate equal to the rate they are generated. Otherwise, bottomhole pressure will increase if cuttings remain in the wellbore which can lead to the fracture of the formation.

2.3. Mud Pump Management

Van Dyke (1998) defined mud pump as “a large, high-pressure reciprocating pump used to circulate the mud on the drilling rig. A typical mud pump is triplex or duplex pump, whose pistons travel in replaceable liners and are driven by a crankshaft actuated by an engine or motor” (p. 214). Furthermore the author emphasized that “the mud pumps, or slush pumps, are the most important pieces of equipment in a circulation system that uses liquid drilling fluid” (p. 95). In case the pumps break down the entire drilling operations will be suspended and non-productive time will rise accordingly. Thus, the pump must be reliable. The author described pumps as “extremely sturdy, capable of handling heavy loads, and can tolerate abrasive fluids” (p. 95). As stated in U.S. Patent No. 4,595,343 (1986) in normal drilling operations, “the mud pumps are controlled by the driller, using the driller’s console located at the driller’s station on a rig to monitor relevant drilling parameters, including the speed of the mud pumps” (p. 1).

2.3.1. Conventional Method of Mud Pump Management

Conventional rotary drilling is based on manually operated mud pumps for circulation of drilling fluids from the surface through the wellbore (U.S. Patent No. 4,595,343, 1986). In the process of conventional drilling, it is not unusual to encounter unexpected pressure increase due to kick caused by formation fluid influx which can influence the circulation of drilling fluid. A choke, in connection with a change in speed of the mud pumps, is used to control any pressure variation. In addition, conventional well control processes also require a choke to manage or control the fluid pressure, particularly when the speed of the mud pump is changing. On most drilling rigs “the choke is normally controlled from a choke console, which can be positioned on the drilling floor, at position remote from the normal location of a driller’s console” (U.S. Patent No. 4,595,343, 1986, p. 1). The driller and the person operating the choke console need to communicate closely in order to achieve a synchronized control of both the mud pumps and the choke. Such communication sometimes can be difficult. In an emergency situation, when the drilling crew is trying to control the well, the accent is put on effective communication and operation, which is difficult by using a conventional way of mud pump management (U.S. Patent No. 4,595,343, 1986).

2.3.2. Automation of Mud Pump Management

Due to the high complexity of conventional pump management, especially with regards to the safety of operations, industry developers are now pursuing a solution that will enable the automation of the operations and reduce rig non-productive time. Specifically, complex drilling processes with narrow geo-pressure windows also can have problems with formation fracturing, due to the inappropriate mud pump management (Cayeux, 2012). An uncontrolled mud pump acceleration or an enormous flow rate can create downhole pressures that surpass the fracture pressure gradient of the open hole formation. These can lead to mud losses and, in the worst scenario, a total loss of circulation. The author explained that limitation of actual flow rate and the mud pumps acceleration while changing the flow rate can be efficiently controlled, and by doing so, avoid increase of downhole pressure and possibility to fracture the open hole.

These mud pump operating limits depend on the operational parameters such as drill-string axial and rotational velocities, and downhole conditions. These conditions develop with time due to the changes of bit and bottom hole depths together with the variations in temperature, mud properties and cutting concentrations. When conditioning mud after a long period of time without circulation, the changes in temperature can be very large. Furthermore, in the case of barite sagging the hole cleaning would not be efficient and high gravity cuttings will sag as well. This might significantly increase a downhole pressure (Cayeux, 2012).

In order to avoid formation fracturing, safeguards must be implemented to the operation of the mud pumps, so as to keep a safe level of downhole pressure. Although, these safeguards can prevent the occurrence of undesirable fracturing and other events that can lead to the irreparable damage to the wellbore while the mud pumps are operating. Thus, an effective time response while controlling the pump rate is crucial to reduce the possibility of permanent harm of wellbore. In order to minimize reaction time and the effect of undesirable event, automatic safety triggers can be applied. Mud pump management includes the following components:

- Pump-start-up management
- Maximum-pump-rate limits

- Automatic pump-shutdown procedure in case of an abnormal situation (Cayeux *et al.*, 2011, p. 41)

For the purpose of this Master Thesis only mud pump start-up limitations of conventional and automated methods will be discussed within the pump start-up management component.

2.3.2.1. Conventional Pump Start-up Limitations

In order to start the mud pump, it is essential to calculate the time from the previous circulation, as gel strength is increasing with time. Typically, the driller needs to start the pump stepwise. It is essential to first start the pump with a low flow rate which is maintained constant for some interval of time until the flow rate from transient reaches a steady state condition due to the gel breaking. Afterwards, the flow rate is increased to another level and held constant for another interval of time. This procedure is repeated in several stages until the pump achieves the maximum required flow rate (Iversen, Cayeux, Dvergsnes, Gravdal, Vefring, Mykletun, Torsvoll, Omdal and Merlo, 2006). According to the same authors “the time necessary to wait for each flow rate level is difficult to evaluate because it depends on the bit position compared with the diameter and length of the open hole section, the mud characteristics and the time since the last circulation” (p. 5). Otherwise, if the mud pump is started ahead of time, then extremely high pressure can occur in the open hole.

2.3.2.2. Automatic Pump Start-up Limitations

Whilst making a pipe connection or tripping the string which has a float valve in the bottom hole assembly, air exists in the upper part of the string which can have a length of few tens of meters. Also, when running string in a hole, it can be several hundred meters long. In order to reduce non-productive time, the air column in the string should be replaced with a relatively high flow rate of fresh mud. As soon as all air in pipes is compressed and fluid starts to move, the flow rate should be reduced to the minimum level as built up pressure will start gel breaking procedure. This should help to prevent extreme pressure within open hole (Cayeux *et al.*, 2011). According to the same authors a Stand Pump Pressure (SPP) raises fast when the air column is being compressed and when fluid starts to flow. It was proposed that this is a good point at which the flow rate should be decreased to a minimum level.

The breaking of circulation has to be maintained for some period of time because the thixotropic fluid has time-dependent gelling behaviour. During gel breaking phase pressure can go beyond fracture pressure if the process is not handled properly. This period of time should be sufficient to ensure that circulation has achieved steady-state conditions (Cayeux et al., 2011). The authors claim that mud pump control system has to prevent increase in flow rate before completion of transient condition in order to achieve safe gel breaking-circulation operation. Once the transient period is completed, the flow rate should be increased to another level and downhole pressure maintained constant without exceeding the fracture pressure of the open hole formation. It is essential to assess the effect of downhole pressure variation for the entire openhole section, not just at the casing shoe as usually performed. Moreover, in the case of a narrow geo-pressure margin, areas of maximum limitation along the openhole section can be placed in different positions. This situation is presented in Figure. 2.6.

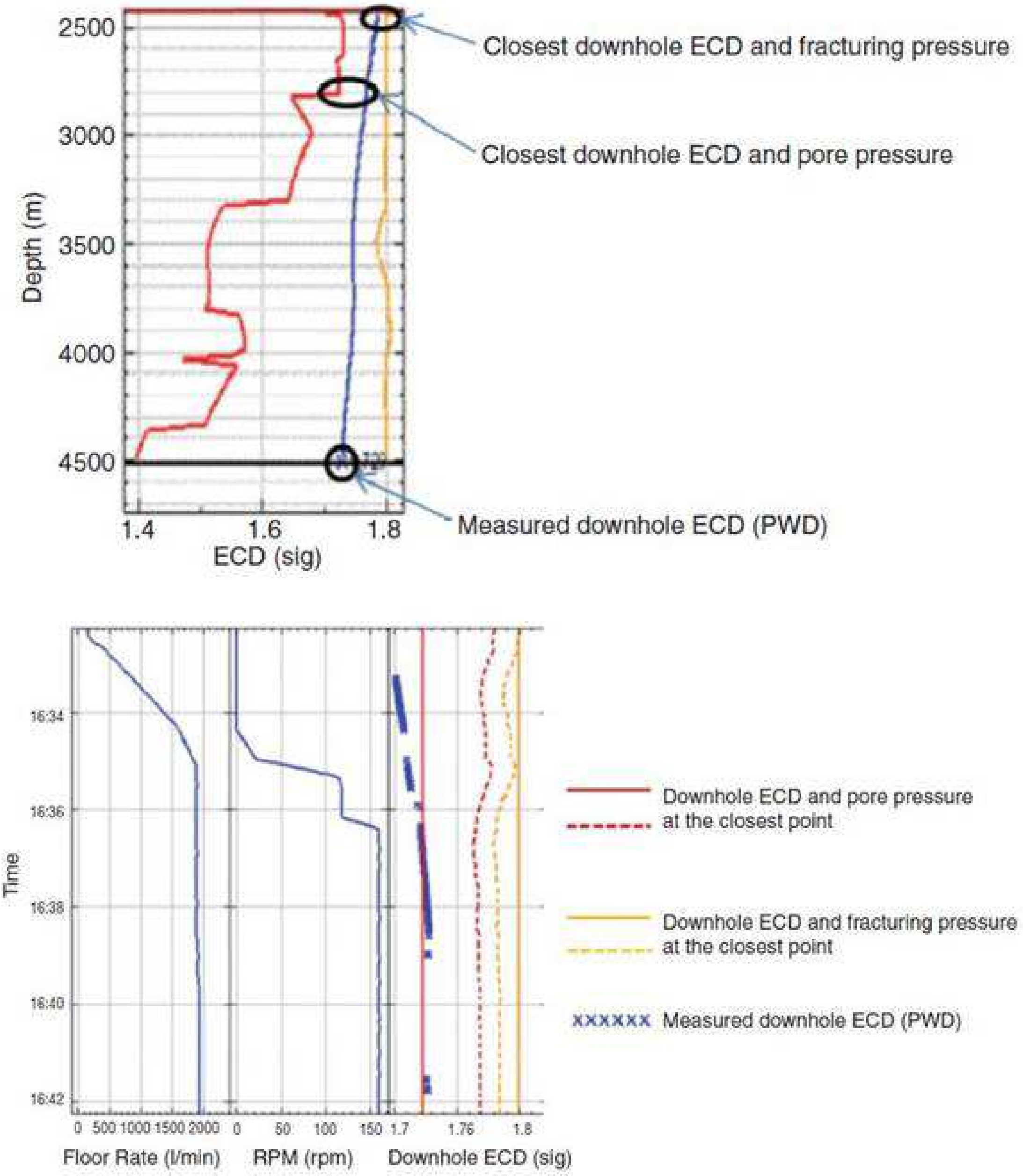

Figure 2.6: Graphs showing importance of performing pressure check along the whole open hole section and not only at casing shoe or the drilling bit (Cayeux *et al.*, 2011)

The first graph is depth based and shows calculated downhole ECD in the annulus (blue line) and computed value of ECD with PWD sensor at time 16:38:15 (blue marker). As can be seen in the first figure, between 2400 [m] and 2800 [m] measured depth (MD), there is a narrow geo-pressure margin. It is located just below the casing shoe at 2400 [m MD].

The second graph is time based. It shows the closest points of downhole ECD and pore pressure in red, and downhole ECD and fracture pressure in yellow together with measured downhole ECD labelled with blue marker. From this graph can be noticed the effect of the pump and top drive start-up on the downhole ECD margins at intervals from 16:32:30 to 16:36:20. However, in this time interval, the margins of PWD checked at the bit depth are frequent enough and not a limiting factor. Furthermore, the fracture pressure prognosis is sometimes described with a single boundary value, particularly when the Formation Integrity Test (FIT) is completed below the casing shoe. Anyhow, the pressure produced by the flow rate at the bottom hole cannot exceed the maximum acceptable limit. In order to support this, Figure 2.7, generated in a virtual rig environment, presents a mud pump start-up without control of acceleration or deceleration. This is a time-based log. On the downhole ECD log, at right-hand side, a pore pressure is shown as a red line and formation fracture pressure as yellow. Note that, when running the pump from 200 to 2000 [liters/minute], the downhole pressure exceeds formation fracture pressure and, on other side, when pumps are turned off, downhole pressure drops below the pore pressure gradient.

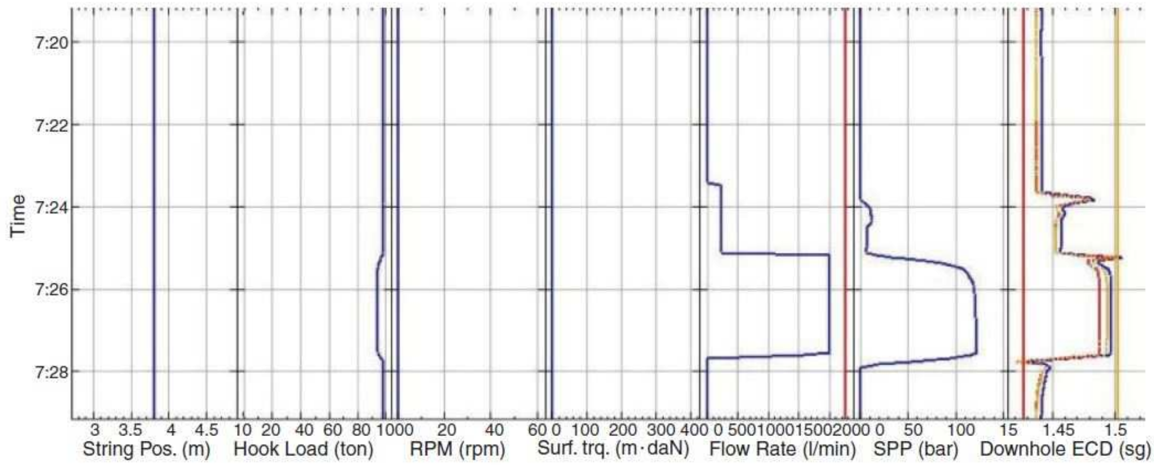

Figure 2.7: Mud pump start-up, with no control of the acceleration, neither deceleration (Cayeux *et al.*, 2011)

However, in order to reduce pump start-up time, best scenario would be if the flow rate is increased gradually and continuously, as already mentioned. In that sense, the driller conducts several stops, until the required flow rate is reached. Also, several acceleration steps are used in order to check if pressure is rising normally. According to Cayeux *et al.* (2011) each of these acceleration steps will increase a pressure which will be stabilized once the steady-state conditions are reached. Therefore “different pump accelerations should be used for each single step, depending on the current conditions and the following pump-rate level" (p. 42). In Figures 2.8 and 2.9, time-based logs produced in virtual rig environment are shown.

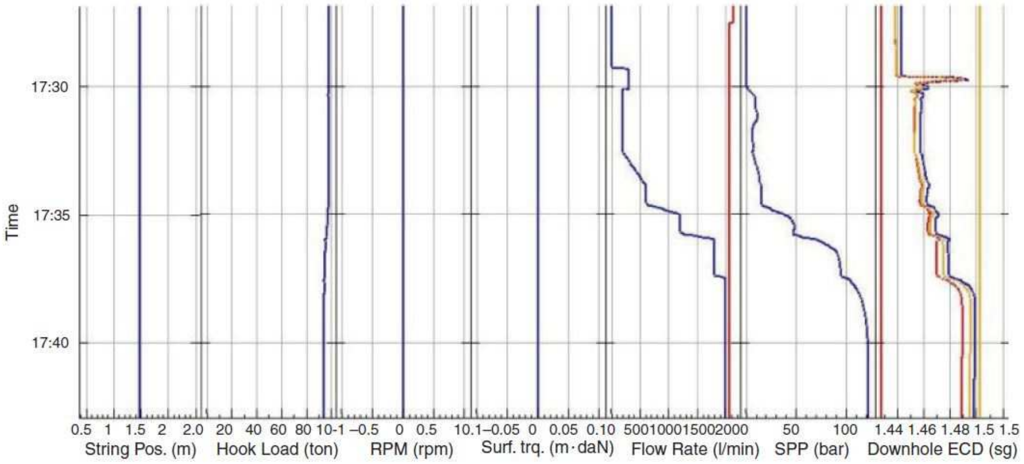

Figure 2.8: Mud pump start-up, with controlled acceleration (Cayeux *et al.*, 2011)

As can be seen in Figure 2.8, during the first step of pump start-up (follow flow rate line) the empty pipes were filled up with fresh mud at rate of 300 [liters/minute] and then, as soon as the pressure started to increase due to gel breaking, the flow rate was reduced to 200 [liters/minute]. Then, the next change to the rate of 600 [liters/minute] is achieved due to the smooth pressure increase and was kept until the flow rate reached steady-state condition. When this steady-state condition was reached, the pump was set to a larger flow rate of 1200 [liters/minute]. Moreover, the next step was introduced when the flow rate increased from 1200 to 1800 [liters/minute] and acceleration was quicker. Lastly, the flow rate was increased to the required flow rate of 2000 [liters/minute] (Cayeux *et al.*, 2011).

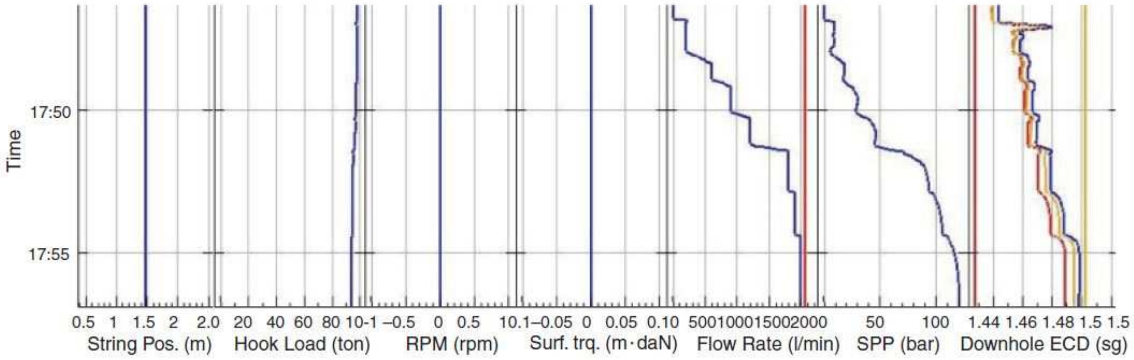

Figure 2.9: Mud pump start-up, with multiple intermediate steps (Cayeux *et al.*, 2011)

Pump acceleration steps are defined in accordance with a detailed procedure for drilling operations. Compared with Figure 2.8, it can be observed that the modification of accelerations is based on the next step of flow rate that has to be reached (Cayeux *et al.*, 2011).

Furthermore, the same authors claim that, in order to prevent the occurrence of formation fracture, when starts-up the pump, the acceleration should be faster up to intermediate level, because of big distance between circulation starting pressure and formation fracture gradient. On the other side, when accelerates the mud pump from high flow rate to the maximum flow rate, the acceleration should be limited to have monotonic rise.

Additionally, Cayeux (2012) asserts that “is possible to calculate the maximum pump acceleration from any given starting flow-rate to any other target flow-rate while respecting the two conditions: stay within the geo-pressure window and have a monotonic increase of the pump pressure” (p. 235). Figure 2.10 shows the maximum acceptable pump acceleration while starting from a given flow-rate to reach a target flow-rate.

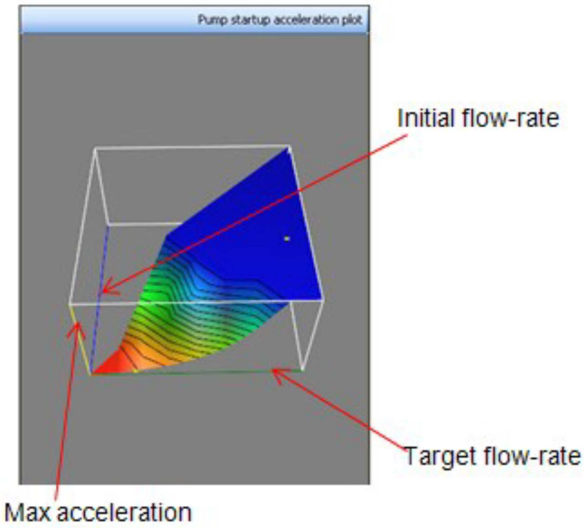

Figure 2.10: Maximum acceptable pump acceleration while starting from a given flow-rate to reach a target flow-rate (Cayeux, 2012)

However, in order to reduce non-productive time due to poor mud pump management, the industry has invested in research and development of better solutions for safer and more economically effective mud pump operation. Iversen *et al.* (2006) presented an integrated system for monitoring and controlling the drilling operation. Models for fluid flow and drilling mechanics, using the Kalman filtering technique, are constantly being updated in real time according to the measured data. Thus, by comparing calibrated models to real-time data, the undesirable events can be detected and manually, or by system control, mitigating action can be taken. Developed modules include pump start-up optimization and monitoring as well. An ideal acceleration curve, like sigmoid curve, for mud pump start-up is calculated by using this pump start-up module. The acceleration curve represents low acceleration at the start and higher values towards the end of the time interval. See Figure 2.11 which shows an ideal pump acceleration curve.

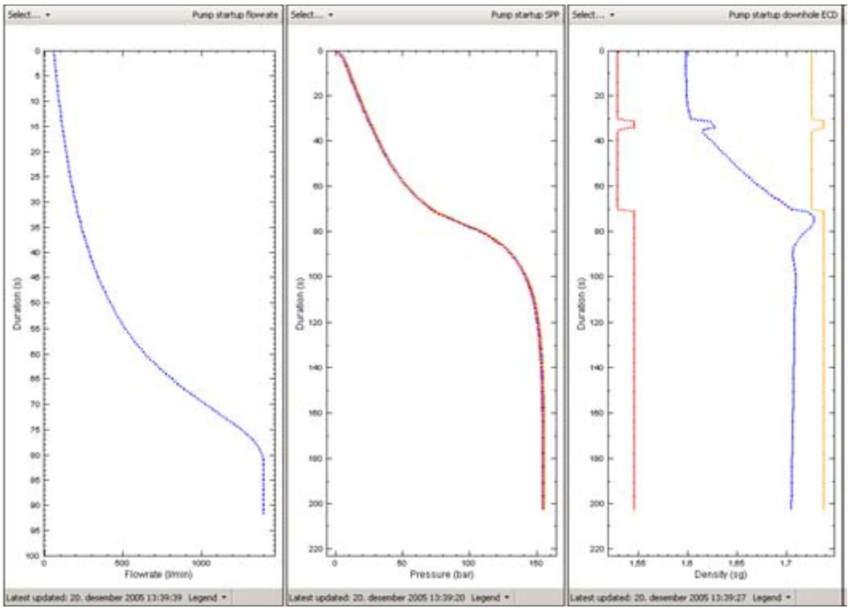

Figure 2.11: Ideal pump acceleration curve (Iversen *et al*., 2006)

The first plot in Figure 2.11 represents an ideal acceleration curve; the second plot is forecasted pump pressure based on the first plot, and the third one is ECD during pump start-up procedure is at the most critical point of the well. Furthermore, in case of a narrow geo-pressure margin (a narrow margin between pore and fracture pressure), the module can use two or even three ideal pump acceleration curves and additionally, a constant flow rate in-between as well (Iversen *et al.,* 2006). This curve is shown in Figure 2.12.

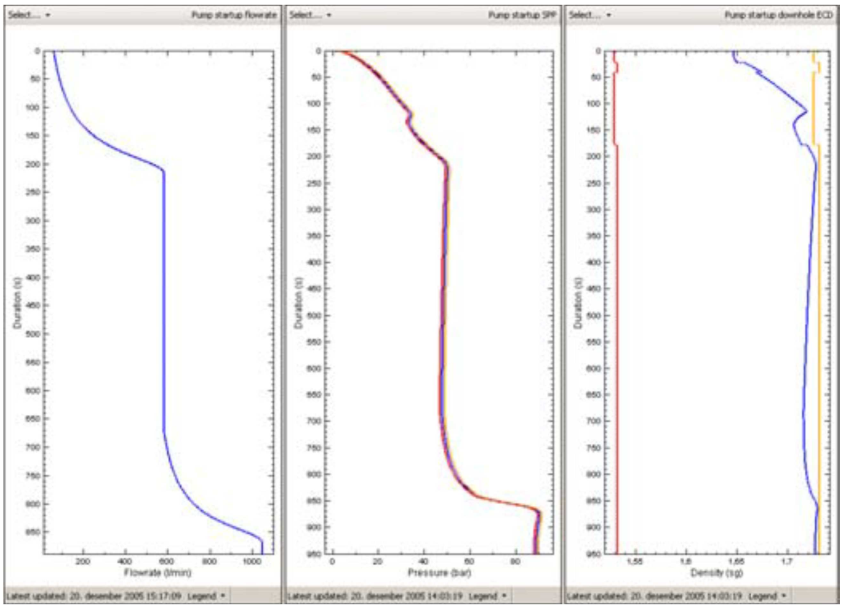

Figure 2.12: Two sigmoid curves with constant flow rate in between (Iversen *et al.*, 2006)

Iversen *et al.* (2006) explained that the model also ensures that the given pump rate is consistent with the open hole formations and equipment limits in the Bottom Hole Assembly (BHA). System reduces the target flow rate automatically if this one is not compatible with open hole formation and BHA elements. In order to avoid the potential imprecision of the gel strength and annulus pressure calculations, the model uses a safety margin that increases the geo-pressure limits. The ideal acceleration curve is roughly equal with a ramping function which is used to produce minimum time for each of the constant flow rate levels (see Figure 2.13).

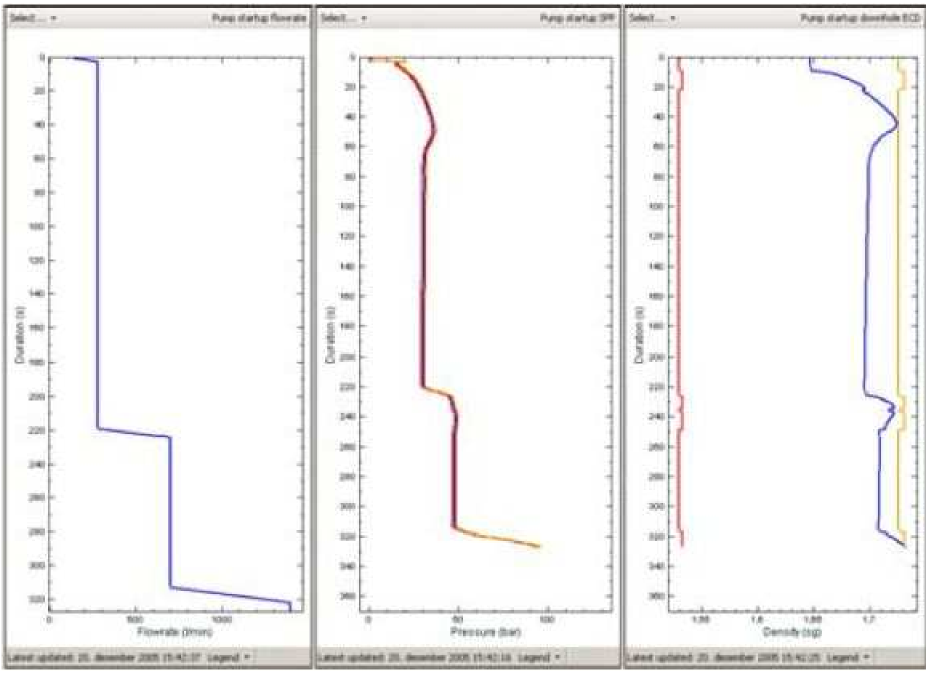

Figure 2.13: A pump start-up acceleration profile based on ramping (Iversen *et al.*, 2006)

Furthermore, as claimed by Iversen *et al.* (2006) this system was tested at ULLrigg, a full scale test facility at the International Research Institute of Stavanger, and the results were promising.

Moreover, Cayeux *et al*. (2011) proposed limits for maximal flow rate and automatic pump shutdown procedure in case of emergency situations as well. They presented a methodology for automation of an advanced mud pump management system that takes care of bottomhole pressure in accordance with the pore pressure and formation fracture pressure. Parts of the system are possible to test during a real operation and were already tested. The feedback received from the drillers involved in this test was positive. After the test was performed, Cauyex (2012) proposed a methodology used in an automatic drilling control system that assists the driller in managing the circulation. Especially, it takes care of mud pump acceleration when changing flow rate and limits actual flow rate to prevent the open hole section from fracturing. According to the same author, operational mud pump limits depends on operational parameters and in-situ conditions downhole as well. Furthermore, he described the complexity of safe mud pump management when conditioning mud, especially in terms of temperature differences over a short interval of time while drilling. This makes the situation even more complex due to the potential barite sag conditions as very modest information is available before the circulation is efficiently started.

3. Results and Analysis

For the purpose of this study, MATLAB® was used to establish gel breaking procedures while starting the mud pump and using thixotropic drilling fluids in horizontal wells. Such highly inclined wells involve the more risky situation for mud pump start-up process due to the possibility of high pressure peaks occurring and consequently, formation fracturing. The aim was to develop a reliable model which can simulate thixotropic drilling fluid behavior. Two MATLAB® codes were produced, one for conventional (see Appendix B.1) and the other for automated mud pump start-up method (see Appendix B.2). Furthermore, detailed descriptions of the MATLAB® source code for both methods are included in Appendix A.

An idea was to set a model which represents a conventional method as close as possible. In this case driller operates mud pump manually with slowly, stepwise increase of the flow rate in order to avoid pressure peaks and break the gel without formation fracturing. In light of this, assumption was made that the driller reduces or increases the flow rate by accelerating the pump with the same step sequence. This corresponds to the following scenario: initially the pump is operated at the required flow rate of 2500 [litres/minute]. Afterwards the pump is ramped down intentionally and the flow rate was decreasing linearly until totally stopped. For instance, this could be due to mating of drill pipes which requires approximately 5 minutes. This operation is fairly regular during drilling operations where usually 3 pipes are connected and form a stand of approximately 27.5 meters (90 feet). These stands are connected while drilling which means that for a 2000 (meters) long well, which is used in this MATLAB model, the connection procedure is run 73 times. Each time the pipe connection work is carried out, the pump has to be stopped and when connection is finished, it is restarted again. When the mud pump is stopped, the fluid flow rate is gradually decreased until it reaches zero.

The model simulated gel build up procedure. An assumption was set that if flow rate goes below the 50 [litres/minute] the gel starts to build up. While performing pipe connections, the gel strength has already been formed in order to keep cuttings from free falling to the well base. After connections are made up, the pump is started-up and required flow rate is reached again. Increase in flow rate, while starting the pump, leads to a pressure build up which initiates the gel breaking procedure. Furthermore, sudden partial plugging of the pipe due to high flow rate is simulated as well. The assumption was set that the inner diameter of the pipe decreases 2 minutes after the pump reaches required flow rate.

An automated method of mud pump start-up procedure was simulated with similar code, and only some parameters were changed. Generally, the same procedure was simulated. The idea of an automated method is to avoid pressure peaks which can lead to formation fracturing. In order to achieve this, mud pump acceleration should be increased gradually that the gel breaking process can be performed with sufficiently high flow rate. Accordingly, the pressure increase will be low. After all the gel is broken down, the estimate is to set the flow rate on the maximum required level as fast as possible and leaving no risk for the possibility of formation fracture. Therefore, the driller reduces flow rate with the same step sequence. When the mud pump is ramped down, the fluid flow is decreasing until it entirely stops. The change, compared to conventional method, was when the pump is started-up. In that sense, when pressure in the pipe is low, acceleration is slowly increasing. This slow and smooth increase breaks the gel with sufficiently high flow rate and pressure, avoiding pressure peaks. Furthermore, when all the gel is broken down the pump acceleration can be rapidly increased to the required flow rate, with no risk of pressure peaks occurring or appearance of sudden partial plugging of the pipe.

The MATLAB® models of conventional and automated methods for pump start-up procedures when working with thixotropic drilling fluids were simulated and the figures were plotted. The figures, showing the same parameters of both conventional and automated methods are compared and discussed.

Flow Rate Through the Pipe

Figure showing flow rate through the pipe is important for the hole cleaning operation since it shows effectiveness of cuttings transport. The graphs for both coventional and automated methods are shown in Figures 3.1 and 3.2 respectively. As stated before, in order to break the gel the driller controls the flow rate manually in the conventional method, while in the automated method the pump start-up procedure is controlled by an automated system. In the conventional method, the driller starts the pump and increases flow rate stepwise all the way up to 2500 [litres/minute]. In this case, the driller needs to perform continuous small increases of flow rate continuously resulting in a gradual pressure increase for breaking the gel. Each step, when the flow rate is increased, the driller has to wait until a steady state condition is reached before an additional increment is added. Furthermore, as can be seen in Figure 3.1, the stepwise process has linear gradual transition until the required flow rate is reached. Also, it is difficult to identify when all the gel is broken down and when the required flow rate can be reached with no risk of sudden pressure peaks leading to formation fracturing. Therefore it is important to have an experienced driller in this position. This is an important prerequisite for performing the job well and safely.

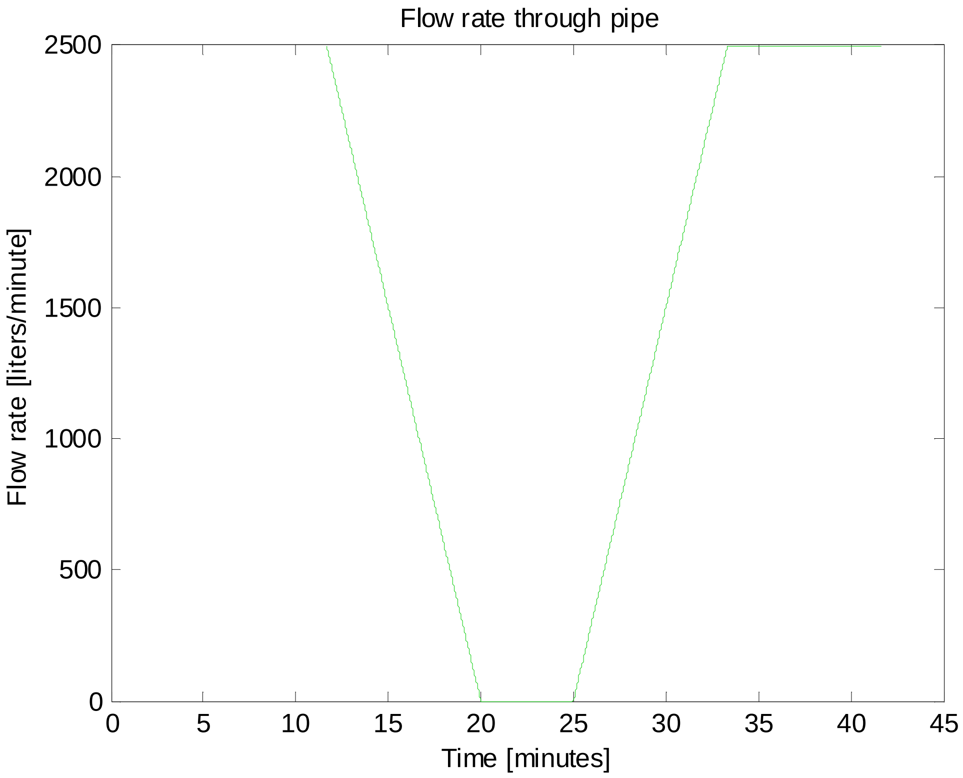

Figure 3.1: Flow rate through pipe when using conventional method

The idea of the automated method is to make sure that all the gel is broken down before the required flow rate is reached with no fear of sudden pressure peaks and fracture of the formation. An automated pump can control flow rate very gently, with smooth and gradually increasing flow rates, in order to break all the gel with the lowest flow rate possible. As can be seen in Figure 3.2 below, when the pump is started, it initiates breaking of the gel and the flow rate linearly increases up to 100 [liters/minute] over the course of 6 minutes. Straight after, the flow rate of gel breaking process grow exponentially up to 304 [liters/minute]. Once the entire gel is broken down, 10 minutes after pump start-up, rapid increase in flow rate up to the required value is possible, which is in this case is 2500 [litres/minute], without risking fracturing of the formation due to overpressure.

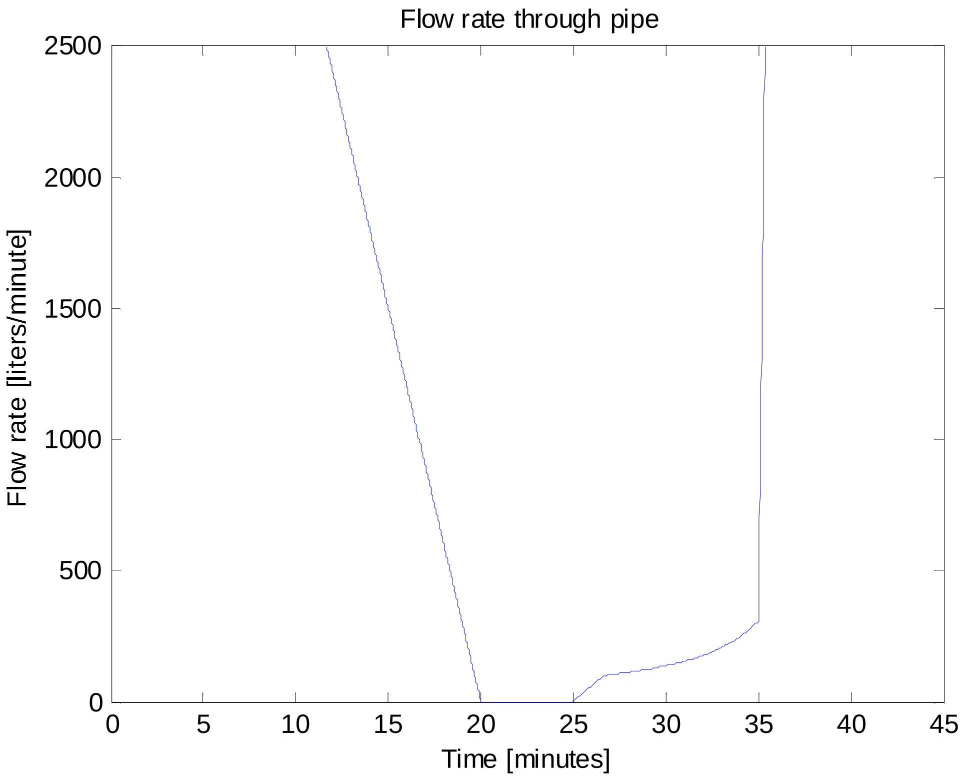

Figure 3.2: Flow rate through pipe when using automated method

Pressure at the Pump

Besides the flow rate figures and by using the same MATLAB® models, the next plotted figures showing pressure at the pump. These figures show pressure behaviour when turning off and starting up the main mud pump. The pump pressure plots for both conventional and automated methods are shown below in Figures 3.3 and 3.4 respectively.

In Figure 3.3, generated by using the model of conventional method, it can be seen that when the pump is turned off, there is a smooth, almost linear decrease of pressure until it reaches zero. After the 5 minutes needed for stand connections, the gel is once again formed. When pump starts-up, the sudden pressure peak of 10 [bar] is formed, which is an undesirable event. This pressure emerges due to the gel breaking process. As the driller operates the mud pump manually, it is difficult to control pressure peaks. Nowadays however, drillers manage this by a stepwise increasing the flow rate as mentioned previously. After the peak occurs, it can be seen that pressure grows exponentially until the required flow rate is reached. Furthermore, as drillers are trying to reach required flow rate in the shortest time possible with no incident, this can consequently cause sudden partial plugging of the pipe. This corresponds to the situation shown in Figure 3.3, where driller increases the flow rate to the required value, but as an undesirable effect, pressure increases due to the sudden partial plugging of the pipe. This situation was simulated 10 minutes after the mud pump start-up as shown in the figure. The pressure rises to 63.1 [bar], which is above the full flow rate pump shut in pressure of 61.6 [bar].

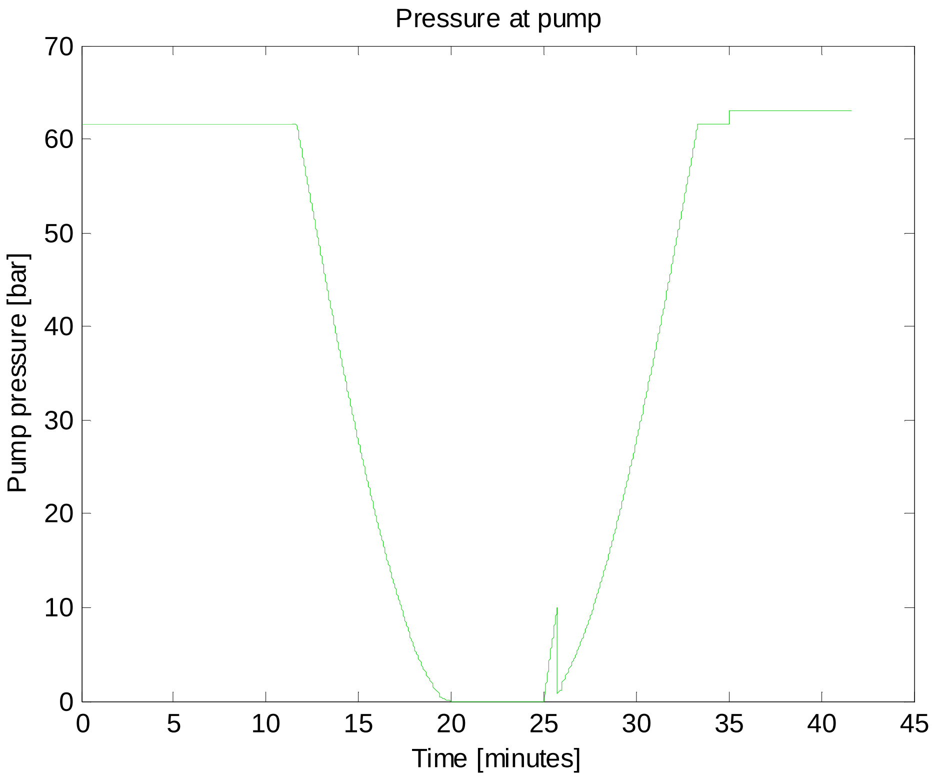

Figure 3.3: Pressure at pump when using conventional method

In the case of the automated method, the exponential decrease of pressure, once the pump is turned off, is the same as in the conventional method. When the pump is started-up, the increase in flow rate increases pressure linearly up to 5 [bar] as shown on the graph. Afterwards, the pressure remains constant for 10 minutes until all the gel is broken down as simulated. After this time sequence, the pressure suddenly increases as the flow rate grows until the required value of 2500 [bar]. Actually, the main advantage of the automated method- to keep the pressure constantly low until all the gel is broken down and then to reach the required flow rate as fast as possible while avoiding pressure peaks.

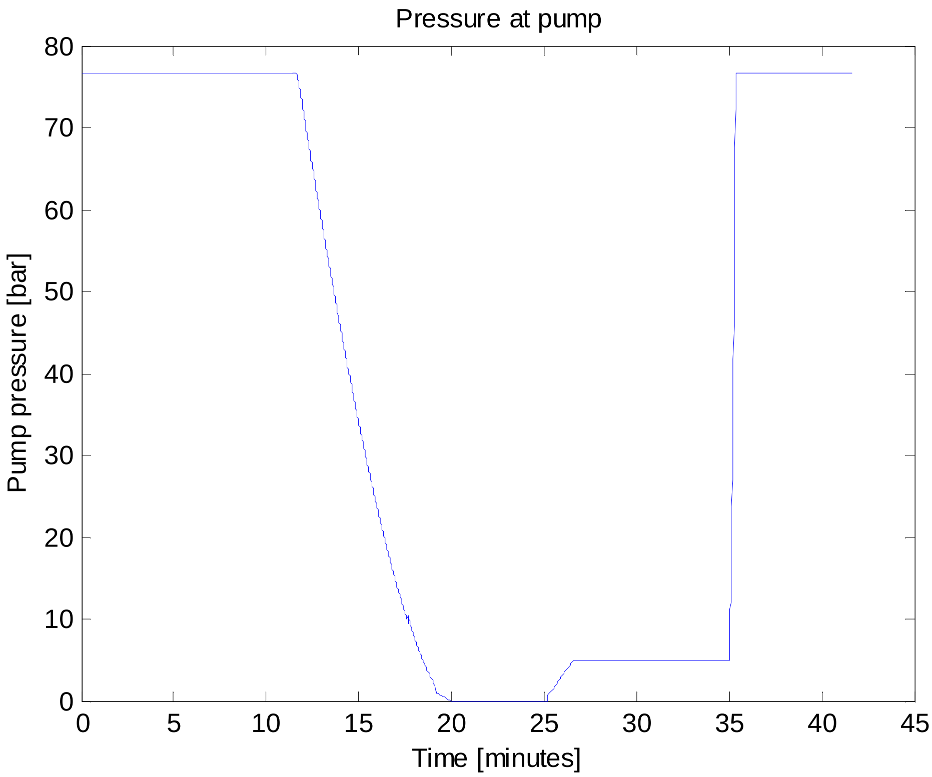

Figure 3.4: Pressure at pump when using automated method

The plots showing pressure at the pump and flow rate through the pipe for both methods were generated with noise effect. Those figures are plotted with small random deviations in simulated method. Also, for the same reason, those figures were generated in the presence of high pass and low pass filters. The figures are presented in Appendix B.1 and Appendix B.2, depending on the method they belong to.

Viscosity Behavior

Further, the following figures show the viscosity behavior during mud pump shutdown and start-up processes. The figures are presented below in Figures 3.5 and 3.6 for the conventional and automated methods respectively. The simulated model uses the same thixotropic drilling fluid mentioned previously which has time independent behavior and it can show gelation in the static period as stated before. From the first graph it can be noted that viscosity is constant over constant flow rate. When the pump is turned off the flow rate goes down and the viscosity value starts to rise linearly. It rises until the flow rate reaches below 900 [liters/minute], and then follows an exponential decrease until the flow rate reaches zero. Once the flow rate is zero, viscosity increases rapidly due to the gelation behaviour of thixotropic fluids. The viscosity rises in the 5 minutes during which the pipe connections are made up. In this time sequence it reaches 19 times larger values in the simulated model. This behaviour is called '*gel build up process*'.

As described before, it is assumed that gel starts to build up when the flow rate decreases below 50 [liters/minute]. After the pipe connection is finished and the pump restarted, approximately 10 seconds later, the viscosity starts to slowly decrease. This decrease lasts about 35 seconds and then in a 2 milliseconds rapidly decreases to about a 12 times lower value. The flow rate difference in 2 milliseconds is from 220 to 225 [liters/minute]. This behaviour is known as '*gel breaking process*'. After the gel breaking process is finished, a slower decrease in viscosity due to the shear thinning effect of thixotropic fluid is noticed. Afterwards, the viscosity remains constant. Between periods when the pump is started-up again until the moment when the viscosity is at a constant value, the flow rate is continuously increasing. Once the flow rate reaches the required set value it becomes constant as well as the viscosity.

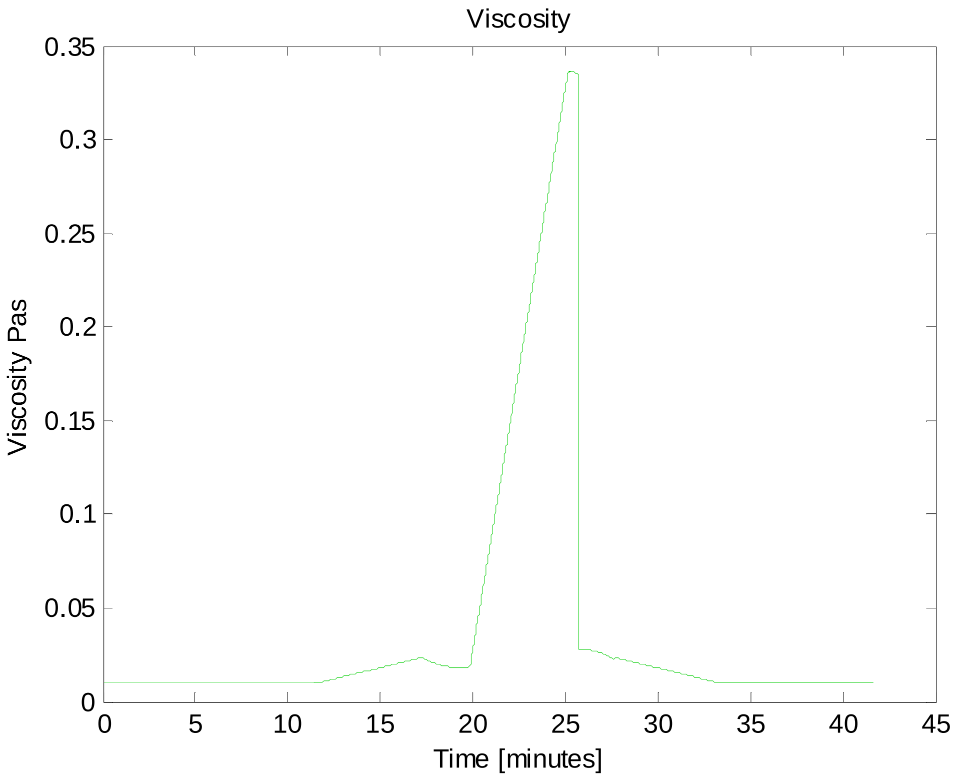

Figure 3.5: Viscosity behavior when using conventional method

Viscosity behavior when using a simulation of automated method, as shown in Figure 3.6, is different when compared to that of a conventional system. After the mud pump is turned off, viscosity changes from a constant value to a small linear increase. Precisely, while flow rate is decreasing, viscosity linearly increases for about 6 minutes. After this time viscosity values became unstable for about 8 milliseconds and it displayed a zigzag behavior (i.e. cycling from high to low values as per Figure 3.7). Once it stabilizes again, the viscosity value increases with a flow rate at that point of 960 [liters/minute]. Furthermore, while the flow rate decreases towards 50 [liters/minute], the viscosity remains constant. After the flow rate drops below 50 [liters/minute], viscosity starts to rapidly increase. It keeps increasing while the pipe connection is performed. Also, once the pump starts-up and the flow rate reaches 50 [liters/minute], viscosity increases and reaches 13 times larger values than previously recorded. This is the '*gel build up process'* as stated before.

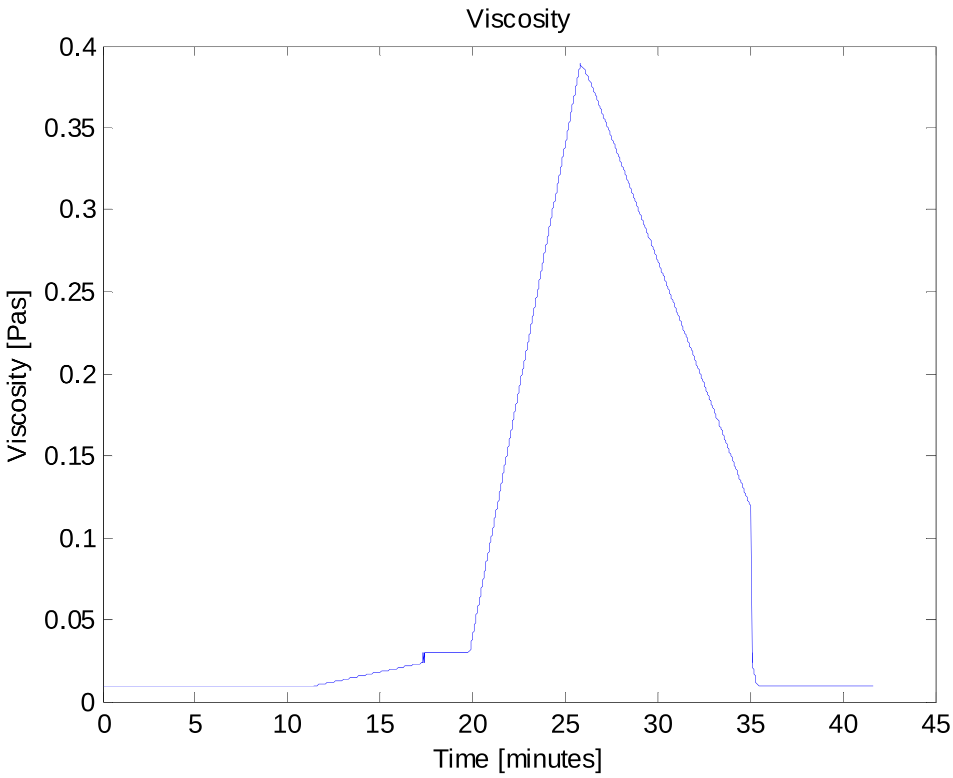

Figure 3.6: Viscosity behavior when using automated method

On the other hand, once the flow rate increases beyond 50 [liters/minute], the gel break up process starts. In this period, the viscosity decreases linearly until the flow rate reaches 304 [liters/minute]. After that, viscosity drops sharply, indicating that all the gel is broken down. In the time sequence of 8 milliseconds, flow rate reaches 805 [liters/minute]. However, the viscosity does not return to the same value as before the pump was turned off. It continues decreasing linearly, but taking on a different slope. This slope is due to the shear thinning effect of the thixotropic fluid. Once the flow rate reaches the required value viscosity starts to be constant and maintains the same value before the mud pump was turned off.

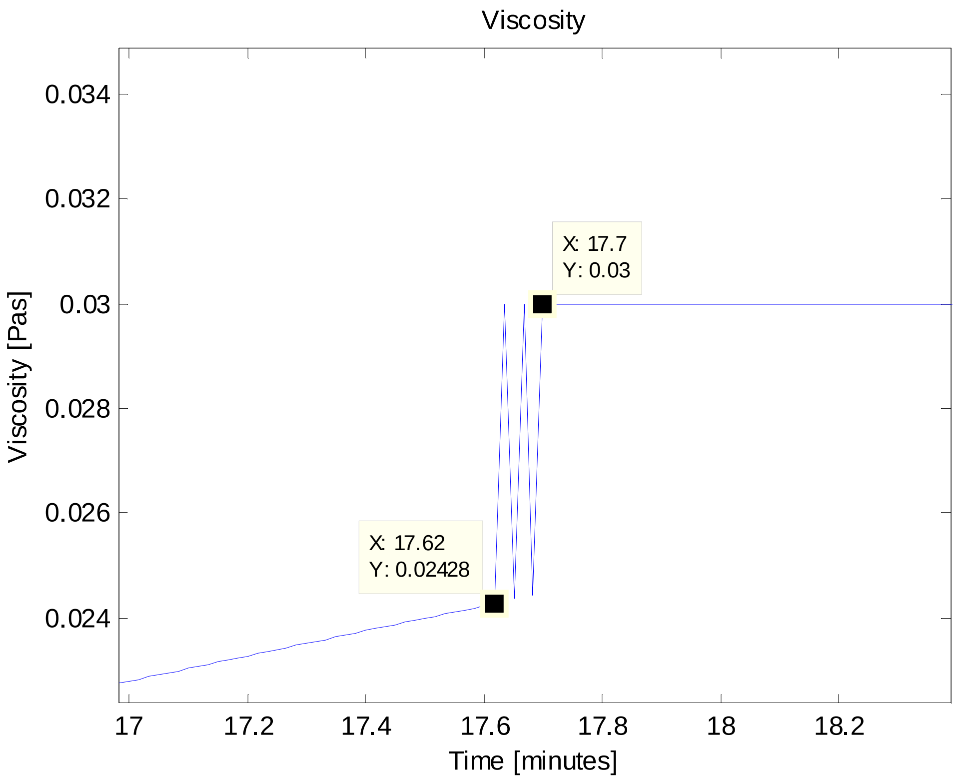

Figure 3.7: Zoomed zigzag behavior of the flow rate while automated method

Pump Pressure Limitation during Gel Breaking Phase

Nowadays, drilling engineers always bear in mind (in order to circulate thixotropic drilling fluid) that they have to break the gel before the flow rate reaches required value when they are starting the pump. Otherwise, there is a possibility of high pressure peaks causing the formation to fracture as previously described. Therefore, drillers start the pump stepwise continuously until required flow rate is reached. However, they are very often unsure when all the gel is broken down, thus high pressure peaks might still occur. Therefore, continuous stepwise flow rate increase is applied until the required flow rate is reached. This reduces the efficiency of cuttings transport and increases run up times since the required flow rates are not reached as soon as possible.

The figure below shows for the conventional method, a slow ramp rate in the beginning of gel breaking phase.

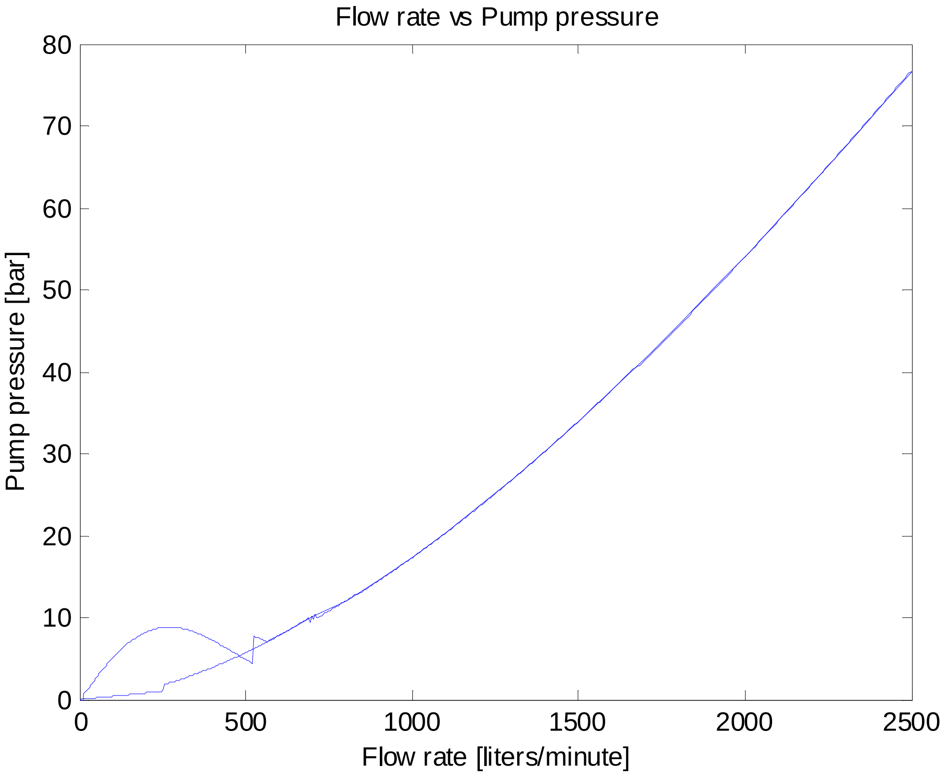

Figure 3.8: Conventional method with slow ramp rate in the beginning of gel breaking phase

Observing the graph, two lines one below the other, are identified. The one on the bottom represents pump pressure versus flow rate when the pump is turned off, and the other represents the pump pressure versus flow rate when the pump is started-up. If the driller accelerates the pump with very slow incremental increases of the flow rate and doing so until required flow rate is reached, the pressure peak in the beginning of the gel breaking phase will be high. As shown in Figure 3.8, it is around 10 [Bar]. As already described, this high peak is undesirable as it can lead to occurrence of formation fracturing and loss of circulation. In addition, circulation can be lost and further lead to well collapse as well. All this will increase non-productive time as in that case well has to be plugged and sidetracked.

In the case of the automated method, the pump operation is supposed to break all gel under sufficiently high flow rate. In this way high pressure peaks are avoided. In order to find out when all the gel is broken down, the graph of pump pressure limitation during gel breaking phase when using automated method is shown in Figure 3.9 below.

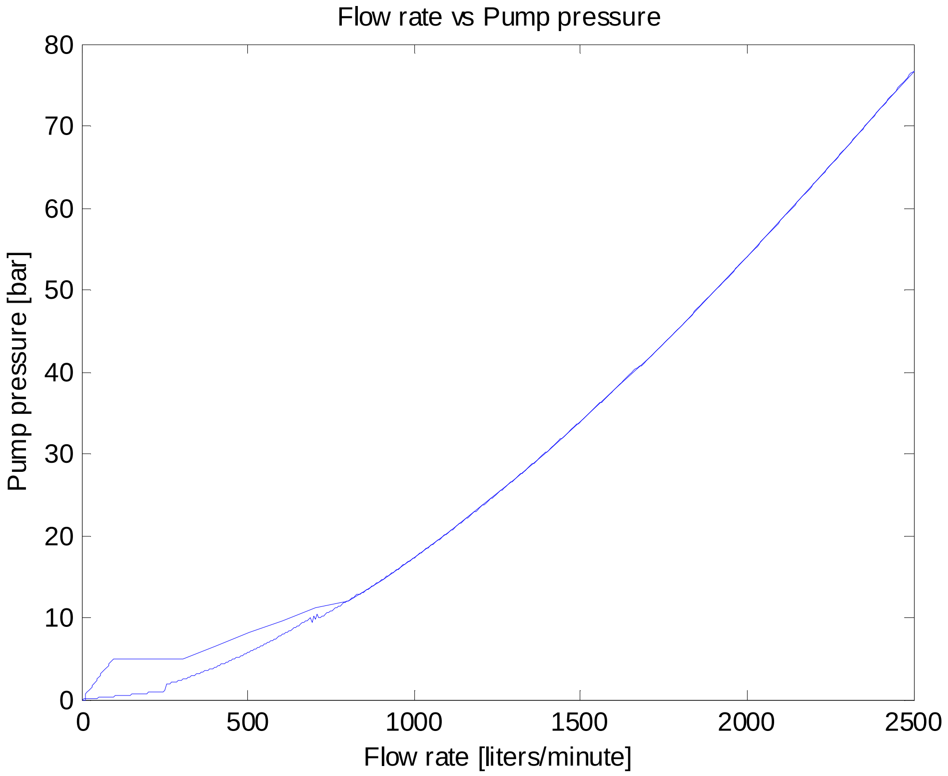

Figure 3.9: Automatic using pump pressure limitation during gel breaking phase

When starting the mud pump, the flow rate starts to build up slowly. The pressure remains zero until flow rate reaches 12 [liters/minute]. This phenomenon is due to the pumping of mud in the newly connected pipe, i.e. air was replaced with fresh mud. Afterwards, the flow rate starts to build pressure against the gel in the circulation system, compared to the line of pump pressure versus flow rate when the pump was turned off. With a small increase in flow rate, the pressure starts to rapidly increase. Fresh mud attempts to displace old mud that is now gelled. Furthermore, the pressure rises until it is higher than the gel strength of the old mud. Thus a gel breaking process commences. The pressure continues to rise rapidly while the flow rate is gradually and smoothly increasing. At the point when the flow rate reaches 100 [liters/minute], the pressure becomes unstable due to the gel breaking process. It shows cyclic behavior (noise) around 5 [Bar] as shown in Figure 3.10. This cyclic behavior has a transient trend in the horizontal direction. It starts with higher frequency and reduces over time, while flow rate increases to the value of 270 [liters/minute]. However, this noise is also affected due to MATLAB® simulation- in real settings noise will be less. Afterwards, the pressure suddenly decreases slightly until the flow rate reaches 304 [liters/minute]. As shown before, this is the value of the flow rate when all the gel is broken down.

Thereafter, the pressure curve starts to suddenly increase, however it is only at approximately 3 [Bar] higher in comparison to the curve of the flow rate when the mud pump is turned off. This behavior is due to the shear thinning effect of a thixotropic fluid. However, the pressure line starts to gradually decrease towards the flow rate line. It keeps that trend until it overlaps with the flow rate curve at the value of 805 [liters/minute]. At this point both lines match. Thus, the line when the pump is turned off and the line when the pump starts-up have the same trend up to 2500 [Liters/minute], which is the required flow rate. This graph might be helpful as by applying it, drillers can calculate when all the gel is broken down and therefore, when higher flow rates may be applied without risking pressure peaks.

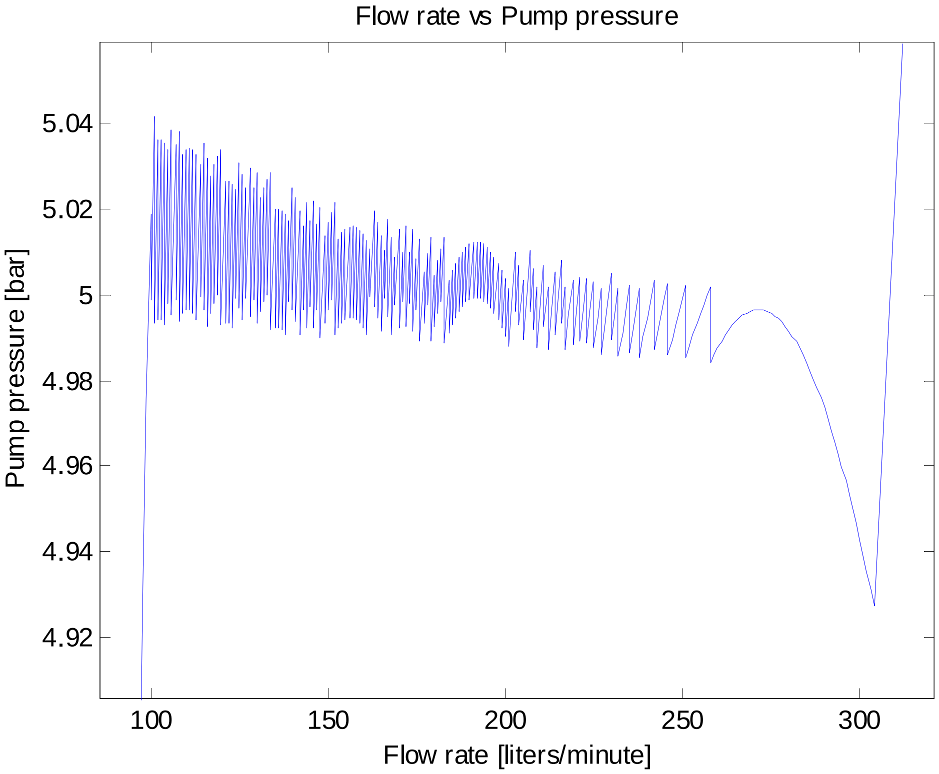

Figure 3.10: Zoomed zigzag behavior of the pressure line extracted from the Flow rate graph versus Pump pressure figure when using automated method

Furthermore, by performing MATLAB® simulation for both methods on the Reynolds number, when mud pumps starting up procedure were generated as well. Those figures are not considered as an essential part of this dissertation and therefore are not discussed further here. Thus, they are included in Appendix B.1 and B.2, depending on method they belong to. However to recap a Reynolds number up to 2300 represents laminar flow and, for greater values, signifies turbulent flow.

4. Discussion and Limitations

As a final point, the modelling of the conventional and automated methods of the mud pump start-up procedures, when working with thixotropic drilling fluid, helped to simulate and allow observation of behaviour of parameters that are important for safe performance and good control of drilling operations in highly inclined horizontal wellbores. Hence, the relevant plots were generated and described above. By parallel comparison of both methods, it is noticed that the automated method might help us to reduce the risk probability of high pressure peaks occurrence and, possibly, formation fracture. Thus, the operations become safer and with reduction of non-productive time. Furthermore, these findings can contribute to a better Health, Safety and Environment control.

Even though the automated method of pump start-up eases drilling operations, a driller cannot be left out of the process itself. Rather, he should control this process by checking the figures plotted during automated mud pump start-up and by observing the behaviour of important parameters he can react timely. Furthermore, in order to be sure when the entire gel is broken down, he should use a figure of pump pressure limitation during gel breaking phase when using automated method and, by doing so, rapidly acquire the required flow rate. In addition, if this is achieved, good hole cleaning can be performed immediately after all the gel breaks down. Thus, setting of cuttings and production of a cutting bed can be largely avoided by reducing the possibility of stack pipe. In this sense, it can reduce the total cost of the well.

The automation of mud pump start-up procedures is very new to the industry and still requires further research. A relative lack of literature within this field was experienced while writing this dissertation. However, some of the recently published papers were essential in building a more complete picture of this topic.

Furthermore, the assumptions made may reduce accuracy of the results. In this sense, the realisation of the small scale flow loop experiment in laboratory conditions with necessary equipment could contribute to better clarification of assumptions made and possibility for testing them.

Although it was aimed to produce the most precise and reliable results, it must be admitted that the short time period within which the thesis was written and assumptions made were limiting factor.

The MATLAB® models did not include temperature effect within the simulation and as one of the factors that affects drilling fluid rheology. Moreover, fluid compressibility is a parameter that should also be included.

Overview of the results is shown Table 1.

Table 1: Comparison of conventional and automated models

Mud pump start-up procedure when using thixotropic drilling fluids	**Conventional method**	**VS** **Automated method**
Flow rate through the pipe	-Stepwise increase in flow rate all the way up to the required flow rate -Big transient conditions -Required flow rate reached slightly faster -Pump operated manually by driller	-Gradually and smoothly increase in flow rate while gel breaking process. The pump reaches required flow rate immediately -Small transient conditions -Required flow rate reached slightly slower
Pressure at the pump	-Sudden pressure increase while gel breaking process	-Constantly low pressure while gel breaking process
Viscosity behavior	-Slightly faster breaks gel strength	-Gradually but slightly slower breaks gel strength
Pump pressure limitation during gel breaking phase	-Occurrence of pressure peaks	-Occurrence of pressure peaks is prevented

5. Future Works

A future work on this concept should include a temperature effect and fluid compressibility as in the simulation. In my opinion, more complex groups of formulas should be applied in order to make precise model that simulates exactly the same behaviour as the real fluid.

Furthermore, besides the simulation, a next step should be a small scale flow loop experiment where many different types of thixotropic drilling fluid can be circulated and accurate data measured. The existence of a database of real measurements can help make better assumptions. Besides the start-up pressure limitations, the focus should be extended on the other parts of automation of mud pump management such as maximal flow rate limits and automatic pump-shutdown procedure in case of atypical situation.

Therefore, there is still a need to conduct more small scale experiments of in laboratory conditions as well as real rig settings in order to produce high-quality and consistent data that would enable a comparison of current and future results and also enrich a scientific data. This could solve the main vagueness of the concept and bring it even closer to the realization.

6. Conclusions

The process of automation of mud pump management is nowadays very important and prioritised in the oil and gas industry as today's needs increase risk of serious problems occurring when drilling long and highly deviated wells in formation with narrow geopressure margins. Such problems include packoffs, formation fracture, loss of circulation, etc. Thixotropic drilling fluids enhance a hole cleaning in a wellbore during connections, but it gives challenges when starting the pump. Pressure peaks are typically seen when starting the pump manually after a connection.

A reliable model that can simulate thixotropic drilling fluid behaviour for conventional and automated mud pump start-up procedure was developed in this thesis. Precisely, this model stimulates gel build up and break down procedures combined with shear thinning effect during mud pump start-up operation when using thixotropic drilling fluids. Established model can help to better understand how the mud pump should work and indicates possible improvements in drilling operations as well. The main advantage of this model is that it can control the pressure in the circulation system as one of the most dangerous parameters that can cause serious problems in operations.

By comparing of both simulated models, conventional and automated, it is found that automated method can better control pressure by preventing the occurrence of pressure peaks. Also, this method controls flow rate very efficient, with smooth and gradually increase in flow rates, in order to break all the gel with the lowest flow rate possible, and to keep the pressure constantly low until all the gel is broken down. In this way required flow rate can be reached as fast as possible while avoiding pressure peaks.

On the other hand, the findings show that the operation of conventional model is slightly faster than automated one. In light of this, in order to optimise a rig time, operators always strive to minimise any operation as much as possible by choosing “faster” solutions, since the rig time is very expensive. Thus, in order to develop and implement mud pump automation in the oil and gas industry it should be developed to be faster as well.

In terms of automated starting of mud pump procedures when working with thixotropic drilling fluid, the oil and gas industry would need more small scale concept experiments in laboratory conditions as well as real rig operation experiments before making decision to implement it to the real rig operation.

The theoretical results found in this thesis where pressure peaks are significantly reduced during pump start-ups, indicate that automations of pump start-up should be implemented in real operation at the field in the near future.

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Appendix A - Comments to MATLAB Source Code Implementation

In order to set calculation for both simulations, a nomenclature of main parameters was defined first. Flow rate was set to be 2500 $[\mathrm{litres/minute}]$, pressure in the pipe of 50 [bar], length of flow loop 2000 [m], density of fluid was 1000 [kg/m^3] and gravity constant $\mathrm{g} = 9.81\ [\frac{\mathrm{m}}{\mathrm{s}^2}]$. Furthermore, inside area of a pipe was calculated with formula $\mathrm{A} = \ \pi * \frac{\mathrm{D}^2}{4}$. In addition, hydraulic diameter of the pipe (D) was set to be 0.1 [m]. Viscosity of thixotropic drilling fluid was assumed to be $\mu = 30 * 10^{-3}$ [Pas] = 30 [cP]. Subsequently, a volume in the flow loop system was calculated as $\mathrm{V} = \mathrm{L} * \mathrm{A}\ [\mathrm{m}^3]$. Also, roughness for steel pipe was set as 0.045$*\ 10^{-3}$[m]. For the better overview see Table 2 below.

Table 2: Defined parameters

Defined parameters:

g=9.81 [m/s^2]
Q = 2500 $[\mathrm{litres/minute}]$
P = 50 [bar]
L = 2000 [m]
ρ = 1000 [kg/m^3]
D = 0.1 [m]
μ = 30 [cP]
ε = 0.045$*\ 10^{-3}$[m]

The pipe was horizontal with steady state flow. Accordingly, inlet pressure is directly proportional to frictional pressure drop in the pipe plus pressure at the outlet.

p_i = p_f + p_o ………………………………………………………………………… (1)

where frictional pressure drop in the pipe was calculated according to Darcy–Weisbach equation with included Fanning friction factor as follows: (Nygaard and Godhavn, 2013)

P_f = ΔP = $(2 * \rho * f * L * \vartheta^2)/D$ ………………………………………………………………………… (1)

Parameter f represents the Fanning friction factor and all the other parameters are listed in nomenclature chapter.

For simulating the fluid flow through the pipe, a “for loop” function was used in this MATLAB® code. This function represents a time and simulates fluid flow through the pipe in a certain period of time. In the for loop function variable “i” was count from 1 to 2500 [seconds] for both methods (Nygaard and Godhavn, 2013).

A.1 Existing Methods for Mud Pump Start-up

In order to simulate changes of flow rate (q_p) in the model of conventional method while turning off and starting the pump, the flow rate was set to change according to the following plan:

In case of conventional method the driller reduces or increases flow rate by acceleration of the pump with the same step sequence of 300 [liters/minute per minute]. In Figure A.1 a sample code of the pump operation is presented. This corresponds to the following scenario: initially the pump is running at 2500 liter/min. After 11.5 minutes the pump is ramped down using a deceleration of 300 [liter/minute per minute]. The flow rate was decreasing linearly and totally stopped at 20.25 minutes. Then the model represents scenario of pipe connection work which takes 5 minutes. In that case the pump was off, as usually is in real operation. In addition the model was simulated gel build up procedure. After these 5 minutes the pump was ramped up at 25 minutes and it was reached required flow rate at 33.33 minutes. In between a gel breaking procedure was simulated. Furthermore, sudden partial plugging of the pipe due to high flow rate was simulated as well. The assumption was set that, due to the sudden partial plugging, inner diameter of the pipe was decreased 2 minutes after the pump reached required flow rate.

```
maxCount = 2500;

q_p = 2500/60000; % flow rate [m^3/s]
p_p = 50e5; % Pressure in the pipe [Pa]
D = 0.1; % inside diameter of the pipe [m]

% main iteration loop
for i = 1:maxCount

% change mud pump rate
```

```
 if (time > 700) && (time < 1300)
    q_p = q_p - 5/60000; % reducing with 5 [l/min per sec]
 end

 if (time > 1500) && (time < 2001)
    q_p = q_p + 5/60000; % increasing with 5 [l/min per sec]
       end

 if (time > 2100)
    D = 0.0995; % sudden partial plugging of the pipe
 end

if q_p < 0
   q_p = 0;
end
```

Figure A.1: Changing of flow rate set in the MATLAB® code – Conventional method

For making code to simulate a gel build up process, an assumption was made that gel starts to form when flow rates is less than 50 [liters / minute]. A following formula for gel build up was used: $\mu = \mu + 1 * 10^{-3}[\mathrm{Pas}]$. This formula represents that when flow rate is less than 50 [Liters / minute], viscosity (μ) growing up for 1 [cP] each second. In other hand, when flow rate was greater than 50 [Liters / minute] and if pressure in the pipe (P_P) was less than 10 [Bar], gel breaking level was simulated by using a condition statement set to be:

$$\mu = \mu - 1 * 10^{-4} * (\mathrm{P\_P}/10 * 10^{5})[\mathrm{Pas}] \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Furthermore, if (p_p) was equal or greater than $10 * 10^{5}$[Pa], viscosity calculation was based on formula:

$$\mu = 30 * 10^{-3} - 20 * 10^{-3} * (\mathrm{q\_p}/(2500/60000))[\mathrm{Pas}] \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

This formula simulated shear thinning effect of thixotropic fluid. Changing of viscosity set in the MATLAB® code is shown in Figure A.2.

```
my = 30e-3;

if q_p < 50/60000
      my = my + 1e-3; % gel build up process
   else
      if p_p < 10e5
         my = my - 1e-4*(p_p/10e5); % gel breaking procedure
      else

     my = 30e-3 - 20e-3*(q_p/(2500/60000)); % shear thinning effect
      end
   end
```

Figure A.2: Changing of viscosity set in the MATLAB® code – Conventional method

Fluid velocity was calculated by using formula:

ϑ = q_p/A [m/s] ………………………………………………………………… (3)

In order to determine regimes of fluid flow through the pipe, laminar either turbulent, while mud pump start-up procedure, the Reynold's number was used. The calculation of Reynold's number (Nygaard and Godhavn, 2013) is according to the formula:

$Re = (\rho * q\_p * D)/(\mu * A)$ ………………………………………………………………… (4)

Accordingly, it was used to calculate Darcy friction factor in the pipe. In that case a following condition (if-then-else) was defined. When Re was less than 10, the Darcy friction factor was equal to zero. In case when Re was greater than 10 and less than 2300, model calculated Darcy friction factor for laminar flow by using formula:

$f_{Darcy_{lam}} = 64/Re$ ………………………………………………………………… (5)

For all other cases when Re was greater than 2300 a Haaland's formula (Nygaard and Godhavn, 2013) for Darcy turbulent friction factor was used as following:

$\frac{1}{\sqrt{f}} \approx -1.8 * log_{10}\left(\left(\frac{\varepsilon/D}{3.7}\right)^{1.11} + \frac{6.9}{Re}\right)$ ………………………………………………………………… (6)

Solving the equation (1) for f, we got the resulting expression:

$$f \approx \frac{1}{\left(-1.8 * log_{10}\left(\left(\frac{\varepsilon/D}{3.7}\right)^{1.11} + \frac{6.9}{Re}\right)\right)^{2}} \quad \text{..........} \quad (7)$$

With correctly calculated Darcy friction factor we got a value of pressure in the pipe calculated by the following formula:

$$\text{P\_P} = f * \left(\frac{L}{D}\right) * (((\rho * v\hat{}2)/2) \quad \text{..........} \quad (8)$$

This pressure in the pipe was calculated the same way for both methods. A part of MATLAB® code that calculates Re and (P_P) is shown in Figure A.3.

```
v = q_p/A;
Re = (rho*q_p*D)/(my*A)

 if Re > 10
   f_darcy_lam = 64/Re;
   inv_sqrt_f_darcy_turb = -1.8*log10((((eps/D)/3.7)^1.11)+(6.9/Re));
   f_darcy_turb = (1/inv_sqrt_f_darcy_turb)^2;

   if Re > 2300
      f = f_darcy_turb;
   else
      f = f_darcy_lam;
   end

   else
   f = 0;
   end

   p_p = f*(L/D)*((rho*v*v)/2);
```

Figure A.3: MATLAB® code for calculation of pressure in the pipe for both methods

A.2 Automated Mud Pump Start-up Procedures

In case of automated method when the mud pump was turned off, the fluid flow was still circulating until it entirely stopped. The decreasing of flow rate remained the same, as the one in conventional method. The change of the flow rate happened when the pump was started-up. In that sense, at time of 25 minutes the pump was started-up and when pressure in the pipe was less than 5 [bar], acceleration was increasing 60 [liters/minute per minute]. This slow and smooth increase was breaking the gel with sufficiently high flow rate and pressure, avoiding pressure peaks. In addition, the change was made when all the gel is broken down, in this case at time of 35 minutes, the pump acceleration was fast increasing of 6000 [liters/minute per minute]. Once all the gel was broken we could perform this fast increase in flow rate to the required value, with no risk of fracturing the formation or appearance of sudden partial plugging of the pipe. Changing of flow rate set in the MATLAB® code is shown in Figure A.4.

```
maxCount = 2500;

q_p = 2500/60000; % volume flow [m^3/s]
p_p = 50e5; % pressure at the pump [Pa]

% “i” is time
for i = 1:maxCount

  if (i > 700) && (i < 1300)
    q_p = q_p - 5/60000; % reducing with 5 [l/min per sec]
  end

  if (i > 1500) && (i < 2500)
    if p_p < 5e5
    q_p = q_p + 1/60000; % increasing with 1 [l/min per sec]
    end
  end

  if (i> 35*60)
    q_p = q_p + 100/60000;
    if q_p > 2500/60000
      q_p = 2500/60000;
    end
```

```
 end

if q_p < 0
   q_p = 0;
end
```

Figure A.4: Changing of flow rate set in the MATLAB® code – Automated method

The last change made in the code, compared to conventional method, is that the gel breaking procedure was performing faster due to smoothly increase of pump acceleration. In that sense, it had a small transient condition of flow rate and accordingly it reaches steady state condition faster. Thus there is no pressure peaks. In the situation when the flow rate was greater than 50 [liters/minute] and the pressure in the pipe less than $10\ [\mathrm{Bar}]$, the gel breaking procedure was simulated by following formula:

$$\mathrm{\mu} = \mathrm{\mu} - 1 * 10^{-3} * (\mathrm{P\_P}/10 * 10^{5}\ )[\mathrm{Pas}] \qquad \text{……………………………………………………………} \qquad (9)$$

Changing of viscosity set in the MATLAB® code is shown in Figure A.5.

```
my = 30e-3;

if q_p < 50/60000
       my = my + 1e-3; % gel build up process
  else
       if p_p < 10e5
           my = my - 1e-3*(p_p/10e5); % gel breaking procedure

           if my < 30e-3
               my =30e-3;
           end

       else
     my = 30e-3 - 20e-3*(q_p/(2500/60000)); % shear thinning effect
       end
end
```

Figure A.5: Changing of viscosity set in the MATLAB® code – Automated method

Both MATLAB® models were made in order to produce relevant plots with the aim to compare and discuss differences between conventional and automated methods of mud pump start-up procedures when working with thixotropic drilling fluid. Those plots include plots of flow rate through pipe, pressure at pump, viscosity, Reynolds number, and flow rate versus pump pressure.

Moreover, the plots, showing flow rate through pipe and pressure at pump, were produced with noise effect in case of random small deviations in calculation (see Appendix B.1 and Appendix B.2). In that sense, for pressure in the pipe with noise effect a following formula in the code was used:

p_p_noise = p_p + $3 * 10^5$*rand() ………………………………………………………… (10)

where pressure in the pipe was either lower or greater for 3 [Bar] times value of random number. Furthermore, the flow rate through the pipe was lower or greater for random deviations of plus 20 [litres/minute] times random number and was calculated with formula:

q_p_noise = q_p + (20/60000)*rand() ………………………………………………………… (11)

The MATLAB® setup of is shown on a Figure 3.6.

```
p_p_noise = p_p + 3e5*rand();
q_p_noise = q_p + (20/60000)*rand();
```

Figure A.6: Setup of noise effect in the MATLAB® code

Furthermore, variables such as pressure in the pipe, pressure in the pipe with noise, flow rate in the pipe, flow rate in the pipe with noise, Reynolds number and viscosity, were calculated and stored in an array. MATLAB® code for storing those variables in array is shown in Figure A.7.

```
% stored variables
   p_p_ar(i) = p_p;
   p_p_n_ar(i) = p_p_noise;
   q_p_ar(i) = q_p;
   q_p_n_ar(i) = q_p_noise;
   Re_ar(i) = Re;
   my_ar(i) = my;
```

Figure A.7: Stored variables in array set in the MATLAB® code

Moreover, the two variables - pressure in the pipe and flow rate in the pipe - in both methods were post-processed and plotted with presence of high and low pass filters (Nygaard and Godhavn, 2013). These plots are not considered as essential for this dissertation and they are not discussed. Thus those filters are included in Appendix B.3 and Appendix B.4 respectively. The MATLAB® code set for post-processing is shown in Figure A.8.

```
%post-processing
   p_p_lpf_ar = lowpassFilter(p_p_n_ar,1,8);
   p_p_lpf15_ar = lowpassFilter(p_p_n_ar,1,15);
   p_p_hpf_ar = highpassFilter(p_p_lpf_ar,1,30);
   p_p_hpf60_ar = highpassFilter(p_p_lpf_ar,1,60);
```

Figure A.8: MATLAB® code for post-processing

As a result of MATLAB® modelling the figures of stored data were plotted for both methods. The MATLAB® code for plotting those figures is shown in Figure A.9. The graphs are presented and discussed in the next chapter.

```
%plotting of figures

figure;
plot((1:maxCount)/60,q_p_ar*60000);
title(‘Flow rate through pipe’);
ylabel(‘Flow rate [liters/minute]’);
xlabel(‘Time [minutes]’);

figure;
plot((1:maxCount)/60,q_p_n_ar*60000);
title(‘Flow rate through pipe with noise’);
ylabel(‘Flow rate [liters/minute]’);
xlabel(‘Time [minutes]’);
print –dpsc2 q_p_noise_ver2;
system(‘epstopdf q_p_noise_ver2.ps’);

figure;
plot((1:maxCount)/60,p_p_ar/1e5);
title(‘Pressure at pump’);
ylabel(‘Pump pressure [bar]’);
xlabel(‘Time [minutes]’);
```

```
%plot p_p with noise
figure;
plot((1:maxCount)/60,p_p_n_ar/1e5);
title(‘Pressure at pump with signal noise’);
ylabel(‘Pump pressure [bar]’);
xlabel(‘Time [minutes]’);
print –dpsc2 p_p_noise_ver2;
system(‘epstopdf p_p_noise_ver2.ps’);

%plot p_p_lpf
figure;
plot((1:maxCount)/60,p_p_lpf_ar/1e5,(1:maxCount)/60,p_p_lpf15_ar/1e5);
title(‘Pressure at pump with signal noise by using low pass filter’);
ylabel(‘Pump pressure [bar]’);
xlabel(‘Time [minutes]’);
legend(‘Filter 1, Tau = 8s’,’Filter 2, Tau = 15s’);
print –dpsc2 p_p_lpf_ver2;
system(‘epstopdf p_p_lpf_ver2.ps’);

%plot p_p_hpf
figure;
plot((1:maxCount)/60,p_p_hpf_ar/1e5,(1:maxCount)/60,p_p_hpf60_ar/1e5);
title(‘Pressure at pump with signal noise by using high pass filter’);
ylabel(‘Pump pressure [bar]’);
xlabel(‘Time [minutes]’);
legend(‘Filter 1, Tau = 30s’,’Filter 2, Tau = 60s’);
print –dpsc2 p_p_hpf_ver2;
system(‘epstopdf p_p_hpf_ver2.ps’);

figure;
plot((1:maxCount)/60,Re_ar);
title(‘Reynolds number’);
ylabel(‘Reynolds number []’);
xlabel(‘Time [minutes]’);
%p_f = (2*rho*v*L*v*v)/D;

figure;
plot((1:maxCount)/60,my_ar);
title(‘Viscosity’);
ylabel(‘Viscosity Pas’);
xlabel(‘Time [minutes]’);
%p_f = (2*rho*v*L*v*v)/D;
```

Figure A.9: MATLAB® code for plotting of figures

Appendix B - Source Code

B.1 Simulating Conventional Method

MATLAB® code for conventional pump start-up procedures:

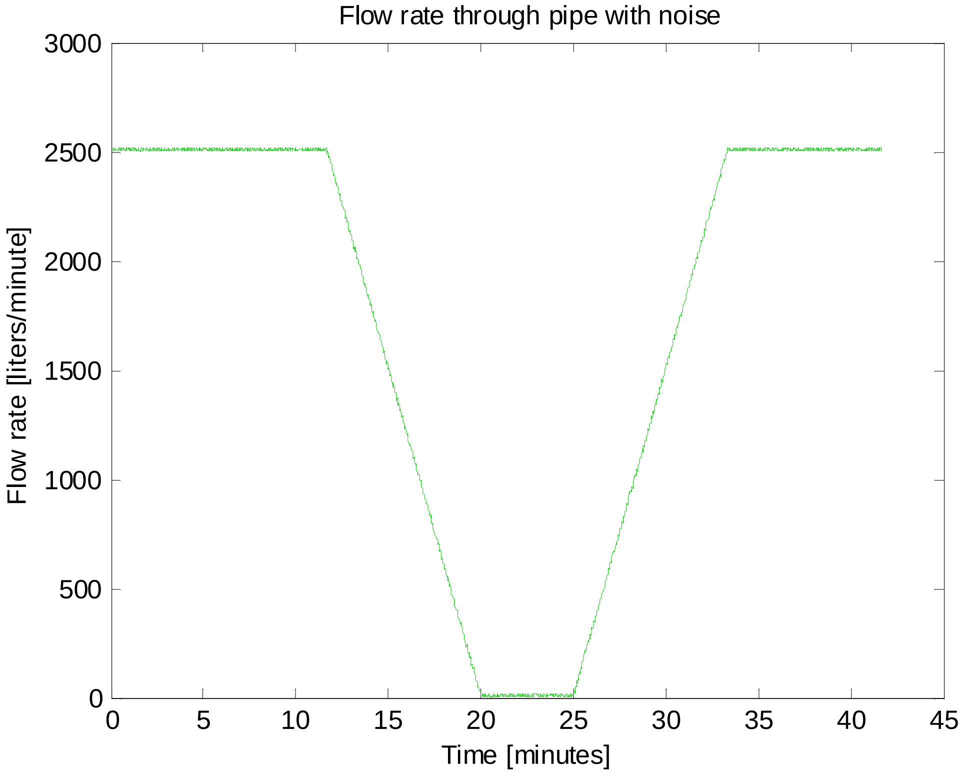
```
%% Dynamic flow through horizontal pipe – Conventional method
%
%
% Nomenclature:
% p : pressure [Pa]
% q : volume flow rate [m3/s]
% L : length [m]
% V : volume [m3]
% D : hydraulic diameter [m]
% rho: [kg/m3]
% eps: roughness [m]
% Re: Reynolds number []
%
% Subscripts
% _i : inlet
% _o : outlet
% _p : pipe
%
% Steady state horizontal pipe
% p_i = p_f + p_o
%
% Defining constants:
g = 9.81;

clear all;
close all;
maxCount = 2500;

q_p = 2500/60000; % volume flow [m3/s]
p_p = 50e5;

D = 0.1;
my = 30e-3;
for i = 1:maxCount

    if (i > 700) && (i < 1300)
        q_p = q_p - 5/60000; % reducing with 5 l/m
    end

    if (i > 1500) && (i < 2001)
        q_p = q_p + 5/60000; % increasing with 5 l/m

    end
    if (i > 2100)
        D = 0.0995; % sudden partial plugging of pipe
```

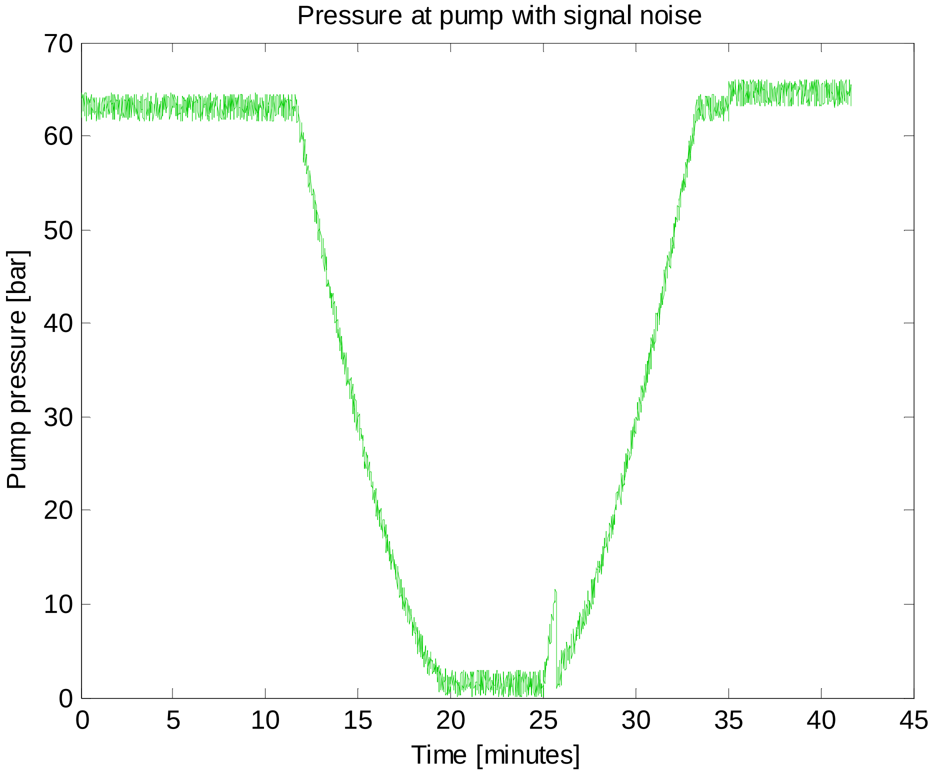
```
    end
   if q_p < 0
      q_p = 0;
   end



    L = 2000;
    rho = 1000;
    A = pi*(D/2)*(D/2);
    V = L*A;
    eps = 0.045e-3; % roughness for steel pipe
    % my =  1.308e-3;% viscosity of water at 10 degC [Pa*s}
    % my =  30.0e-3;% viscosity of drilling fluid

    if q_p < 50/60000
       my = my + 1e-3; % gel build up process
    else
        if p_p < 10e5
           my = my - 1e-4*(p_p/10e5); % gel breaking procedure
        else

      my = 30e-3 - 20e-3*(q_p/(2500/60000)); % shear thinning effect
        end
    end
    v = q_p/A;

    Re = (rho*q_p*D)/(my*A)
    if Re > 10

    f_darcy_lam = 64/Re;
    inv_sqrt_f_darcy_turb = -1.8*log10((((eps/D)/3.7)^1.11)+(6.9/Re));
    f_darcy_turb = (1/inv_sqrt_f_darcy_turb)^2;
    if Re > 2300
        f = f_darcy_turb;
    else
        f = f_darcy_lam;
    end
    else
    f = 0;
    end

    p_p = f*(L/D)*((rho*v*v)/2);
    p_p_noise = p_p + 3e5*rand();
    q_p_noise = q_p + (20/60000)*rand();

    % store variables
    p_p_ar(i) = p_p;
    p_p_n_ar(i) = p_p_noise;
    q_p_ar(i) = q_p;
    q_p_n_ar(i) = q_p_noise;
    Re_ar(i) = Re;
    my_ar(i) = my;

end
%postprocessing
```

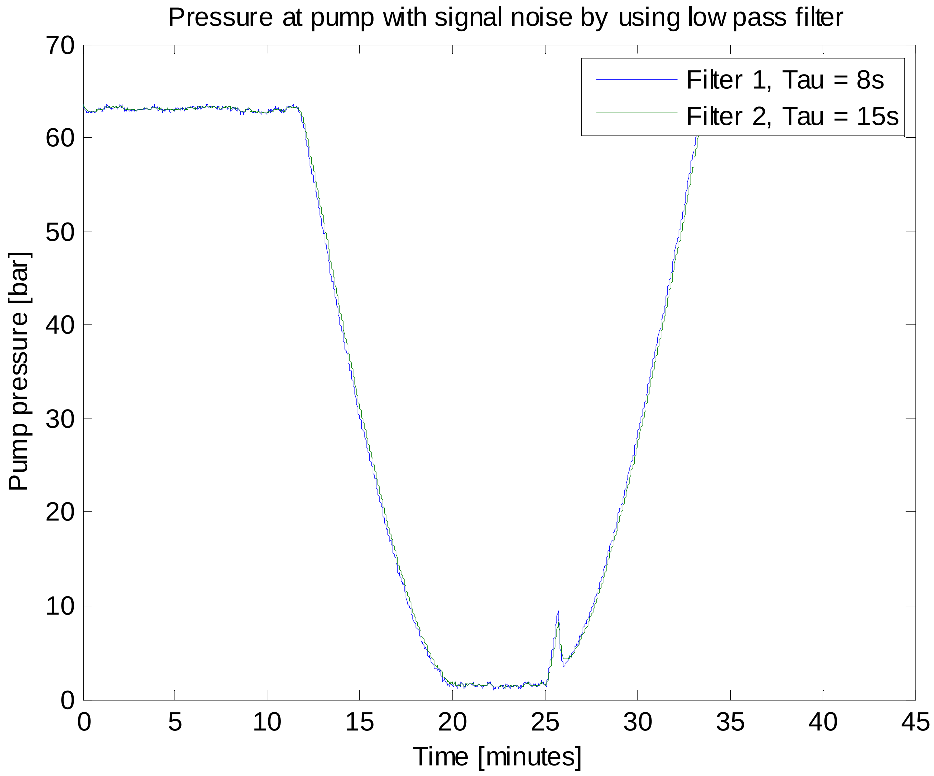
```
  p_p_lpf_ar = lowpassFilter(p_p_n_ar,1,8);
  p_p_lpf15_ar = lowpassFilter(p_p_n_ar,1,15);
  p_p_hpf_ar = highpassFilter(p_p_lpf_ar,1,30);
  p_p_hpf60_ar = highpassFilter(p_p_lpf_ar,1,60);



%plotting
figure;
plot((1:maxCount)/60,q_p_ar*60000,'color',[0.0, 0.8, 0.0]);
title('Flow rate through pipe');
ylabel('Flow rate [liters/minute]');
xlabel('Time [minutes]');

figure;
plot((1:maxCount)/60,q_p_n_ar*60000,'color',[0.0, 0.8, 0.0]);
title('Flow rate through pipe with noise');
ylabel('Flow rate [liters/minute]');
xlabel('Time [minutes]');
print -dpsc2 q_p_noise_ver2;
system('epstopdf q_p_noise_ver2.ps');

figure;
plot((1:maxCount)/60,p_p_ar/1e5,'color',[0.0, 0.8, 0.0]);
title('Pressure at pump');
ylabel('Pump pressure [bar]');
xlabel('Time [minutes]');

%plot p_p with noise
figure;
plot((1:maxCount)/60,p_p_n_ar/1e5,'color',[0.0, 0.8, 0.0]);
title('Pressure at pump with signal noise');
ylabel('Pump pressure [bar]');
xlabel('Time [minutes]');
print -dpsc2 p_p_noise_ver2;
system('epstopdf p_p_noise_ver2.ps');

%plot p_p_lpf
figure;
plot((1:maxCount)/60,p_p_lpf_ar/1e5,(1:maxCount)/60,p_p_lpf15_ar/1e5);
title('Pressure at pump with signal noise by using low pass filter');
ylabel('Pump pressure [bar]');
xlabel('Time [minutes]');
legend('Filter 1, Tau = 8s','Filter 2, Tau = 15s');
print -dpsc2 p_p_lpf_ver2;
system('epstopdf p_p_lpf_ver2.ps');

figure;
plot((1:maxCount)/60,p_p_lpf_ar/1e5,(1:maxCount)/60,p_p_lpf15_ar/1e5);
%title('Pressure at pump with signal noise');
%ylabel('Pump pressure [bar]');
%xlabel('Time [minutes]');
%axis([XMIN XMAX YMIN YMAX]);
axis([10 15 42 52]);
legend('Filter 1, Tau = 8s','Filter 2, Tau = 15s');
print -dpsc2 p_p_lpf_ver2_zoom;
```

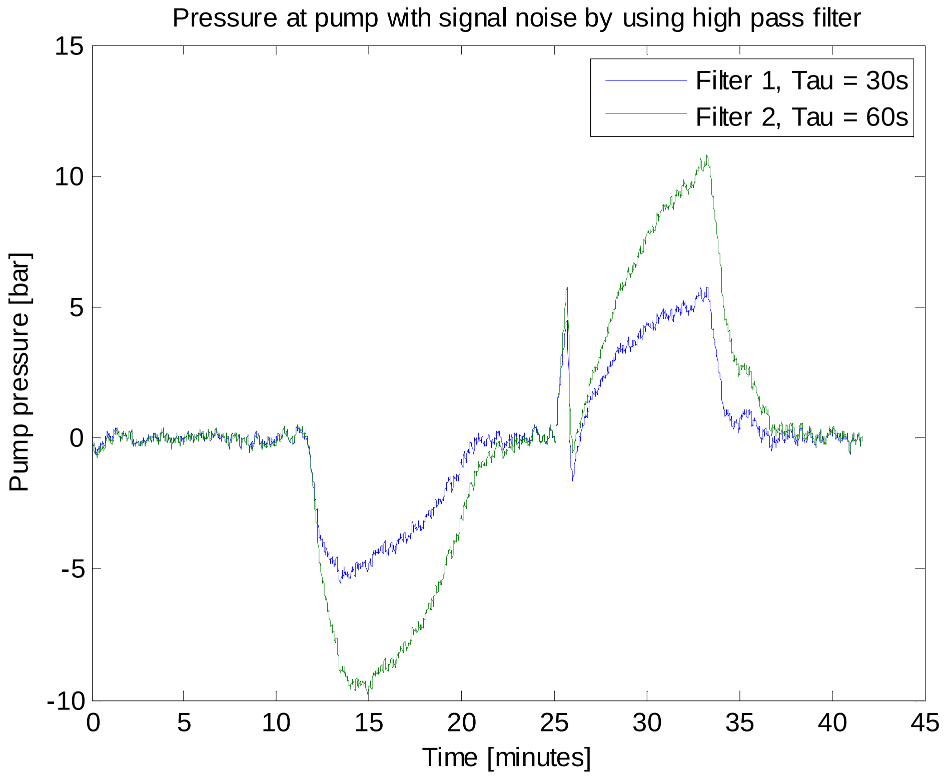
```
system('epstopdf p_p_lpf_ver2_zoom.ps');

%plot p_p_hpf
figure;
plot((1:maxCount)/60,p_p_hpf_ar/1e5,(1:maxCount)/60,p_p_hpf60_ar/1e5);
title('Pressure at pump with signal noise by using high pass filter');
ylabel('Pump pressure [bar]');
xlabel('Time [minutes]');
legend('Filter 1, Tau = 30s','Filter 2, Tau = 60s');
print -dpsc2 p_p_hpf_ver2;
system('epstopdf p_p_hpf_ver2.ps');



figure;

plot((1:maxCount)/60,Re_ar,'color',[0.0, 0.8, 0.0]);
title('Reynolds number');
ylabel('Reynolds number []');
xlabel('Time [minutes]');
%p_f = (2*rho*v*L*v*v)/D;

figure;

plot((1:maxCount)/60,my_ar,'color',[0.0, 0.8, 0.0]);
title('Viscosity');
ylabel('Viscosity Pas');
xlabel('Time [minutes]');
%p_f = (2*rho*v*L*v*v)/D;
```

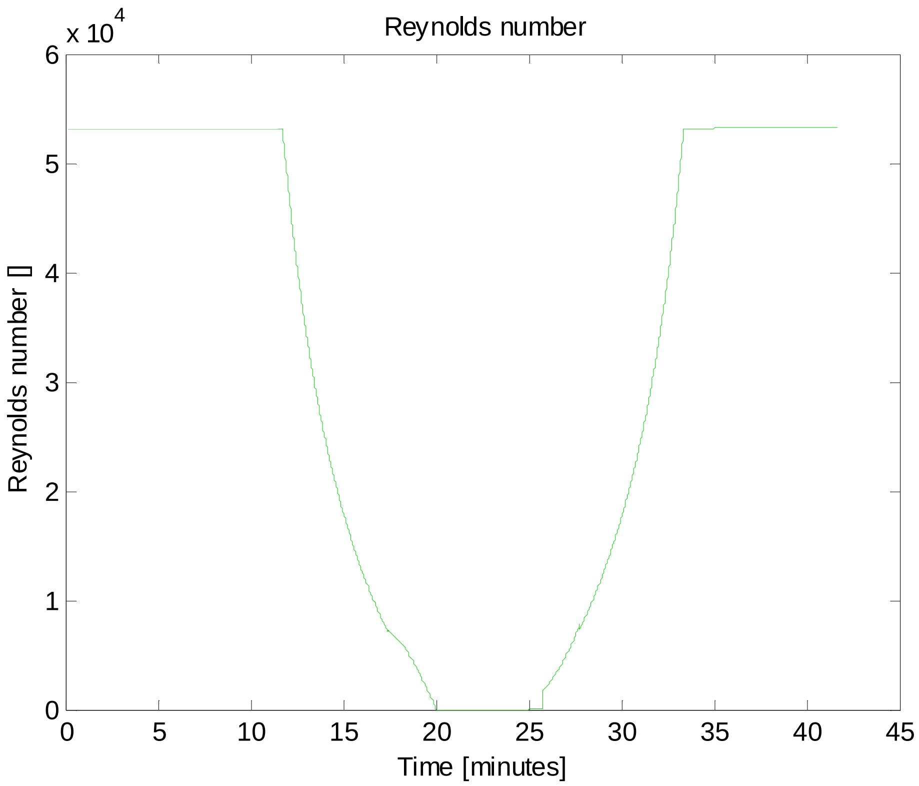
Remain figures simulated by automated method:






Pressure at pump with signal noise by using low pass filter
Filter 1, Tau = 8s
Filter 2, Tau = 15s
Pump pressure [bar]
Time [minutes]
0
10
20
30
40
50
60
70
0
5
10
15
20
25
30
35
40
45


Pressure at pump with signal noise by using high pass filter
Filter 1, Tau = 30s
Filter 2, Tau = 60s
Pump pressure [bar]
Time [minutes]
-10
-5
0
5
10
15
0
5
10
15
20
25
30
35
40
45


Reynolds number
x 10^4
Reynolds number []
Time [minutes]
0
1
2
3
4
5
6
0
5
10
15
20
25
30
35
40
45

B.2 Simulating Automated Method

MATLAB® code for automated pump start-up procedures

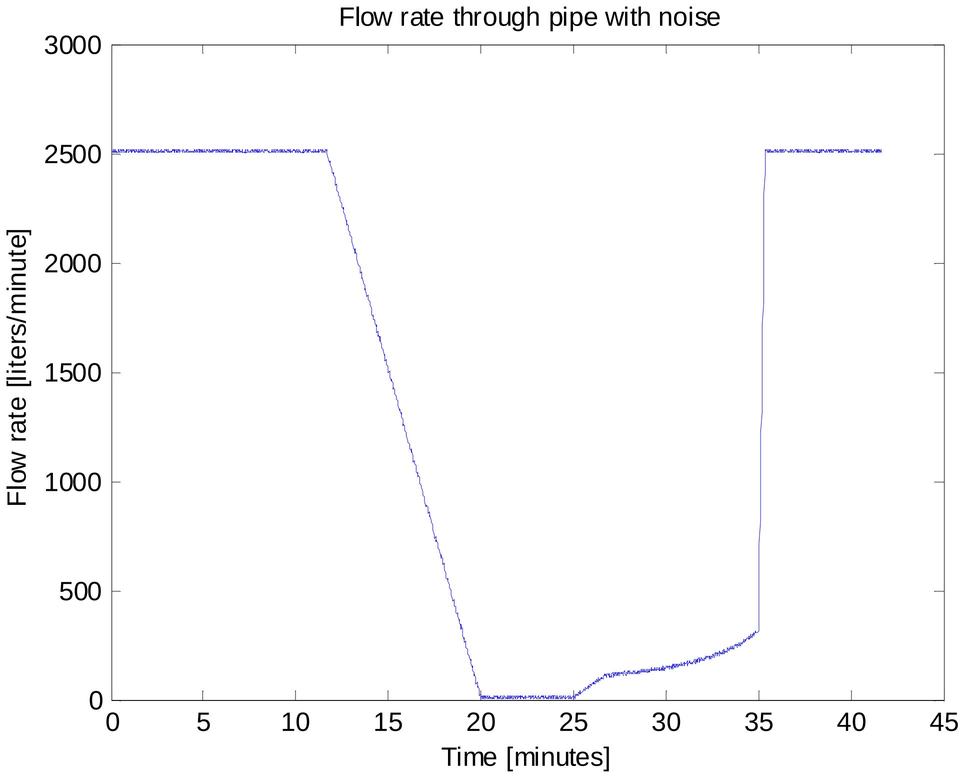
```
%% Dynamic flow through horizontal pipe – Automated method
%
%
% Nomenclature:
% p : pressure [Pa]
% q : volume flow rate [m3/s]
% L : length [m]
% V : volume [m3]
% D : hydraulic diameter [m]
% rho: [kg/m3]
% eps: roughness [m]
% Re: Reynolds number []
% My: Viscosity [cP]
%
% Subscripts
% _i : inlet
% _o : outlet
% _p : pipe
%
% Steady state horizontal pipe
% p_i = p_f + p_o
%
% Defining constants:
g = 9.81;

clear all;
close all;
maxCount = 2500;

q_p = 2500/60000; % volume flow [m3/s]
p_p = 50e5; % pressure at the pump [Pa]

D = 0.1;
my = 30e-3;
for i = 1:maxCount

    if (i > 700) && (i < 1300)
        q_p = q_p - 5/60000; % reducing with 5 l/min
    end

    if (i > 1500) && (i < 2500)
        if p_p < 5e5
        q_p = q_p + 1/60000; % increasing with 1 l/min
        end

    end
    if (i> 2100)
        q_p = q_p + 100/60000;
        if q_p > 2500/60000
            q_p = 2500/60000;
```

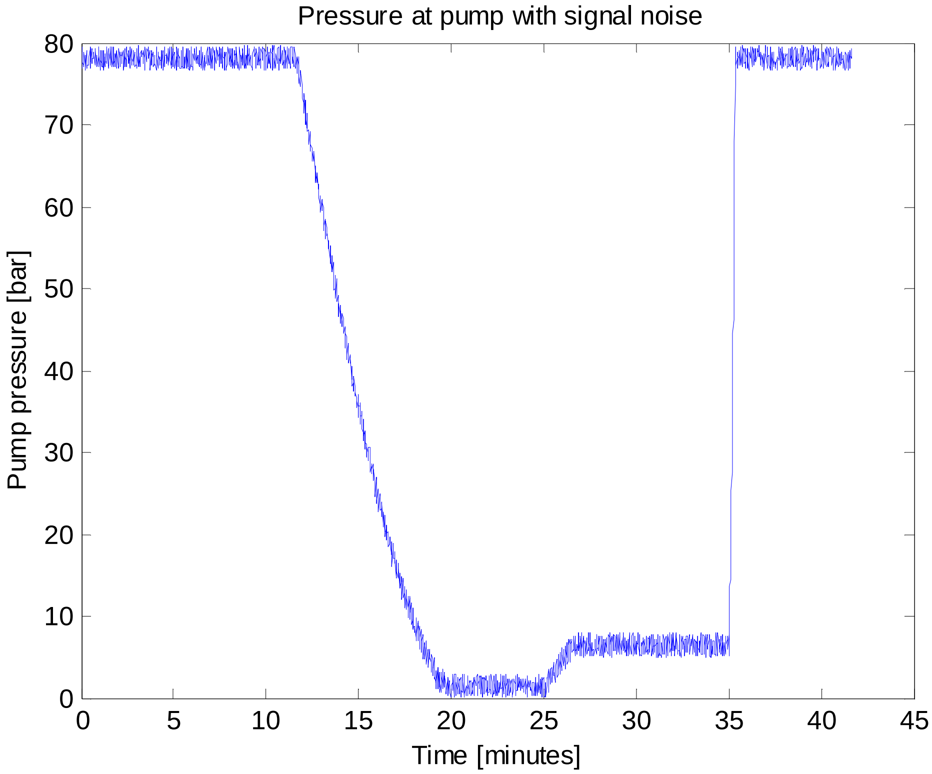
```
    end
  end

 if q_p < 0
    q_p = 0;
 end

  L = 2000;
  rho = 1300;
  A = pi*(D/2)*(D/2);
  V = L*A;
  eps = 0.045e-3; % roughness for steel pipe
  % my =  1.308e-3;% viscosity of water at 10 degC [Pa*s}
  % my =  30.0e-3;% viscosity of drilling fluid

  if q_p < 50/60000
     my = my + 1e-3; % gel build up process
  else
      if p_p < 10e5
          my = my - 1e-3*(p_p/10e5); % gel breaking procedure
          if my < 30e-3
              my =30e-3;
          end
      else



    my = 30e-3 - 20e-3*(q_p/(2500/60000)); % shear thinning effect
      end
  end
  v = q_p/A;

  Re = (rho*q_p*D)/(my*A)
  if Re > 10

  f_darcy_lam = 64/Re;
  inv_sqrt_f_darcy_turb = -1.8*log10((((eps/D)/3.7)^1.11)+(6.9/Re));
  f_darcy_turb = (1/inv_sqrt_f_darcy_turb)^2;
  if Re > 2300
      f = f_darcy_turb;
  else
      f = f_darcy_lam;
  end
  else
  f = 0;
  end

  p_p = f*(L/D)*((rho*v*v)/2);
  p_p_noise = p_p + 3e5*rand();
  q_p_noise = q_p + (20/60000)*rand();

  % stored variables
  p_p_ar(i) = p_p;
  p_p_n_ar(i) = p_p_noise;
  q_p_ar(i) = q_p;
  q_p_n_ar(i) = q_p_noise;
```

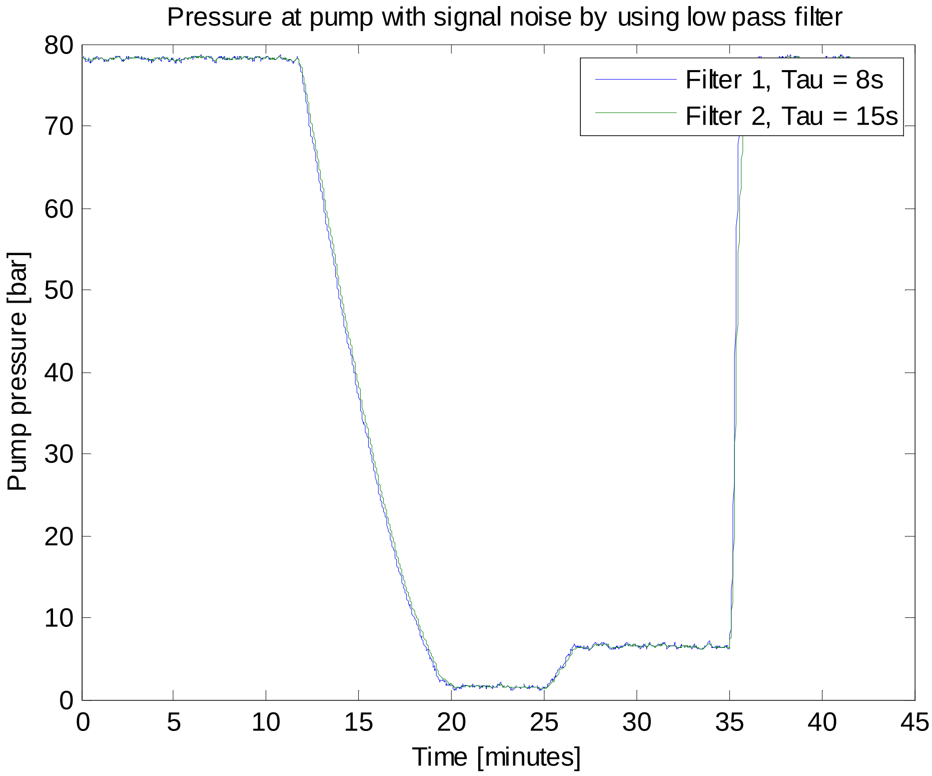
```
   Re_ar(i) = Re;
   my_ar(i) = my;

end
%postprocessing
   p_p_lpf_ar = lowpassFilter(p_p_n_ar,1,8);
   p_p_lpf15_ar = lowpassFilter(p_p_n_ar,1,15);
   p_p_hpf_ar = highpassFilter(p_p_lpf_ar,1,30);
   p_p_hpf60_ar = highpassFilter(p_p_lpf_ar,1,60);




%plotting
figure;
plot((1:maxCount)/60,q_p_ar*60000);
title('Flow rate through pipe');
ylabel('Flow rate [liters/minute]');
xlabel('Time [minutes]');

figure;
plot((1:maxCount)/60,q_p_n_ar*60000);
title('Flow rate through pipe with noise');
ylabel('Flow rate [liters/minute]');
xlabel('Time [minutes]');
print -dpsc2 q_p_noise_ver2;
system('epstopdf q_p_noise_ver2.ps');

figure;
plot((1:maxCount)/60,p_p_ar/1e5);
title('Pressure at pump');
ylabel('Pump pressure [bar]');
xlabel('Time [minutes]');

%plot p_p with noise
figure;
plot((1:maxCount)/60,p_p_n_ar/1e5);
title('Pressure at pump with signal noise');
ylabel('Pump pressure [bar]');
xlabel('Time [minutes]');
print -dpsc2 p_p_noise_ver2;
system('epstopdf p_p_noise_ver2.ps');

%plot p_p_lpf
figure;
plot((1:maxCount)/60,p_p_lpf_ar/1e5,(1:maxCount)/60,p_p_lpf15_ar/1e5);
title('Pressure at pump with signal noise by using low pass filter');
ylabel('Pump pressure [bar]');
xlabel('Time [minutes]');
legend('Filter 1, Tau = 8s','Filter 2, Tau = 15s');
print -dpsc2 p_p_lpf_ver2;
system('epstopdf p_p_lpf_ver2.ps');



%plot p_p_hpf
figure;
```

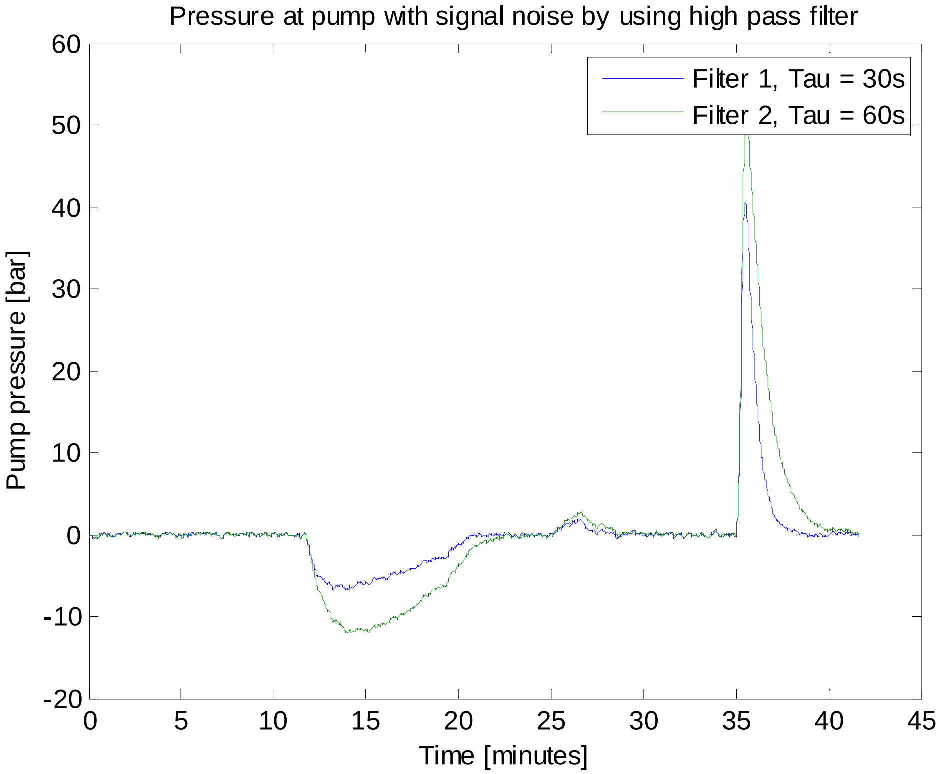
```
plot((1:maxCount)/60,p_p_hpf_ar/1e5,(1:maxCount)/60,p_p_hpf60_ar/1e5);
title('Pressure at pump with signal noise by using high pass filter');
ylabel('Pump pressure [bar]');
xlabel('Time [minutes]');
legend('Filter 1, Tau = 30s','Filter 2, Tau = 60s');
print -dpsc2 p_p_hpf_ver2;
system('epstopdf p_p_hpf_ver2.ps');


figure;

plot((1:maxCount)/60,Re_ar);
title('Reynolds number');
ylabel('Reynolds number []');
xlabel('Time [minutes]');
%p_f = (2*rho*v*L*v*v)/D;

figure;

plot((1:maxCount)/60,my_ar);
title('Viscosity');
ylabel('Viscosity [Pas]');
xlabel('Time [minutes]');
%p_f = (2*rho*v*L*v*v)/D;

figure;
plot(q_p_ar*60000,p_p_ar/1e5);
title('Flow rate vs Pump pressure');
ylabel('Pump pressure [bar]');
xlabel('Flow rate [liters/minute]');
```

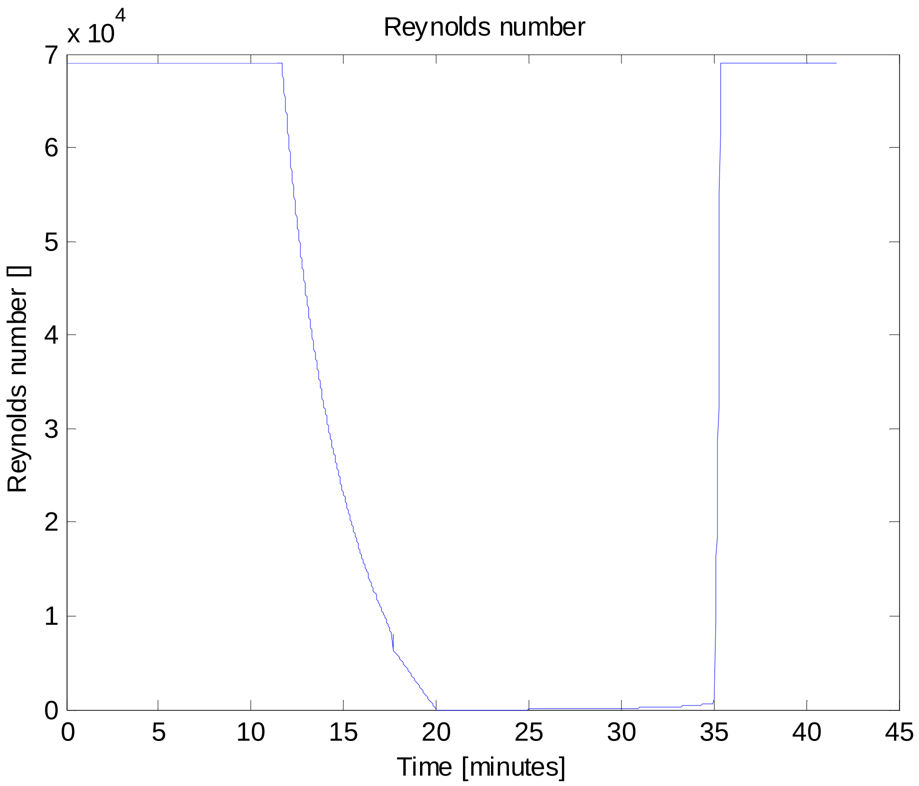
Remain figures simulated by automated method:






Pressure at pump with signal noise by using low pass filter
Filter 1, Tau = 8s
Filter 2, Tau = 15s
Pump pressure [bar]
0
10
20
30
40
50
60
70
80
Time [minutes]
0
5
10
15
20
25
30
35
40
45


Pressure at pump with signal noise by using high pass filter
Filter 1, Tau = 30s
Filter 2, Tau = 60s
Pump pressure [bar]
-20
-10
0
10
20
30
40
50
60
Time [minutes]
0
5
10
15
20
25
30
35
40
45


Reynolds number
x 10^4
Reynolds number []
Time [minutes]
0
1
2
3
4
5
6
7
0
5
10
15
20
25
30
35
40
45

B.3 High Pass Filter

Highpass Filter

```
function y = highpassFilter(x,dt,timeConstant)

alpha =  timeConstant / (timeConstant + dt);

y(1) = 0;
n=length(x);

for i=2:n
   y(i) = alpha * y(i-1) + alpha * (x(i) - x(i-1));
end

end
```

B.4 Low Pass Filter

Lowpass Filter

```
function y =lowpassFilter(x,dt,timeConstant)

alpha = dt / (timeConstant + dt);

y(1) = x(1);
n=length(x);

for i=2:n
   y(i) = alpha * x(i) + (1-alpha) * y(i-1);
end

end
```