Design, Development and Control of a Managed Pressure Drilling Setup

by

©Al Amin

A Thesis
submitted to the School of Graduate Studies
in partial fulfillment of the requirements for the degree of

Master of Engineering

Faculty of Engineering and Applied Science

Memorial University of Newfoundland

June 2017

St. John's Newfoundland

Abstract

Drilling in challenging conditions require precise control over hydrodynamic parameters for safer and efficient operation in oil and gas industries. Automated managed pressure drilling (MPD) is one of such drilling solution which helps to maintain operational parameters effectively over conventional drilling technique. The main goal is to maintain bottomhole pressure between reservoir formation pressure and fracture pressure with kick mitigation ability. Real life MPD system has to confront nonlinearity induced by drilling fluid rheology and flow parameters. To obtain a better understanding of this operation, a lab scale experimental setup has been developed. Reynolds number and pressure drop per unit length were considered to obtain hydrodynamic similarity. A vertical concentric pipe arrangement has been used to represent the drill string and annular casing region. A linearized gain switching proportional integral (PI) controller and a nonlinear model predictive controller (NMPC) have been developed to automate the control operation in the experimental setup. A linearizer has been designed to address the choke nonlinearity. Based on the flow and pressure criteria, a gain switching PI controller has been developed which is able to control pressure and flow conditions during pipe extension, pump failure and influx attenuation cases. On the other hand, a nonlinear Hammerstein-Weiner model has been developed which assists in bottomhole pressure estimation using pump flow rate and choke opening. The identified model has been integrated with a NMPC algorithm to achieve effective control within predefined pressure and flow constraints. Lastly, a performance comparison has been provided between the linearized gain switching PI controller and NMPC controller.

Acknowledgements

At first, I would like to thank my supervisors Dr. Syed Imtiaz and Dr. Aziz Rahman, for their continuous help, suggestions and financial support throughout my program in the university. It was never possible to succeed without their help and support. Besides my supervisor, I would like to thank Dr. Faisal Khan for providing the major resources for developing the experimental setup. I would also like to thank Dr. Salim Ahmed for providing valuable suggestions in designing the experimental setup. I am grateful to Samith Rathnayaka, Dan Chen, Anirudh Nandan, Md. Aminul Islam Khan and Dinesh Hearth for their contribution in design and development of the setup. The workmanship and fabrication was done by the mechanical and electrical technical services teams of Memorial university led by Stephen Sooley and Bill Maloney respectively, I gratefully acknowledge their support. Finally, funding from NSERC is gratefully acknowledged. I would like to thank Dr. Leonard Lye who continuously encouraged me to participate in different events organised by Faculty of Engineering and Applied Science, Memorial University. My heartfelt thanks also goes to his team including Moya Crocker, Colleen Mahoney and Nicole Parisi who work day and night to make things go right in the graduate office. Finally, I would like to thank my loving and supportive wife, Munzarin Morshed and my family for encouraging me in each and every stage of my research program.

Co-Authorship Statement

I, Al Amin, hold principal author status for all the chapters in this thesis. However, each manuscript is co-authored by my supervisors and co-researcher, who have directed me towards the completion of this work as follows.

- **Al Amin, Syed Imtiaz, Aziz Rahman & Faisal Khan, "Design, Development and Control of an Experimental Managed Pressure Drilling Setup," to be submitted to a journal.**

  Statement: I am the principal author and carried out the design and development of the presented experimented setup and implemented controllers. I drafted the manuscript and incorporated the comments of the co-authors in the final manuscript. Co-authors assisted me in formulating research goals and experimental techniques

- **Al Amin, Syed Imtiaz, Aziz Rahman & Faisal Khan, "Nonlinear Model Predictive Control of a Hammerstein Weiner Model based Experimental Managed Pressure Drilling Setup," to be submitted to a journal.**

  Statement: I am the principal author and carried out the design and development of the presented controller. I drafted the manuscript and incorporated the comments of the co-authors in the final manuscript. The co-authors assisted me in formulating research goals and experimental techniques.

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List of Abbreviations

cfm	cubic feet per minute
ft	feet
in	inch
lpm	liters per minute
m	meter
mA	milliampere
min	minute
psi	pounds per square inch
sec	second

Chapter 1

Introduction

1.1 Motivation

The quest for fossil fuel due to the high demand of energy has driven oil and gas industries towards ambitious onshore and offshore petroleum explorations. After extracting oil and gas resources from most of the easiest wells, the petroleum industries are focusing on drilling in challenging rock formations and environmental conditions. This leads to the innovation of enhanced technologies and methods for safer drilling operation. The decade-old practice to rely on human skills and expertise in drilling is being challenged due to a higher probability of accidents resulting from undesirable influx or kick from the reservoir to drilling system. Reservoir influx can happen due to pressure imbalance among bottomhole pressure BHP, reservoir pressure and fracture pressure. It is desired to have the magnitude of BHP maintained between reservoir pressure and fracture pressure. Whenever BHP is lower than reservoir pressure, it results in influx or kick. On the other hand, BHP higher than fracture pressure results in lost circulation. Failure to maintain pressure may result into devastating accidents such as the Deepwater Horizon accident in Gulf of Mexico which resulted in loss of 11 lives with release of 4 million barrels of crude oil in the ocean (U.S. Chemical Safety and Hazard Investigation Board). The aftermath of this accident had a huge detrimental impact on the human life and ecological system in the contaminated region.

While drilling at greater depth, it is also required to add large number of pipes at regular time interval to extend the drill string length known as pipe extension scenario. Addressing this issue with traditional technique results in longer non productive time (NPT) with significant pressure fluctuation which has higher likelihood of developing a kick in the wellbore. The pressure balance can also be changed if one of the primary component in the system such as drilling fluid pump fails suddenly. Summing up all the factors that may affect the pressure management, a managed pressure drilling (MPD) is put into place to maintain the operation in the allotted pressure window enhancing safety and productivity. Conventionally, MPD is utilized based on operator's skill and experience to avoid kick and regulate BHP manually using control valve/choke and back pressure pump. Automation in MPD operation can eliminate the risk of human error in the operation with increased safety and efficiency. The aim to automate this operation would have been lot easier if the process was linear. However, in reality, MPD is a nonlinear operation due to dynamic variation in hydrodynamic properties. This induces challenge in modelling strategy which is ultimately the foundation of automated MPD control system. Even though most of the challenging phenomena have been addressed in the surface level equipment through technological development, there is still a long way to explore the uncertain hydrodynamic states present in the bottomhole region. In recent times, several controllers have been developed including proportional-integral (PI) controller, internal model controller (IMC), model predictive controller and non linear model predictive controller (NMPC) to automate the MPD operation. The compatibility and performance of these controllers varies based on the application in MPD operation.

The control system design becomes challenging also due to modelling uncertainties. Kaasa et al. (2012) presented a simple hydrodynamic model based on the conservation of mass and momentum considering the drill string and annular casing as two separate control volumes. The primary focus of this model is to capture the significant dynamics narrowing the parameter selection. However, the number of parameter requirements increased as the explorations continued to the offshore areas. Landet et al. (2013) proposed a partial derivative model by discretizing the ordinary differential equation model along the control volume. Even though this model is pretty successful in capturing important dynamics such as heave motion, the computational effort and complexity were significant. Constant bottomhole pressure (CBHP) and flow control modes are two main modes where the controller has to manipulate the input variables such as choke opening, pump flow rate to control the target states such as bottomhole pressure and outlet flow rate. For fast pressure control objective, PI controller has shown promising results. However, due to modelling uncertainty, performance of controllers such as NMPC are still under experimentation. In this thesis, our focus is to demonstrate the performance of PI and NMPC controller in a lab scale experimental setup which can replicate the hydrodynamic phenomena occurring in a real life MPD system. Also, the implementation challenges of these two controllers are reviewed.

1.2 Objective

The goal of this research is to design and develop an experimental setup that can replicate the behavior of a real MPD system primarily focused on controller implementation. The development of the setup is followed by implementation of a linearized gain-scheduled PI controller and an NMPC controller. The controllers implemented should be able to provide constant bottomhole pressure control during normal drilling and pipe extension operation. The PI controller was implemented using a valve linearizing technique. On the other end, the NMPC controller was designed and implemented based on a nonlinear model named Hammerstein-Weiner model. We identified the modelling and operational challenges encountered while developing and implementing the controllers.

1.3 Structure of the thesis

The rest of the thesis is organized as follows: Chapter 2 provides an overview on MPD variants, essential components and recent developments in MPD operation. The modelling and implementation challenges are also identified and summarized from simple to complex controllers. Chapter 3 presents the design and development stages of the MPD setup with a linearized gain scheduled PI controller implementation. A Hammerstein-Weiner model based NMPC controller performance is demonstrated and compared with the preceding gain scheduled PI controller in Chapter 4. Chapter 5 provides concluding discussion on the contributions of this thesis with recommendations for further research.

Chapter 2

Literature Review

In this chapter, a brief overview on the scopes of improvement in MPD technique is presented. Moreover, a sequential development of different control strategies based on the application areas are provided.

2.1 Traditional drilling technique

The earliest known oil well drilling dates back to 347 AD where bamboo poles were used in China to extract hydrocarbon resource from 240 m below the earth surface (Totten, 2007). The drilling procedure, technology and complexity have changed significantly over the years. Conventionally, a rotating drill bit is attached to a drill string which crushes the rock formation and drives it to the reservoir section below the earth surface. In an ideal scenario, it is desired to have bottomhole pressure marginally over the reservoir pressure but below fracture pressure p_{frac} of the rock. As the drill string progresses it becomes necessary to remove the cuttings and maintain pressure inside drilling hole. A drilling fluid is pumped into the downhole region through the drill string pipe and circulated back to the surface through the annular section removing the formation cuttings. A schematic representation of the overall operation is shown in Figure 2.1.

Aadnoy et al. (2011) provided a brief overview of pressure management in the drilling operation. The pressure balance mainly involves bottomhole pressure p_{bh}, reservoir pressure p_{res} and fracture pressure p_{frac}. Equation 2.1 represents the hydrostatic

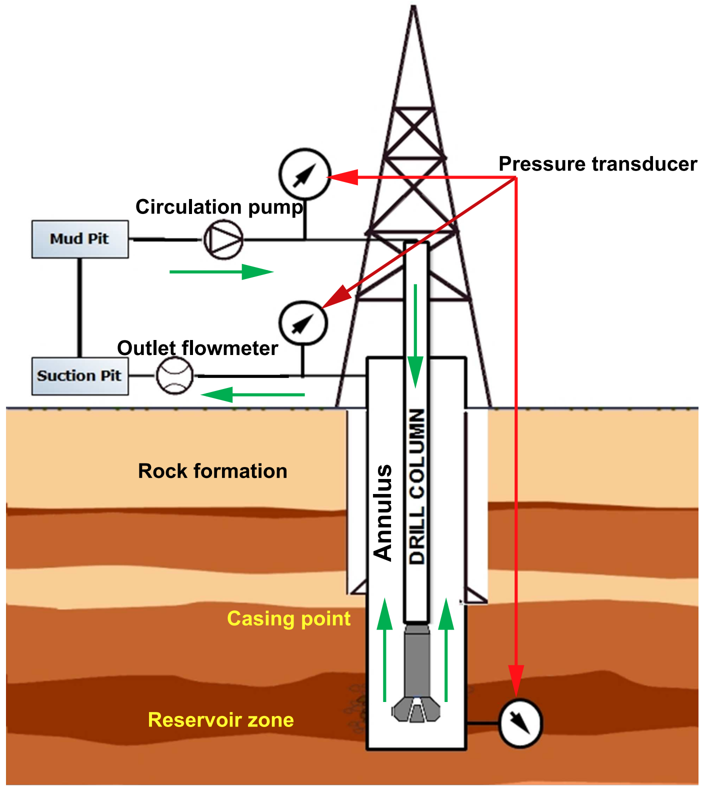


Figure 2.1: Schematic of a conventional drilling rig

pressure exerted by the drilling fluid depending on the depth and density of the fluid. Bottomhole pressure depends on the type of drilling fluid, hydrostatic head based on the true vertical depth, pressure at the pump exit, and the circulation rate of drilling fluid (i.e. frictional pressure drop). Generally, a pump circulates the drilling fluid at a particular flow rate q_p which exerts a pressure p_p on the drilling fluid. When the drill string reaches the reservoir zone, the reservoir fluid exerts pressure p_{res} at the bottomhole through porous rock formation. According to Equation 2.2, the resulting bottomhole pressure is the sum of hydrostatic head p_h, pump pressure p_p and frictional pressure drop p_f.

Conventional drilling technique utilizes drilling fluid as the primary tool for maintaining the downhole pressure. Operators vary circulation rate, pump pressure, and mud properties to attain desired bottomhole pressure. Based on the pressure management, a drilling operation can be broadly classified as underbalanced and overbalanced drilling. In under balanced drilling (UBD) condition, the bottomhole pressure p_{bh} is not sufficient to resist the inflow of the reservoir fluid q_k. During this operation the pore pressure is maintained between bottomhole pressure p_{bh} and formation pressure p_{frac}. The underbalanced condition is developed intentionally using surface level equipments such as rotating control device (RCD), choke and multiphase separator (Malloy et al., 2009). It is a production oriented drilling technique where the goal is to obtain maximum formation fluid without affecting the structural integrity of the well bore. Moreover, this allows for simultaneous drilling and production. Conversely, overbalanced condition aims at maintaining down hole pressure above formation pressure. However, in order to maintain well integrity, the bottomhole pressure is never allowed to exceed above fracture pressure of the rock p_{frac}. The bottomhole pressure p_{bh} is maintained marginally above the pore pressure p_{res} to avoid inflow from the reservoir.

$$p_h = \rho g h \tag{2.1}$$

$$p_{bh} = p_h + p_p - p_f \tag{2.2}$$

Occasionally, the pressure window offered by the rock formation and reservoir condition poses challenges to the operator. With the conventional method of drilling, there is a higher probability of exceeding the fracture pressure in narrow pressure window due to a limited range of pressure manipulating capacity of the system (Rehm et al., 2013). On the other hand, bottomhole pressure maintained below pore pressure leads to inflow from the reservoir. Drilling has to be stopped in the event of reservoir influx which leads to unnecessary non-productive time (NPT). Moreover, an uncontrolled influx situation can create devastating blowout situation. Thus, online pressure regulation during drilling is a prime need for industries to maintain safety and productivity in drilling operation. MPD provides an opportunity to drill safely and efficiently.

2.2 Managed pressure drilling (MPD)

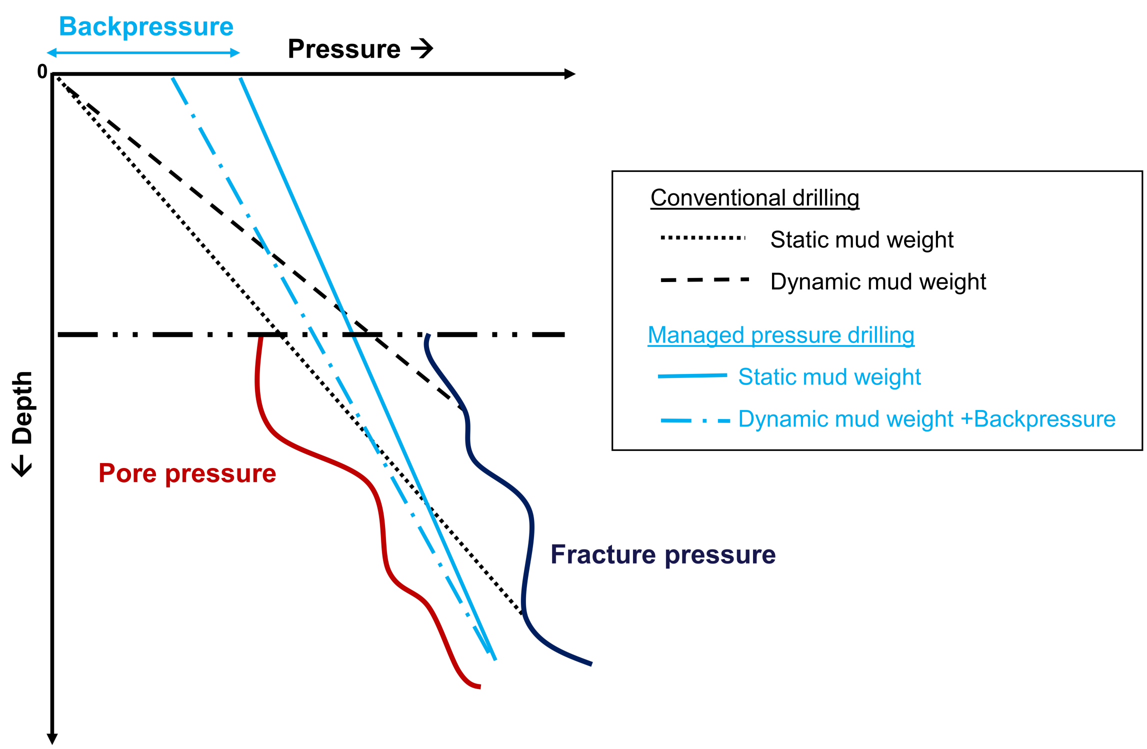


Figure 2.2: Comparison between conventional and managed pressure drilling

MPD helps to overcome the limitations of traditional drilling methods by dynamically adapting and adjusting the drilling condition at a particular instant. The ultimate goal of MPD is to provide an accurate pressure management within the pressure window maintaining well integrity. The use of additional components such as choke and backpressure pump provides more degrees of freedom to MPD system to control downhole conditions more effectively. In addition to circulation pump pressure and drilling fluid hydrostatic pressure, the choke and backpressure pump help to obtain additional backpressure. As explained in Figure 2.2, MPD does not solely rely on hydrostatic pressure p_h and circulation pressure p_p, choke valve and backpressure p_b provide more flexible pressure varying capacity to the system. Thus, bottomhole pressure is provided by the summation of p_h, p_p, p_f and p_b as given in Equation 2.3. According to international association of drilling contractors (IADC) drilling manual, some of the variations of MPD operation are presented below.

i. Pressurized mud cap drilling (PMCD)

ii. Dual gradient drilling (DGD)

iii. Constant bottomhole pressure drilling (CBHP)

PMCD is suitable for formation which experiences total loss of circulation. A sacrificial fluid is pumped through the annular pipe to compensate for the loss of hydrostatic pressure due to loss of circulation. Typically, the hydrostatic pressure of annular region is maintained marginally below reservoir pressure with a slight backpressure offered by surface level containments. Whenever an influx is experienced additional fluid is pumped through the annular pipe to prevent influx of reservoir fluid. The requirement of large supply of sacrificial fluid makes PMCD more suitable for offshore application which has abundant supply of seawater.

DGD operation focuses on stabilizing the well bore pressure profile by using subsea containments to manipulate mud return. In DGD offshore applications, the drilling fluid from the annular casing does not travel back to the rig through conventional riser setup. Additional components such as subsea mud lift pumps, gas injection or use of lighter mud in the return line imposes a dual gradient pressure on the annular region. This enables to control bottomhole pressure effectively by exposing the mud return at seawater hydrostatic pressure gradient. The main objective in CBHP drilling is to maintain the bottomhole pressure at a constant pressure setpoint defined within the pressure window. Figure 2.3 shows a typical setup required for an MPD system. In a manual MPD operation, an operator controls the choke opening u_c and backpressure pump flow q_b to avoid unwanted influx in the system. The effect of changes in pressure and flow rate is shown in Table 2.1. In an event free drilling, the reduction of choke opening induces backpressure to the control volume in the upstream choke location. On the other hand, the increase in circulation flow rate and backpressure pump flow increase system pressure. Figure 2.2 shows that the additional backpressure by the surface level containments provide opportunity to manage bottomhole pressure between the pore pressure and fracture pressure effectively. Controlling choke opening and pump flow rates manually requires operator's skill and expertise and in most of the cases does not deliver desired precision. This opens door for innovation in automated drilling solution. This thesis mainly focuses on automation of MPD operation using constant bottomhole pressure drilling approach.

$$p_{bh} = p_h + p_p - p_f + p_b \tag{2.3}$$

Table 2.1: Flow and pressure interaction in an event free drilling scenario

Component	**Operation**	**Choke pressure (p_c)**	**Bottomhole pressure (p_{bh})**
Choke opening (u_c)	+/-	-/+	-/+
Backpressure pump flow (q_b)	+/-	+/-	+/-
Circulation rate (q_p)	+/-	+/-	+/-

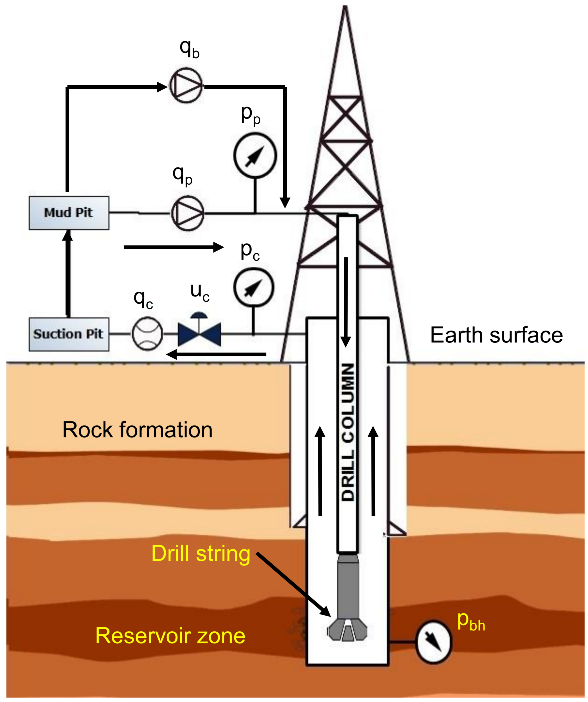


Figure 2.3: Schematic of a managed pressure drilling rig setup

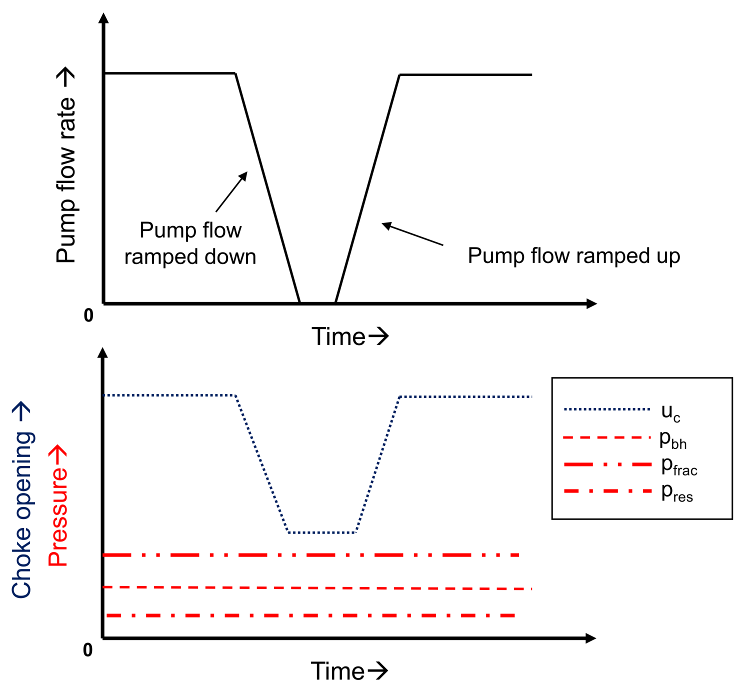


Figure 2.4: Pipe extension scenario in ideal condition

2.3 Control objectives in managed pressure drilling

In an automated MPD controller, the main objective is to track the pressure trajectory and to maintain the desired flowrates in the system. Pressure setpoint can either be set externally or determined dynamically through observer based on available measurements (i.e. choke pressure, flow rate). In addition the controller is expected to handle several operational and failure scenarios such as, pipe extension, kick rejection and circulation loss due to pump failure (Rehm et al., 2013). In a drill string extension scenario as shown in Figure 2.4, firstly the drill string rotation is halted and pump flow rate is gradually ramped down to zero over a fixed time. Once the circulation rate is brought down to no flow condition, a new drill pipe is added. During this time, it is desired to have constant bottomhole pressure in the bottomhole region. Once the placement is done, the pump flow rate is ramped up to the desired value and the drill string rotation is resumed.

Figure 2.5 depicts sudden failure of circulation pump which is one of the primary points of control. In both pipe extension and pump failure cases, it is desired to maintain the bottomhole pressure within the narrow pressure window by manipulating the choke valve position and changing the mud density. On the other hand, for some reason, if reservoir pressure exceeds the bottomhole pressure, reservoir fluid will flow into the bottomhole. These influx situations commonly known as reservoir kick must be managed by a controller. During an influx situation, typically the pressure control is stopped and the flow control is activated. As reservoir fluid enters into the casing, choke flow will be higher than pump flow. A convenient control strategy is to gradually close the choke opening until both flow rates are equal. This will raise bottomhole pressure as well and stop reservoir fluid from entering into the bottomhole. Subsequently pressure setpoint will be revised to a higher value marginally above

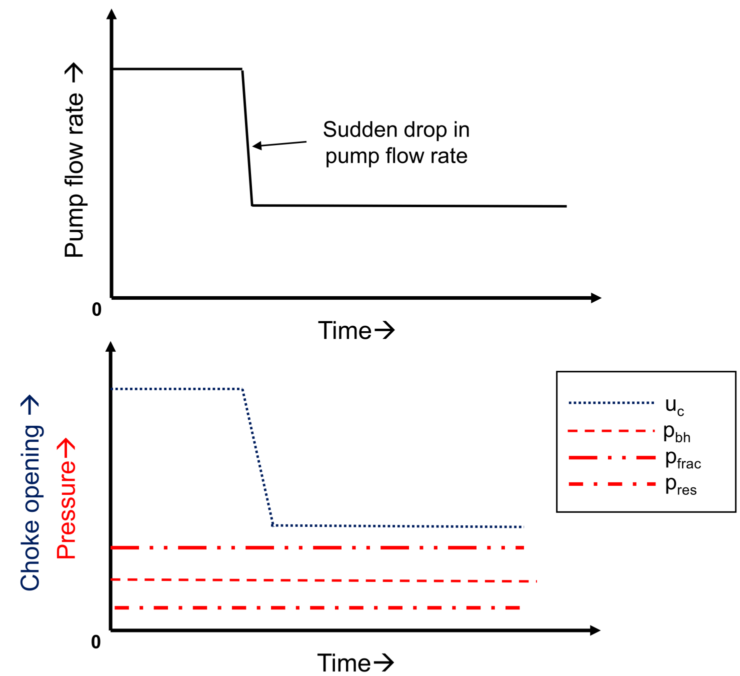


Figure 2.5: Pump failure scenario in ideal condition

the reservoir pressure and controller will return to pressure control mode. This can happen for several reasons as follows.

i. selection of setpoint based on poorly estimated condition.

ii. poor control of bottomhole pressure.

iii. drill string hits a high pressure pocket in reservoir.

2.3.1 Control relevant models for MPD

Over the years, researchers have developed models of varying complexity for MPD system. Nygaard and Nævdal (2005) proposed a low order two-phase flow model for managed pressure drilling applications. The model included the nonlinear behaviour due to gas-liquid interaction in a two phase flow to calculate bottomhole pressure. Lastly, the accuracy of the low-order lumped model and a distributed mechanistic model was compared. The low order model was developed by dividing the overall system into two control volumes i.e. drill string and annular region. The mass balance, pressure balance were used to solve ordinary differential equations (ODE) for pressure and mass flow rate in the bottomhole and well head region. In order to include the nonlinear behavior due to two phase flow, gas liquid void fraction and gas compressibility effect was introduced. On the other hand, the detailed mechanistic model uses spatially discretized control volume. Even though the mechanistic model is computationally demanding, the model provides better estimation of bottomhole pressure comparing the low order model at varying mixture flow rates. However, it was also observed that, the low order model provides reasonably accurate estimation while drilling continues. Petersen et al. (2008) used partial differential equations (PDE) to solve conservation of mass, momentum, and energy equations to evaluate the dynamic states such as pressure, flow rates, and temperature. The distributed model was developed by discretizing the overall system into small segments. The PDEs based on continuity equations are solved sequentially from the first segment to the last segment. Two consecutive segments share a common boundary conditions. This model can be used in multiphase drilling and DGD operations where the flow network is complex. The use of conservation equation enables the model to provide accurate representation of real life scenarios. However, this model is computationally demanding and requires expertise. Chin (2012) presented a simulator that can evaluate dynamic states during an MPD operation. The model is capable of considering drill pipe eccentricity, Newtonian and non-Newtonian flow phenomena, steady and transient flow conditions. The overall system is distributed into small segments using a curvilinear grid system. Each segment in the grid conforms to the traditional boundary conditions with respect to adjacent segments. The use of curvilinear grid simplify the problems associated with complex geometry. The hydrodynamic states in each segment is solved using finite difference method. However, the models did not consider the influx situations. Kaasa et al. (2012) presented a nonlinear ODE based hydrodynamic model for estimating bottomhole pressures. The main contribution of this work was to remove the complexity in modelling the pressure estimators and bring focus to the vital parameters during drilling operations. The model derivation considered functional relationship of fluid viscosity, equation of state, conservation of mass, momentum and energy. The modelling strategy considered a homogeneous and incompressible flow problem. The transient effect on the viscosity was considered negligible in the momentum balance equation. Based on the available surface measurements such as pump flow rates, circulation pressures and outlet pressures, the bottomhole pressure and frictional pressure drops can be estimated by using nonlinear ODE based observers. The performance of the model was validated using the field measurements from North sea well and data from Stavanger's full scale experimental rig setup. However, the model is limited to single phase flows only. Landet et al. (2013) developed a hydraulic transmission line model based on annular flow path for mitigating disturbance induced by heave motion experienced in the offshore drilling operations. PDEs were developed using the conservation of mass and momentum equations across differential control volumes. The discretization is done using finite volume method. The PDEs in distributed control volume solves for pressure and volumetric flow rate for all available spatial coordinates. The model is able to include the hydrodynamic behavior due to changing annular volume and frictional loss across drill bit in the bottomhole zone. Experimental data from Ullrigg facility was used to verify the model performance. To conclude, various modelling approach has been made to develop an accurate model for MPD applications. The chosen method largely depends on the demand of required parameters and its associated accuracy.

2.3.2 Controllers in drilling automation

The shifting industry focus from manual operation to automated well control has stressed the need for innovation of efficient control strategies. The potential controller algorithm ranges from simple proportional integral derivative (PID) controllers to advanced non-linear model predictive controllers (NMPC). The computational effort, desired level of accuracy and selection of variables is necessary for successful controller implementation. Below we provide an overview of controllers implemented on MPD systems.

2.3.2.1 Feedback controllers

Godhavn et al. (2010) demonstrated the use of a simple PID controller whose ultimate goal is to track choke pressure during the normal drilling operation, pipe extension, surge and swab operations. An online hydraulic model was used along with instantaneous formation pressure determination which measured the pressure states and solves for an optimal choke opening for downhole pressure management. The controller configurations were obtained from ordinary differential equation based transfer function model. The tuning parameters vary when sudden flow fluctuations are experienced. It was proposed that a gain switching PID controller can handle flow variations and stabilize the operation. The stability and accuracy of the controller can be increased by removing human effort in handling pipes and improving bottomhole pressure measurement technologies. Zhou et al. (2011) presented a novel switched control scheme for pressure regulation in the annular casing region with automatic kick attenuation. The controller operates in two modes i.e. pressure control mode and flow control mode. The overall control volume is divided into drill string and annular casing control volume. An observer has been developed using the nonlinear ODE equations to estimate the bit flow rate, reservoir pressure and kick flow rate. Pump pressure, choke pressure, and pump flow rate are directly measured during operation. The measurements are fed into the nonlinear observer which estimates the bit flow rate. When a kick is experienced, the switching algorithm activates flow control mode which utilizes the reservoir pressure estimate to choose a new BHP setpoint. Once the kick is rejected by tracking the new BHP setpoint, the controller switches back to its previous pressure control mode with the new pressure setpoint value after a stabilization time has elapsed. The controller switches to flow control mode whenever the kick estimate exceeds the assigned threshold value. Godhavn et al. (2011) demonstrated the use of a simplified nonlinear system of equations to estimate the bottomhole pressure and developed a feedback linearized choke controller. The controller's goal is to drive the choke pressure to desired setpoint value. Achieving accurate frictional pressure estimation also enables the system to obtain desired bottomhole pressure setpoint. The controller has been implemented experimentally and provide better performance over conventional PID controller. Reitsma and Couturier (2012) provided a comprehensive overview on the use of choke pressure controller in managed pressure drilling operation. The review pointed out the need of handling control valve non-linearity which occurs due to variable flow coefficients at changing flow demands. The development of choke based controller is progressing with technological development. These developments enable integration of simple PI control algorithms to advanced control algorithms. It is also observed that the nonlinear controller provided promising results over conventional PID controller in terms of response, robustness, and stability.

Siahaan et al. (2012) proposed an PID controller where the tuning parameters are selected from a set of parameters based on the realtime measurements and cost function. A high fidelity drilling simulator WeMod was used to demonstrate the effectiveness of the controller. When a PID controller tuning parameters are fixed to constant values, there is a possibility of oscillation in the states when flow demand changes and the controller tries to compensate the change. Prior to controller application, a set of candidate parameters were designed. Based on the measured data and evaluation of cost function, right candidate parameter is chosen to counteract the oscillation effect and stabilize the operation quickly. However, the computation for selecting the right setting is challenging without prior knowledge and expertise of the system. Hauge et al. (2012) used feedback linearization technique to develop a choke controller. The controller uses an adaptive observer for estimating downhole measurements. The hydrodynamic model is a set of nonlinear ODEs based on conservation of mass and momentum across drill string and annulus control volume. Hauge et al. (2013) presented a further extension of his previous work where the controller performance was demonstrated on an experimental system and high fidelity OLGA simulator. The ultimate goal of this work was to locate the influx initiation point and estimate the magnitude of the flow. Based on the quantity, a choke opening is set and the kick is rejected by activating flow control mode in operation. A choice has to be made in selecting BHP control mode or flow control mode based on the control requirement. Nandan et al. (2014) proposed a robust gain switching scheme for automating MPD operation using constant bottomhole pressure control technique. The gain scheduling is performed based on magnitude of circulation rate and choke opening. The overall operating region was divided into six operating regions with H_∞ loop shaping controller designed for each region. First order transfer function models between choke pressure and choke opening has been used for designing the feedback controller. The transfer function model incorporates set of gain and time constant values to operate at different flow ranges. The controller is able to handle uncertainty offered by the mud density of the drilling fluid. In normal condition the controller tracks the bottomhole pressure at different mud densities. In event of influx, the reservoir pressure is estimated from the nonlinear ODE based observers, and a new pressure setpoint is revised to mitigate kick in the system. The controller performance was simulated in normal drilling, pipe connection, pump failure and kick attenuation cases. However the experimental implementation is yet to be explored.

2.3.2.2 Predictive controller

Nygaard and Nævdal (2006) developed an NMPC controller using a distributed mechanistic model. The optimization scheme is based on Levenberg–Marquardt algorithm. The controller was compared to a low order model based PI controller. The controller design utilized the dynamics of two phase flow phenomena. The goal of the controller is to control the choke opening based on the fluctuating flow needs in the drilling operation. The NMPC controller had better performance over PI controller because the PI controller configurations need to be changed with the change in operating parameters. Carlsen et al. (2013) compared different control algorithms which can be used to automate the sequential control operations in an influx situation. High fidelity simulators were used to evaluate the controller performances. A PI controller, an internal model controller (IMC) and a model predictive controller (MPC) were designed to control the pump flow rate and choke pressure to handle kick situations. The controller parameters were derived from first order process models. It is observed that the IMC and MPC controller performances were better compared to the PI controller. The MPC controller showed better performance when the control horizon is increased. However, the robustness of the controller was compromised with an increase in control horizon.

Breyholtz et al. (2010) presented a multivariable controller approach. An MPC controller was implemented using a high fidelity simulator where flow rates and drill string velocity were fed as input states and bottomhole pressure and hook position were set as output states. The controller model used a single-shooting multi-step quasi- Newton method based solver. The simulation results were promising in rejecting disturbance and regulating BHP. However, drill pipe extension and flow control cases were not dealt in the study. Møgster et al. (2013) proposed a linear MPC controller in MPD. For using PID controller with a fixed tuning constant, multiple PID controllers must be integrated for flow and pressure control operation at the same time. The linear MPC controller uses flow and pressure constraints which eliminate the need of using multiple conventional PID controller. Pump flow rate q_p and choke opening u_c has been considered as manipulated variable. For efficient flow and pressure controller, a linear first order transfer function model is utilized for manipulating choke opening and pump speed. The controller was tested in high fidelity WeMod software along with Statoil's SEPTIC MPC software. However, the potential of this controller could be explored in mitigating influx and pipe extension scenarios. Eaton et al. (2015) proposed a combination of three model predictive controllers with advanced switching algorithm in MPD operation. The study presents the multivariable control process on a high fidelity simulator where three different MPC models i.e. high fidelity MPC controller, low order controller and empirical controller are used. The high fidelity MPC controller is based on a high fidelity SINTEF flow model. The low order model is based on a set of nonlinear ODEs. Lastly, the empirical controller is based on the data obtained from the simulation. The combination of these three controllers provide optimal choke opening and pump flow rate for pressure tracking in normal drilling and pipe connection cases. Even though this controller is reasonably successful in handling measurement inaccuracy, it requires significant computational power and expertise to design and successfully implement the controller. Nandan and Imtiaz (2017) designed an NMPC control scheme which utilizes the constraint handling capacity of NMPC and automatically switches from pressure control mode to flow control mode in case of reservoir kick. Thus the controller is able to deliver optimal performance during normal as well as abnormal condition. The control algorithm is based on an output feedback structure. An nonlinear ODE observer has been utilized to estimate the bit flow rate q_{bit} and kick volume q_{kick}. Whenever the kick volume q_{kick} goes beyond a threshold value indicated by the difference between inlet and outlet flow rate, the flow control mode is activated to drive the kick out of the system. The controller was developed and tested on a simulated ODE model proposed by Kaasa et al. (2012) which solves for optimal choke opening by optimizing the constraint values in predefined cost functions. The performance of the controller was verified simulating in normal drilling, pipe extension and flow control cases. The controller needs further experimental evaluation before it is ready for field application. Zhou and Krstic (2016) included the time delay parameter in designing an adaptive predictive control. Transient behavior is always experienced in a typical drilling operation. For the sake of simplicity time dependent behaviors are generally ignored for hydrodynamic modelling and controller design. This study presented a comparison between PI controller and predictive controller with time delay parameter inclusion. However, the full potential of this model is yet to be explored in real field application.

2.3.3 Experimental implementations of MPD

In order to design MPD operation efficiently, it is important to understand the actual dynamics and challenges experienced in real field implementation. Researchers have investigated the dynamic behaviour of MPD systems in setups ranging from lab scale experiments to full-scale or actual field tests. Santos et al. (2007) demonstrated real field application of micro flux control (MFC) as a form of MPD technology. The feasibility of the MFC control approach was evaluated in LSU petroleum engineering research & technology transfer laboratory (PERTT) through several experiments.

The facility is equipped with 15000 gallon capacity water circulating system. The experimental well is 5884 ft deep supported by two triplex pumps and able to circulate water from 250 gpm to 500 gpm. The pressure can be as high as 5000 psi. The aim of the MFC technique is to drill maintaining marginal overbalance in the bottomhole pressure and using corrective action as soon as the first kick is detected. Fredericks et al. (2008) presented the implementation of MPD in a real field exploratory shallow gas well in Myanmar. The ultimate goal of MPD application was dynamic control of pressure while drilling, pipe extension cases and flow control scenarios. Real-time surface measurements were fed into a system which predicted the BHP instantaneously. The coriolis flow meter measuring the outlet flow provided an early indication of the kick situations. In the event of influx, the dynamic annular pressure control (DAPC) was switched from real time pressure measurement mode to integrated pressure manager (IPM) mode to preserve the well integrity. Three different choke openings and a triplex backpressure pump were regulated accordingly to achieve flow control and constant BHP objectives. The overall technology integration was followed by proper risk assessment, commissioning and testing from an operator point of view. Several experiments were performed in the Kvitebjørn well to determine the feasibility of MPD operation. Syltoy et al. (2008) demonstrated the integration of continuous circulation system (CCS) and use of Caesium/Potassium (Cs/K) Formate based drilling mud with MPD operation in maintaining the BHP requirement through automatic choke control. The operations were performed in Kvitebjørn well where the formation-pressure-while-drilling (FPWD) tool was used to evaluate the reservoir pressure at every instant. The pressure requirements were adjusted by marginally placing the pressure setpoints above measured reservoir pressure and the predicted reservoir pressure to be encountered while drilling. However, successful implementation of these advanced technologies requires proper training of the operators and hazard identification of the site to be drilled. Bjorkevoll et al. (2008) tested an automatic choke controller in Kvitebjørn well where choke regulating decisions were made based on the online and offline hydrodynamic state evaluation. In the online mode, the properties such as flow rate, pressure, density and temperatures were checked to solve for an optimal choke opening. On the other hand, the offline mode dealt with the influx situations and provided assistance in planning for long-term operations involving multiple process sequences. Reitsma (2010) presented a modified dynamic annular pressure control (DAPC) which can detect influx occurrence without the use of outlet flow measurement. The need for flow meter was eliminated by accurate pressure prediction and pressure based influx detection algorithm. Based on the pressure evaluation a decision is made to regulate the choke opening and control the bottomhole condition. The system was tested in petroleum engineering research & technology transfer laboratory (PERTT) facility installed at Lousiana state university. The test showed, pressure transducer alternatives can be used for reliable kick detection. Godhavn et al. (2011) presented the experimental implementation of a feedback linearized choke pressure controller. The Ullrigg test facility in Stavanger, Norway with a true vertical depth of 1540 m was utilized to show the effectiveness of the proposed feedback linearized controller and traditional PID controller. The main pump flow rate can reach as high as 1500 lpm. The choke manifold can be operated remotely and able to withstand a maximum pressure of 345 bar. The setup has bottomhole pressure estimation, pipe connection scenario and stepped choke pressure tracking experiment features. Borgersen (2013) presented influx attenuation methods in MPD operation using a lab scale test rig installed in University of Stavanger. PVC pipe was coiled to obtain an overall length of 50 m. Pipes of 40-75 mm diameter has been used to build up the flow loop. Well control valve and several manual valves are placed across the overall length to manipulate the pressure at different points of interest. The setup is suitable for simulating reservoir kick scenario. First a pump flow is set to a constant value, after few minutes as the pump flow rates stabilizes, and the kick is injected. Gain switching PI controller is activated when an influx is detected and rejected by pressure regulation using the installed flow control valves. However, measurement noise was encountered which must be taken care of for reliable measurements. Hauge et al. (2013) proposed an adaptive observer for detecting influx initiation point, magnitude and mitigation strategies. The results were validated with multiple experimental data sets obtained from the same setup used by Borgersen (2013). The friction parameters and bulk modulus parameters were tuned using the experimental data based correlation equation. The experiments showed that the influx detection relies on the magnitude of kick occurence. The higher the magnitude, easier it is to detect influx event. However, the experiments were limited to water based drilling fluid. The use of non-Newtonian fluid can reduce the prediction accuracy of the dynamic states. Ånestad (2013) presented a lab-scale experimental setup which can simulate the heave induced disturbance in a managed pressure drilling operation. The experimental setup was designed based on data from 4000 m deep vertical well. Copper pipes were coiled together to obtain an overall length of 900 m. Flow and pressure transducers were installed at different points of interest. The mathematical model demonstrated the need for handling non-linearity in the choke. The pressure and velocity information were obtained by solving PDEs describing the system.

2.4 Conclusions

From the previous discussion, it is evident that a lot of progress has been made in accurate modelling and design of controller in MPD operation. The design and implementation vary based on the control requirement. Even though a controller model may be successful in simulation, but it is not guaranteed to comply with the challenges experienced in the real operation in the field. This is due to the presence of non ideal behaviour in drilling fluid, or nonlinearity in components such as choke manifold. Thus, linearization techniques is yet to be explored while working in real field experiments. It is also clear that even after a successful performance in simulation-based implementation of NMPC controllers, there was no experimental implementation of the NMPC for MPD system.

In this study, a lab-scale managed pressure drilling setup is presented with the implementation of a gain switching PI controller and an NMPC controller. The main goal for implementation is to identify the operational challenges and mitigate them in the experiment. The linearized gain switching PI controller was designed based on a novel choke control valve linearization technique. On the other hand, the NMPC controller has been developed based on data-driven nonlinear Hammerstein Weiner model. The controller performance was demonstrated for normal drilling operation, pipe extension scenario, pump failure and flow control cases.

Chapter 3

Design, Development and Control of an Experimental Managed Pressure Drilling Setup

Al Amin, Syed Imtiaz, Aziz Rahman & Faisal Khan

Department of Process Engineering,

Memorial University of Newfoundland,

St. John's, Newfoundland and Labrador, Canada A1B 3X5

Abstract

In this paper, we present the design, development and control of a lab scale managed pressure drilling (MPD) experimental setup. This scaled-down experimental setup was built to study the hydrodynamics of MPD operation. A brief overview of the design and development stages of the experimental setup is provided, followed by simulation of different operational and abnormal scenarios, and comparison of the experimental frictional loss with theoretical friction loss models. The experimental setup is a 16.5 ft tall concentric flow loop where the inner pipe simulates the drill string and outer pipe represents the annular casing in a drilling operation. Reynolds number and 'pressure drop per unit length' of the experimental setup were matched as close as possible to a field scale drilling system in order to maintain hydrodynamic similarity. However, the flow loop is limited to static drill string. There is no axial rotation or progression in vertical direction. A set of proportional integral (PI) controller with

linearized valve and gain switching were applied to test a variety of drilling operational scenarios including drill pipe extensions, pump failure and gas kick attenuation.

3.1 Introduction

The concept of MPD was formally introduced in the late 1960s in the abnormal pressure symposiums at Louisiana state university (Rehm et al., 2013). According to international association of drilling contractors (IADC), MPD is a condition based adaptive technique which maintains the downhole pressure conditions in conjugation to the annular pressure profile by using components such as backpressure control, bottomhole annular pump or mechanical devices. The overall objective of this technique is to maintain the downhole pressure within an allowable pressure window provided by pore pressure and fracture pressure.

3.1.1 Experimental studies on MPD

Since the inception of MPD technique, several experimental investigations has been performed to confirm the reliability of this operation. Technological advancement, hydrodynamic model development, drilling automation, controller design and drilling strategy formulation are some of the primary areas of focus during experimental analysis. Based on the desired area of concentration, experimental setups are designed. Santos et al. (2007) demonstrated the feasibility of the micro flux control (MFC) approach which was evaluated in LSU petroleum engineering research & technology transfer laboratory (PERTT) through several experiments. The experimental well is 5884 ft deep and able to circulate water from 250 gpm to 500 gpm. The maximum pressure can be as high as 5000 psi. The aim of the MFC technique is to maintain marginal overbalance in the bottomhole pressure and take corrective action as soon as the first kick is detected. Reitsma (2010) presented a modified dynamic annular pressure control (DAPC) which can detect influx occurrence without the use of outlet flow measurement. The need for a flow meter was eliminated by accurate pressure prediction and pressure based influx detection algorithm. The system was tested in PERTT facility installed at Lousiana state university. The test showed that, pressure transducer alternatives can be used for reliable kick detection. Godhavn et al. (2011) presented the experimental implementation of a choke pressure controller. The Ullrigg test facility in Stavanger, Norway with a true vertical depth of 1540 m was utilized to show the effectiveness of the proposed feedback linearized controller and traditional PID controller. The main pump flow rate can reach as high as 1500 lpm with a maximum pressure upto 345 bar. The setup has bottomhole pressure estimation, pipe connection scenario and stepped choke pressure tracking experiment features. Borgersen (2013) presented influx attenuation methods in MPD operation using a lab scale test rig installed at the University of Stavanger. PVC pipe was coiled to obtain an overall length of 50 m. Pipes of 40-75 mm diameter has been used to build up the flow loop. The setup is suitable for simulating reservoir kick scenario. First a pump flow is set to a constant value, after few minutes as the pump flow rates stabilizes, the kick is injected. Gain switching PI controller is activated when an influx is detected and rejected by pressure regulation using the installed flow control valves. However, measurement noise was encountered which must be taken care of for reliable measurements. Hauge et al. (2013) proposed an adaptive observer for detecting influx initiation point, magnitude and mitigation strategies. The results were validated with multiple experimental data sets obtained from the setup used by Borgersen (2013). The experiments showed that the influx detection relies on the magnitude of kick occurrence. However, the experiments were limited to water-based drilling fluid. The use of non-Newtonian fluid can reduce the prediction accuracy of the dynamic states. Ånestad (2013) presented a lab-scale experimental setup which can simulate the heave induced disturbance in a managed pressure drilling operation. The experimental setup was designed based on data from 4000 m deep vertical well. Copper pipes were coiled together to obtain an overall length of 900 m. Flow and pressure transducers were installed at different points of interest. The mathematical model demonstrated the need for handling non-linearity in the choke. The pressure and velocity information were obtained by solving PDEs describing the system.

3.1.2 Controllers in MPD

The control algorithms ranges from simple PI controller to model based predictive controllers such as non linear model predictive controller (NMPC). Godhavn et al. (2010) demonstrated the use of a simple PID controller whose ultimate goal is to track choke pressure during the normal drilling operation, pipe extension, surge and swab operations. The controller configurations were obtained from ordinary differential equation based transfer function model. It is proposed that a gain switching PID controller can handle flow variations and stabilize the operation. Zhou et al. (2011) presented a novel switched control scheme for pressure regulation in the annular casing region with automatic kick attenuation. The controller operates in two modes i.e. pressure control mode and flow control mode. The overall control volume is divided into drill string and annular casing control volume. An observer has been developed using the nonlinear ODEs to estimate the bit flow rate, reservoir pressure and kick flow rate. When a kick is experienced, the switching algorithm activates flow control mode which utilizes the reservoir pressure estimate to choose a new BHP setpoint. Once the kick is rejected by tracking the new BHP setpoint, the controller switches back to its previous pressure control mode with the new pressure setpoint value after a stabilization time has elapsed. Godhavn et al. (2011) demonstrated the use of a simplified nonlinear system of equations to estimate the bottomhole pressure and developed a feedback linearized choke controller. The controller's goal is to drive the choke pressure to desired setpoint value. Achieving accurate frictional pressure estimation also enables the system to obtain desired bottomhole pressure setpoint. The controller has been implemented experimentally and provide better performance over conventional PID controller. Reitsma and Couturier (2012) provided a comprehensive overview on the use of choke pressure controller in managed pressure drilling operation. The review pointed out the need of handling control valve nonlinearity which occurs due to variable flow coefficients at changing flow demands. It is also observed that the nonlinear controller provided promising results over conventional PID controller in terms of response, robustness, and stability.

Siahaan et al. (2012) proposed an PID controller where the tuning parameters are selected from a set of parameters based on realtime measurements and cost function. A high fidelity drilling simulator WeMod was used to demonstrate the effectiveness of the controller. When a PID controller tuning parameters are fixed to constant values, there is a possibility of oscillation in the states when flow demand changes and the controller tries to compensate the change. However, the computation for selecting the right setting is challenging without prior knowledge and expertise of the system. Hauge et al. (2012) used feedback linearization technique to develop a choke controller. The controller uses an adaptive observer for estimating downhole measurements. The hydrodynamic model is a set of nonlinear ODEs based on conservation of mass and momentum across drill string and annulus control volume. Hauge et al. (2013) presented a further extension of his previous work where the controller performance was demonstrated on an experimental system and high fidelity OLGA simulator. The ultimate goal of this work was to locate the influx initiation point and estimate the magnitude of the flow. Based on the quantity, a choke opening is set and the kick is rejected by activating flow control mode in operation. A choice has to be made in selecting BHP control mode or flow control mode based on the control requirement. Nandan et al. (2014) proposed a robust gain switching scheme for automating MPD operation using constant bottomhole pressure control technique. The gain scheduling is performed based on magnitude of circulation rate and choke opening. The overall operating region was divided into six operating regions with H_∞ loop shaping controller designed for each region. First order transfer function models between choke pressure and choke opening have been used for designing the feedback controller. In normal conditions the controller tracks the bottomhole pressure at different mud densities. In the event of influx, the reservoir pressure is estimated from the nonlinear ODE based observers, and a new pressure setpoint is revised to mitigate kick in the system. The controller performance was simulated in normal drilling, pipe connection, pump failure and kick attenuation cases. However the experimental implementation is yet to be explored.

Our objective is to design and develop a scaled down lab scale MPD system with similar hydrodynamic properties of a typical wellbore system. The developed system should be capable to replicate different operational scenarios including drill pipe extension, pressure tapping, drill mud loss and gas kick; and test the performance of a variety of control algorithms. We demonstrated the design methodology for developing the experimental setup and discussed the results from different operational scenarios using the controller.

3.2 Design methodology

In the design, geometric similarity i.e. model should be an exact geometric replica of the prototype; hydrodynamic similarity i.e. Reynolds number (Re) and pressure drop

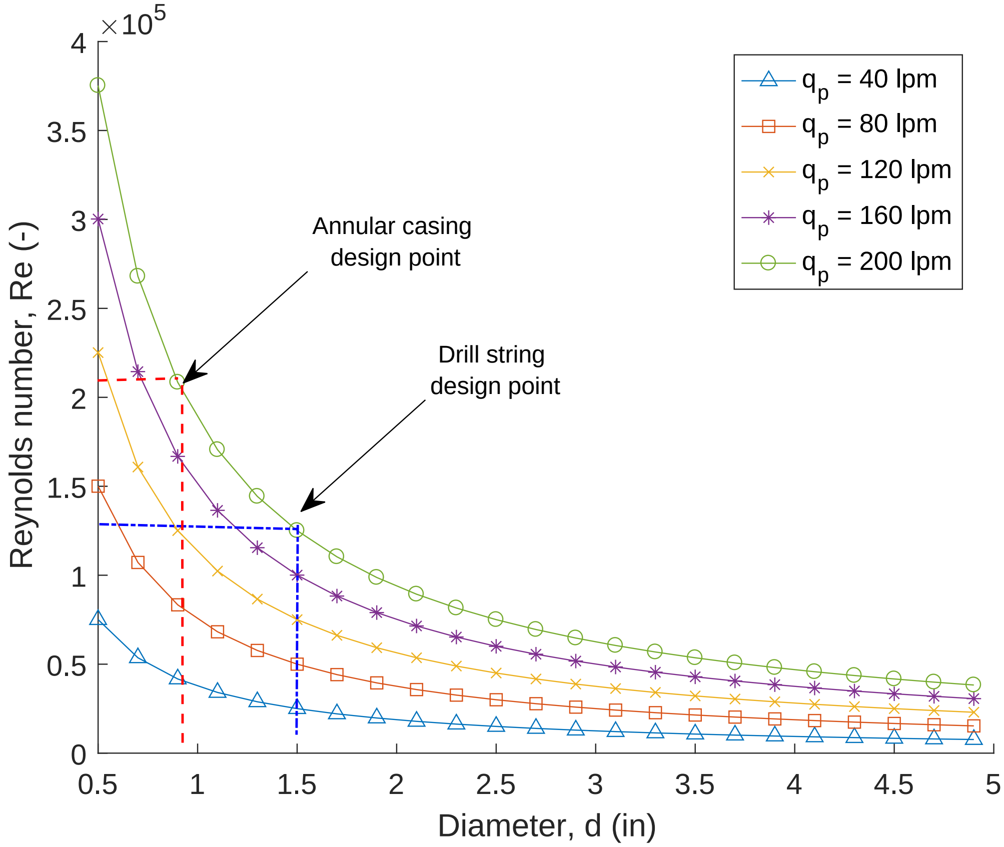


Figure 3.1: Selected pipe diameter design point

per unit length ($\Delta P/L$) were considered. The field data were collected from Birkeland (2009). In the full scale setup, the drill string and annular casing pipe length ranges from 17000 to 18350 ft. The vertical length in the experimental setup was determined based on the available headroom in the laboratory and was set to 16.5 ft. In real field setup, considering water as drilling fluid, the maximum Reynolds number can reach upto 230000. The pressure drop per unit length can be as high as 0.03 psi/ft with a maximum flow rate of 1400 lpm. The experimental setup was designed to match with the real field design parameters as close as possible. The maximum Reynolds number was considered to reach as high as 200000. The design pressure drop can be between 0.03 and 0.8 psi/ft in the lab scale experimental setup. Figure 3.1 shows that, Reynolds

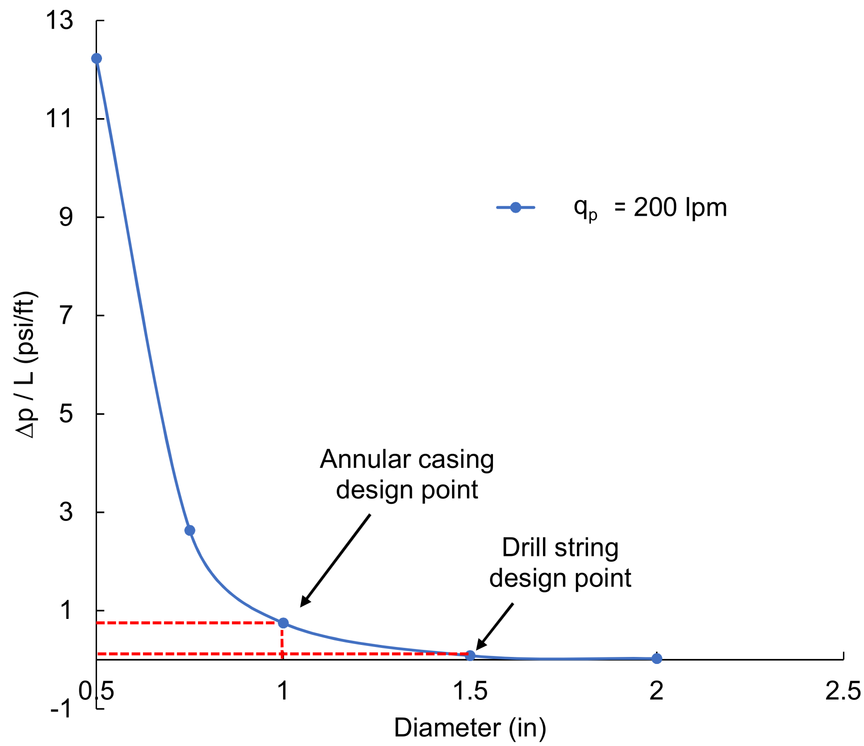


Figure 3.2: Pressure drop per unit length for different pipe diameters

number was calculated for drill string pipe and annular casing with nominal diameter between 0.5 to 5 inches for a pump flow rate upto 200 lpm. The Reynolds number for annular flow path is based on equivalent diameter $D_{eq} = D_{ai} - D_{do}$. Figure 3.2 shows the pressure drop per unit length for the experimental setup for pipes with different diameters at 200 lpm pump flow rate. Using the design constraints, the required pipe diameters were chosen as shown in Table 3.1. In order to comply with the frictional pressure drop for chosen diameters, pressure drops per unit length has been calculated. Finally, the design parameters were checked to make sure the values are feasible to build the flow loop. Several assumptions were made while designing the experimental setup. In order to minimize complexity in operation, water is chosen as the primary drilling fluid. However, the setup is designed to deal with viscous fluid upto 1.8 specific gravity (S.G.), constraint arising from pump specification. The designed experimental setup is only suitable to investigate the flow behavior of a static drill string (i.e. no rotation) at a particular depth. The reservoir fluid is considered to be air. Pressurized air will be injected to replicate the influx situations. Due to the smaller height of flow loop there is very small time delay and dynamic response of outflow due to any change in inflow is quick. As such, the inlet and outlet flow should be same within experimental error at zero influx condition. Under no influx condition there is no change in fluid density or viscosity in the system.

Table 3.1: Dimension of designed drill string and annular casing pipe

	Length (in)	**Nominal diameter** (in)	**Pipe Schedule**	**Material**
Drill pipe	187	1.5	80	Black PVC Plastic
Annular	175	3	80	Clear PVC Plastic

3.3 Experimental setup

The flow diagram and a photograph of the setup are shown in Figures 3.3 and 3.4. The core of the setup is a 1.5 inch diameter PVC pipe which is installed vertically to represent the tubular drill string and a 3 inch clear PVC pipe placed concentric to the inner pipe representing the casing. A 600 l capacity tank is constructed to supply drilling fluid to the progressive cavity pump. The drilling fluid returns back to the tank after being pumped through the flow loop completing the closed loop circulation system. The screw type progressive cavity pump (PCV 101) circulates drilling fluid with a circulation rate between 20 lpm and 200 lpm. The pump is capable to deliver drilling fluid with a discharge pressure as high as 145 psi. A variable frequency drive (VFD) is used to control the pump rpm to obtain the desired flow rate and pressure during the experiment. The VFD frequency can be regulated between 5 Hz to 60 Hz. For ensuring safer operation during any blockage condition in the flow path, a bypass line has been created in the pump outlet region using a pressure safety valve (PSV 101). If the system pressure exceeds 150 psi due to blockage in the flow loop, the PSV will open the bypass line to release the excess pressure by redirecting the flow from pump outlet to drilling fluid container. A non return valve (NRV 201) has been placed in the drill pipe head near bottomhole region. This divides the overall control volume into drill pipe control volume and annular control volume. The valve prevents backflow with minimum opening pressure of 0.5 psi. A plug type pneumatic actuator (CV 302) is installed in the wellhead region to control the upstream system pressure. The valve stem travel in the actuator decides the choke opening between 0% and 100%. Both actuators requires a continuous air supply of 35 psi to be able to manipulate the valve opening corresponding to the current signals obtained from the control system. The choke opening can be calibrated automatically using the digital positioner equipped with the valve travel mechanism. An air compressor has been used to supply air to the pneumatic actuators and the air injection port in the bottomhole region. The compressor can supply air to simulate the 'gas kick' in the bottomhole region with pressure between 0 to 100 psi and air flow rate as low as 2.7 lps. Manual pressure regulators has been installed to regulate the supply pressure as desired. An air flow meter (AF 501) has been used in the air supply line to measure the air flow rate between 0 to 25 cfm with 2% full scale accuracy. A non return valve installed in the air supply line ensures unidirectional air supply through the air injection port to emulate the 'gas kick'. Table 3.2 provides a brief overview of sensors and actuators used in the experimental setup with its corresponding locations. The compatibility and sizing of the sensors were determined based on the dimension of the flow loop, budgetary limitations, and feature requirements. The sensors were wired to the data acquisition and control system in the control station. 8 pressure transmitters and 3 flow meters are placed in the overall flow path as shown in Figure 3.3. The pressure transmitters provides pressure measurements in current signal ranging from 4-20 mA with an accuracy of 0.1%. The flow meters provides instantaneous flow measurements in current signals between 4-20 mA which is further converted in the control system to record data in actual physical units. For safety, it is desired to operate with a maximum system pressure of 150 psi with a flow rate ranging from 20 lpm to 100 lpm.

Table 3.2: Sensors and Actuators used in the system

Component	**Equipment**	**Operating range**	**Position**
Flowmeter	Rosemount 8711	0 - 200 lpm	FM101, FM401
	Krohne Optiflux 3000	0 - 200 lpm	FM301
	Omega FLR 6725D	0 - 25 cfm	AF501
Pressure transmitter	Rosemount 2088	0 - 150 psi	PT101, PT302
	WIKA P31	0 - 300 psi	PT102, PT201, PT202 PT203, PT204, PT302
Control valve	Baumann 24000CVF	0 - 100%	CV302
	Apollo ball valve	0 - 100%	CV101

3.4 Data acquisition and control system

The schematic of MPD data acquisition and control system is shown in Figure 3.5. The control system is built on MATLAB Simulink and Advantech ADAM 5000 controller platform. ADAM 5000 is a 8 slot distributed data acquisition and control system which can accommodate analog input or output cards for bidirectional data transmission. Communication between the MPD plant and MATLAB Simulink was established using ADAM 5000 TCP/IP, OPC Server, and MATLAB OPC toolbox. Three input cards and one output card had been used for reading the measurements

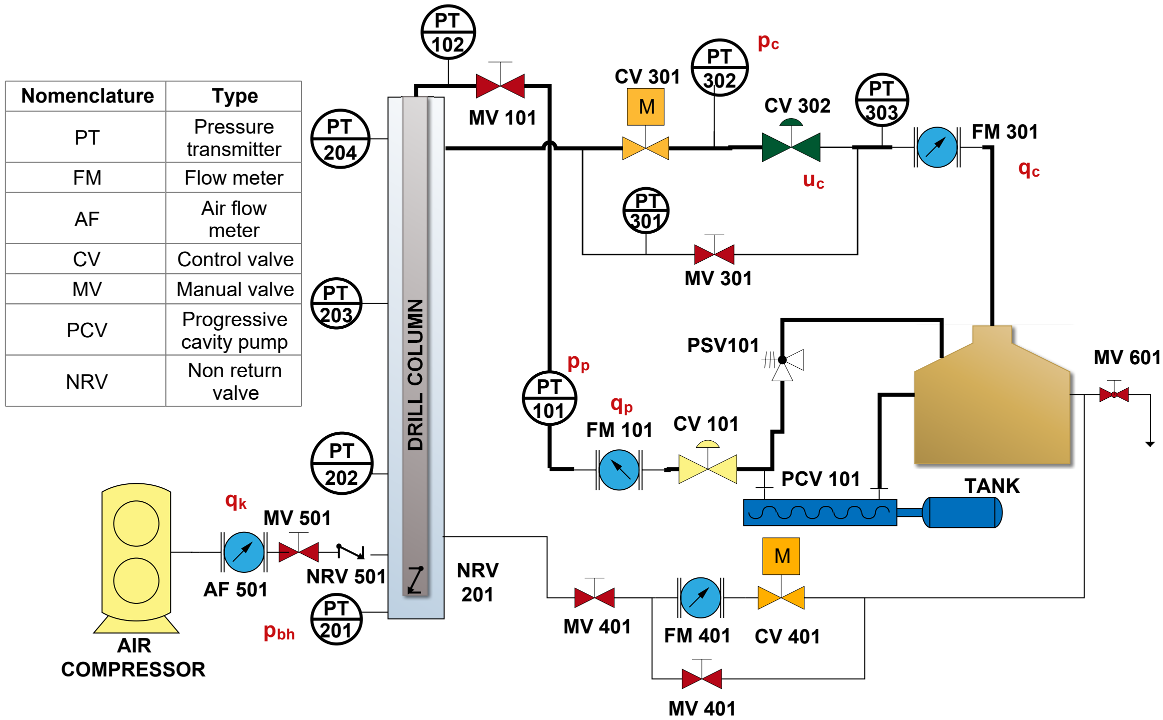


Figure 3.3: Schematic of experimental setup

Figure 3.4: Actual experimental setup

and writing the control outputs. ADAM 5017 input cards were used as analog input module which can record data at 10 samples/sec with an accuracy of ±0.1%. The pressure and flow measurements are recorded through the input module with an effective data resolution of 16 bit. Sensor calibration was performed using the maximum and minimum ranges of the measuring component with corresponding current input signals obtained between 4 to 20 mA. ADAM 5024 output module was selected for sending the analog output signals with an effective resolution of 12 bit. Two pneumatic actuators wired to the output module receive current signal between 4 to 20 mA to drive the choke valve to a desired opening position between 0 to 100%. OPC server and client pairs were configured in the computer using the Advantech OPC server software. ADAM 5000 TCP/IP sends and receives data in the computer using RS-485 communication standard. The OPC server converts the data and forwards it to MATLAB OPC toolbox for monitoring and control purposes.

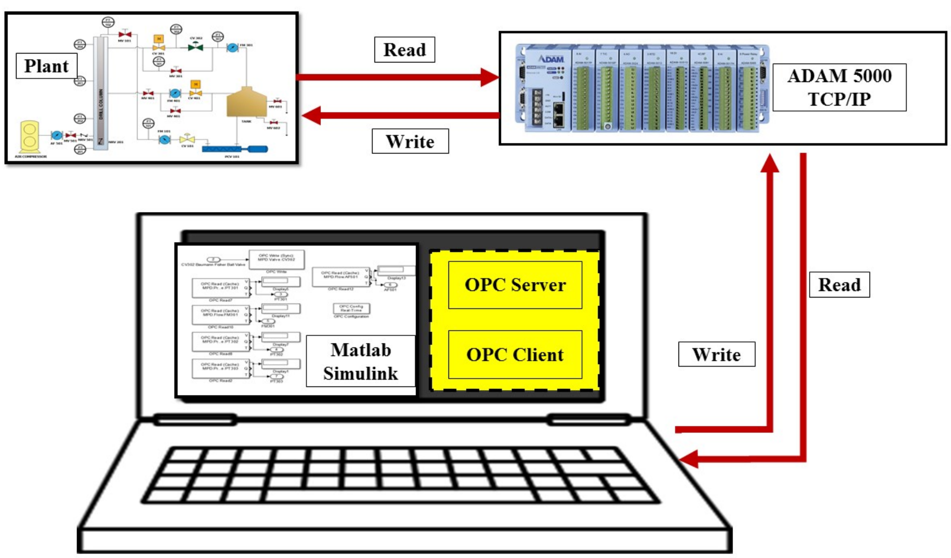


Figure 3.5: MPD data acquisition and control system

3.5 Manual operation of the MPD system

The main objective of these experiments was to verify whether the MPD setup complies with the design specifications and mimics the operational features. The experiments were conducted by varying the pump flow rate and choke opening manually from the control station. In order to observe the setup's response to abnormal scenario, 'gas kick' case was emulated using the air compressor.

3.5.1 Pressure drop characterization

In the MPD setup the progressive cavity pump circulates the drilling fluid (i.e. water) at a desired volumetric flow rate q_p, pressure at the pump outlet p_p depends on the flow rate and the overall dynamics of the system. The drilling fluid is pumped through the drill string to the downhole region and circulated back to the surface through the annular pipe. The non return valve (NRV 201) attached to the drill pipe head ensures unidirectional flow in the bottomhole region. This helps to separate the drill pipe and annular control volume. The pressure drop across the check valve is calculated in the drill string frictional pressure drop (Δp_{fd}) as shown in Equation 3.1. Choke valve (CV 302) placed on the flow path at the exit of the annular section to manipulate pressure p_c in turn maintains bottomhole pressure p_{bh}. The choke opening imposes a backpressure to increase the bottomhole pressure.

$$p_{bh} = p_p - \Delta p_{fd} + \rho_d g h_t \tag{3.1}$$

$$p_{bh} = p_c + \Delta p_{fa} + \rho_a g h_t \tag{3.2}$$

$$p_h = \rho g h_t \tag{3.3}$$

Steady state bottomhole pressure can be calculated by summation of choke pressure, annular frictional pressure drop and hydrostatic pressure in the annular section as shown in Equation 3.1 and 3.2; Δp_{fd} and Δp_{fa} are frictional pressure drop in the drill string and annular control volume; p_h is the hydrostatic pressure offered by drilling mud; q_k is the influx flow rate obtained from the interaction between reservoir pressure p_{res} and bottomhole pressure p_{bh}. Frictional pressure drop can be obtained by Darcy-Weisbach equation from Moody and Princeton (1944) as shown in Equation 3.4 and Equation 3.5.

$$h_f = f \frac{L}{D} \frac{v^2}{2g} \tag{3.4}$$

$$\Delta P_{overall} = \rho g h_f + \rho g k \frac{v^2}{2g} \tag{3.5}$$

h_f is the frictional pressure drop coefficient at velocity v. Length L and Diameter D is the geometric properties of the flow path. f is the friction factor which depends on the flow regimes and pipe roughness. For simplicity, Reynolds number above 2100 was considered as turbulent flow. For turbulent flow, the friction factor is obtained by solving Colebrook equation approximated by Haaland equation from Colebrook and White (1937) and Massey and Ward-Smith (1998). This equation primarily requires Reynolds number and pipe roughness for solving the equation. The Reynolds number can be evaluated using Equation 3.6, and the friction factors are evaluated from Equation 3.7. For annular section instead of diameter D, an equivalent diameter $D_{eq} = D_a - D_d$ was used. The overall pressure drop due to circulating flow path, bends and fittings is the summation of major loss and minor loss. For the designed experimental setup, the sum of minor loss friction coefficient k is considered to be 24 which includes a 90° elbow, 180° flow reversal and non-return valve.

$$Re = \frac{\rho v D}{\mu} \tag{3.6}$$

$$\frac{1}{\sqrt{f}} = -2log_{10}\Big(\frac{\frac{\epsilon}{D}}{3.7} + \frac{2.51}{Re\sqrt{f}}\Big) \tag{3.7}$$

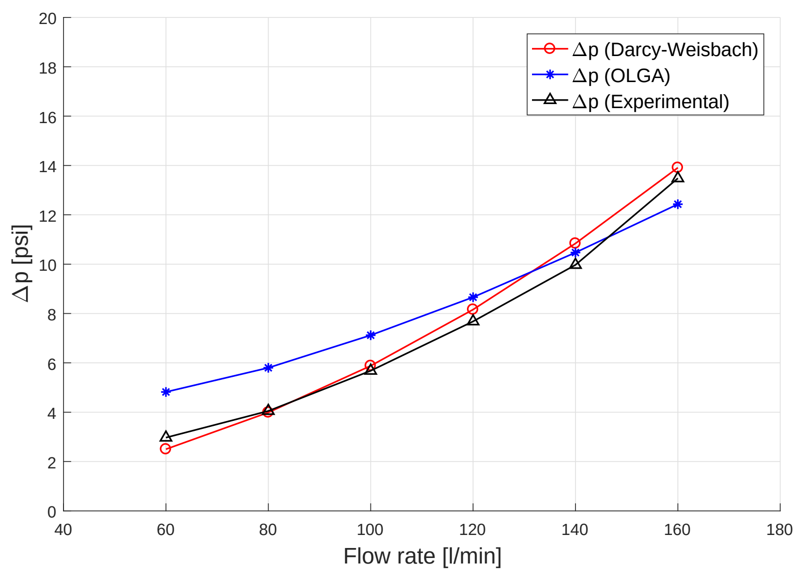


Figure 3.6: Pressure drop comparison

Experiments were conducted to observe the pressure drop characteristics of the setup. The experiments were performed for water flow rate between 20 lpm and 160 lpm, while the choke opening was varied between 20% - 100%. No influx and influx scenarios were simulated in the setup. The experimental frictional pressure drop was compared with the pressure drop calculated from Darcy Weisbach equation and OLGA simulation. Figure 3.6 shows the comparison between the theoretical and experimental pressure drops at different flow rates with an error ranging from 7 to 15%. From the obtained results it is evident that the flow loop follows the theoretical friction loss equations. Figure 3.7 shows the calculated bottomhole pressure using Equation 3.1

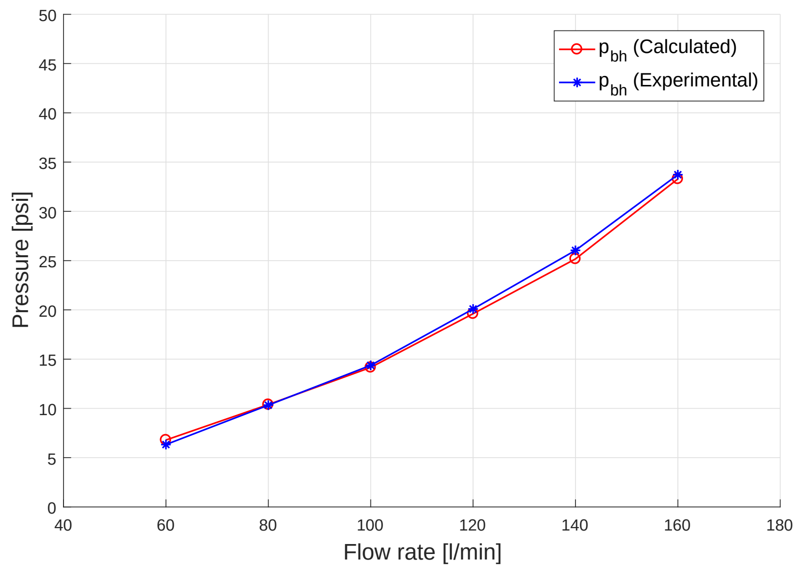


Figure 3.7: Bottomhole pressure estimation and comparison with experimental values

and measured bottomhole pressure. The average error between the measured and calculated bottomhole pressure is less than 2%.

3.5.2 Flow manipulation - No influx scenarios

Next we made some manual steps to the pump flow rate to observe the pressure and flow response at the pump inlet, bottomhole and near choke region. In this experiment water flowrate was incrementally increased by 20 lpm. The choke opening was maintained at 100% open. Figure 3.8 shows that the system has very fast dynamics. The majority of the loss were associated with a frictional pressure drop across non-return valves and control valves. The difference between p_p, p_{bh} and p_c is due to frictional loss experienced across the flow path.

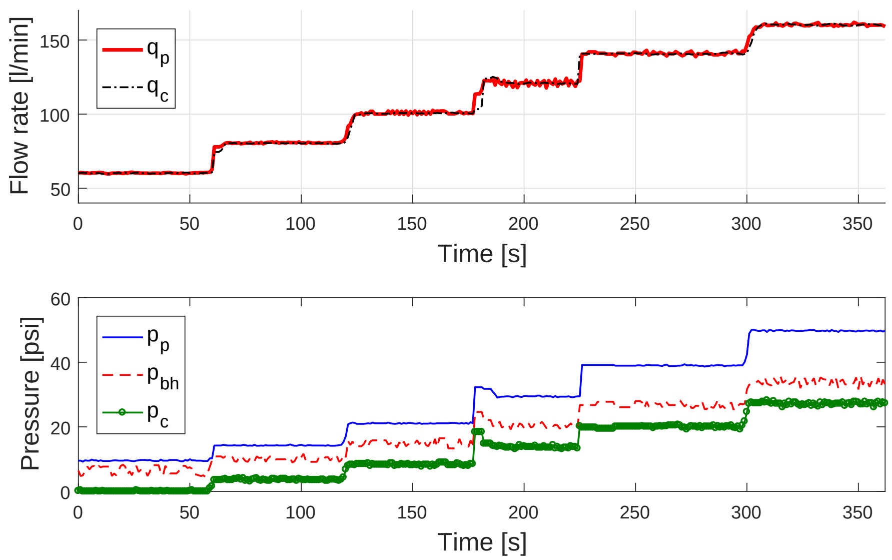


Figure 3.8: Inlet and outlet flow behaviour in the experimental setup

3.5.3 Choke manipulation - Influx scenario

The goal of this set of experiments is to confirm the ability of the setup to manipulate bottomhole pressure, simulate influx scenarios and demonstrate effectiveness of choke in mitigating the kick. In this experiment, the flow rate was kept constant at 60 lpm. In order to simulate 'gas kick' air was injected into the system at 40 psi after 30^{th} sec from the start of the pump. After 60^{th} sec, the choke opening was reduced by 5% in every 10 secs to observe the setup's response in handling 'gas kick'. The pressure due to the choke manipulation are shown in Figure 3.9. Initially due to 'gas kick' choke flow increased and the deviation between pump flow and choke flow kept growing. As the choke was gradually closed the choke pressure and bottomhole pressure started creeping slowly. Finally as the choke opening was down to 60% the deviation between pump flow and choke flow reduced back to '0' essentially showing mitigation of 'gas kick'. During this process the bottomhole pressure raised by 10 psi. With this scheme it took 100 secs to mitigate the kick. From experimental results, it can be concluded that the setup is able to generate influx situation. Moreover, the choke manipulation controls the abnormal situation typically desired for a managed pressure drilling setup.

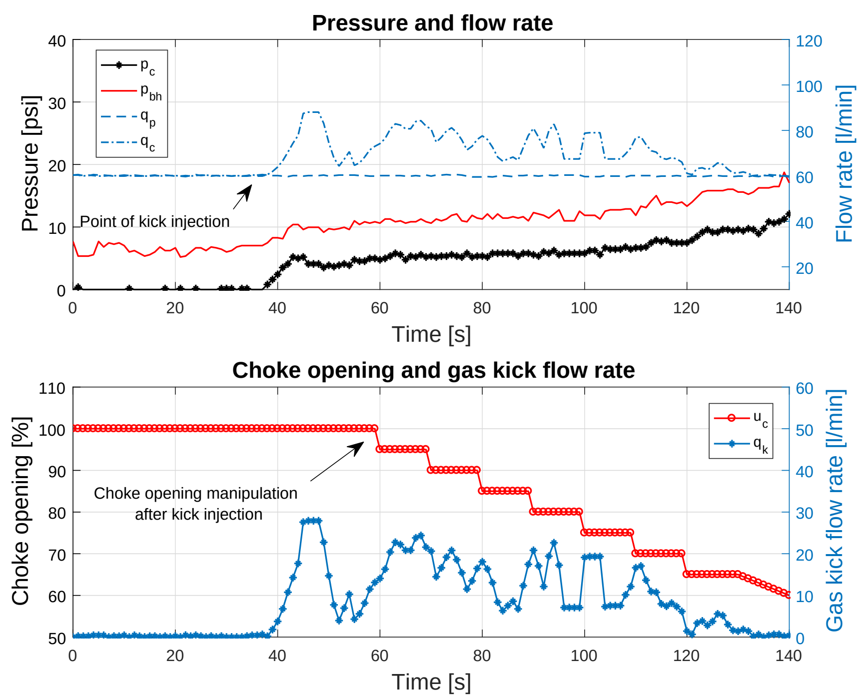


Figure 3.9: Influx scenario at 60 lpm pump flow rate

3.6 Automatic operation of MPD system

After confirming the experimental setup's ability to replicate the MPD hydrodynamic characteristics through multiple series of manual experimental operation, the automatic control methods were applied to observe the controller's performance in handling normal drilling, pipe extension, pump failure and influx attenuation cases. The following sections provide a brief discussion on the controller design and the obtained experimental results.

3.6.1 Control valve linearization

One of the major challenges in MPD operation is due to the nonlinearity in the system. The nonlinearity makes it difficult in control using linear controller. Edgar et al. (1999) demonstrated the need for linearizing the control valve for precise control through PID algorithm. An industrial wastewater problem was considered where the pH values had a nonlinear relationship with the reagent delivery. A characteristic equation was used to transform the nonlinear values to a linear scale which eases the controller gain calculations. According to Smuts (2011), the control valve assumes a pressure differential across inlet and outlet. If the obtained measurements do not correspond to the change of input proportionally then the nonlinearity can be identified. The nonlinearity relating flow parameters can be addressed by valve transform for the desired variable. Reitsma and Couturier (2012) reviewed the nonlinearity in choke based controllers in managed pressure drilling operation. The variation in choke flow coefficient due to flow rate change induces nonlinearity in the hydrodynamic behavior. In this experimental study, it was observed that the flow rate is independent of the choke opening value since we used a positive displacement pump to circulate the fluid. The choke pressure is nonlinearly related to the choke opening. Based on the circulation rate, the flow coefficient of the choke control valve varies. Thus, a nonlinear correlation was developed to transform the nonlinear pressure values to a linear scale which simplified the controller design. The transformation equation is developed based on experimental flow and pressure measurements taken by operating the control valve in the entire operating range. After obtaining a complete set of choke opening and pressure measurements a correlation is developed between the measured pressure and valve opening.

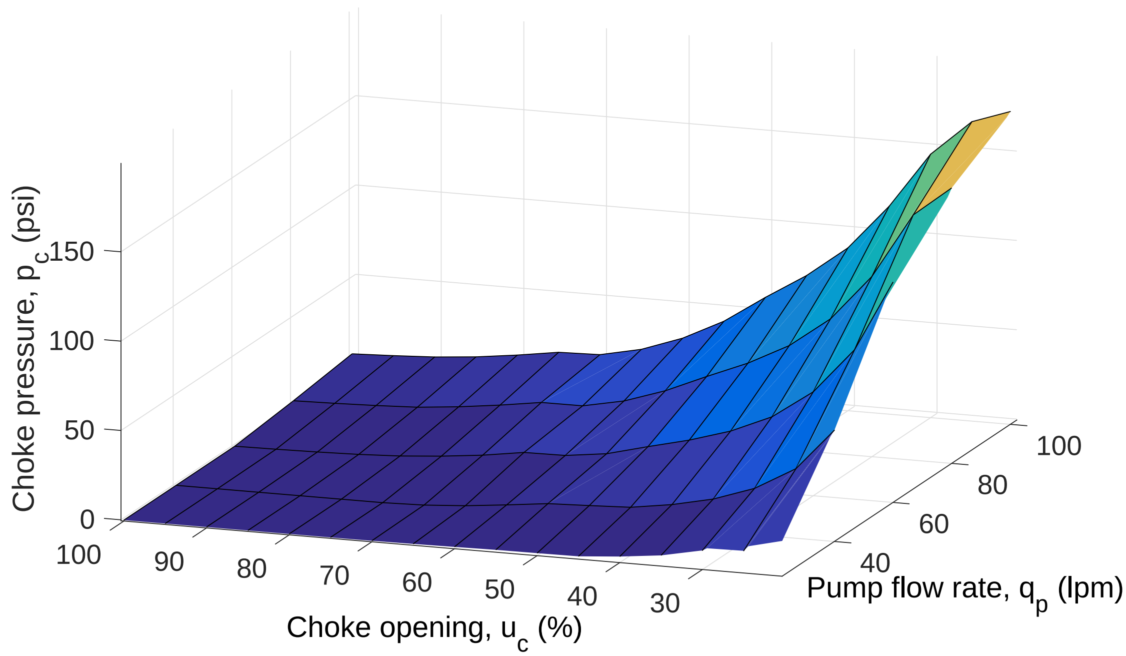
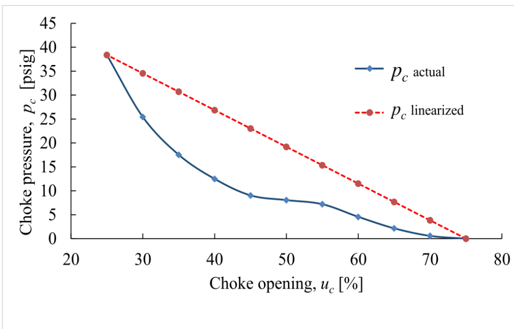


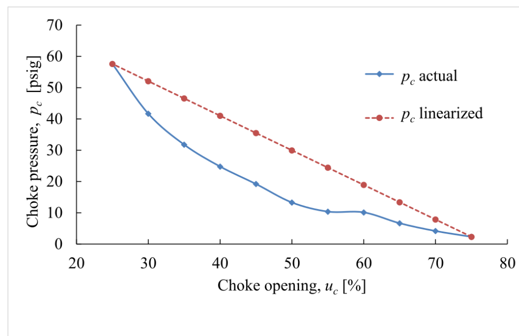
Figure 3.10: Resulting choke pressures at different choke opening and pump flow rate

3.6.2 Valve characterization

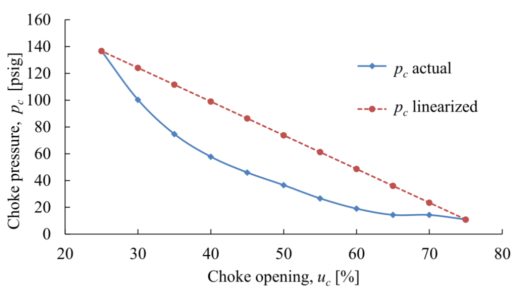
Figure 3.10 shows that at 20 lpm pump flow rate, the change in choke pressure is not significant compared to choke pressure change at 100 lpm circulation rate. At 20 lpm pump flow rate, choke pressure drops to zero at 50% choke opening. On the other hand, at 100 lpm and 20% choke opening the choke pressure reaches 175 psi which is above the maximum allowable pressure in our system. Thus the operating range for flow rate was chosen between 40 and 100 lpm and the range for choke opening was set between 25% to 85%. 40, 60, 80 and 100 lpm are chosen as representative flow rate to cover the entire range of operation. Based on the experimental data a correlation given by Equation 3.8 has been developed which transform the nonlinear pressure values to a linear scale. The correlation model can be expressed as a cubic equation as given in Equation 3.8. p_1, p_2, p_3 and p_4 are constants based on circulation rate in the system as shown in Table 3.3. These constants were selected from correlation model estimated in the MATLAB curve fitting toolbox. Figure 3.11 provides a comparison between obtained linear relationship and the nonlinear pressure values from the measurement. The intermediate pressure values at flow rates other than 40, 60, 80 and 100 lpm are calculated using in linear interpolation. Finally, the transformed linear values are presented as shown in Figure 3.12.



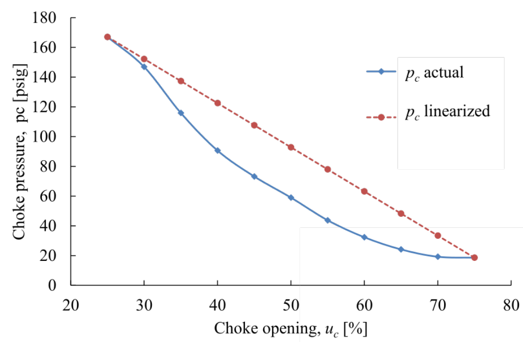
(a) $q_p = 40$ lpm



(b) $q_p = 60$ lpm



(c) $q_p = 80$ lpm



(d) $q_p = 100$ lpm

Figure 3.11: Nonlinear and linear pressure values at variable choke opening and fixed flow rate

$$p_{linear} = p_1 * p_{actual}^3 + p_2 * p_{actual}^2 + p_3 * p_{actual} + p_4 \tag{3.8}$$

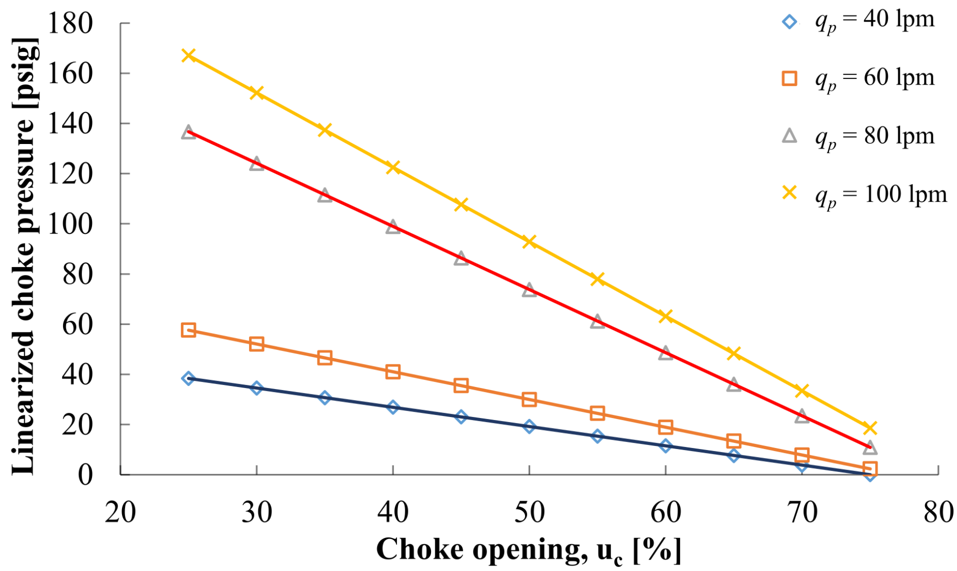


Figure 3.12: Linearized pressure at different choke opening and flow rate

Table 3.3: Constant values in correlation model

Flow rates(lpm)	p_1	p_2	p_3	p_4
40	0.0008991	-0.08535	2.926	0.8964
60	0.0004918	-0.0648	3.182	-4.494
80	0.0001094	-0.0327	3.546	-15.67
100	0.0000649	-0.02264	3.1	-20.8

3.6.3 Linearized gain switching PI controller design

After linearization of the choke pressure a set of gain switching PI controllers was designed to control bottomhole pressure using choke valve. The controller structure is presented in Figure 3.13. The entire flow range was divided into four sections. Identified system models for each segment are given in Table 3.4. The corresponding plant output is shown in Figure 3.14. Proportional gains (k_p) and integral gains (k_i) for the PI controllers are calculated based on Ziegler Nichols tuning method. Switching between these PI controller was done based on flow rates. From Table 3.4 it can be seen that for flow rate between 65 and 105 lpm, the k_p gains do not change

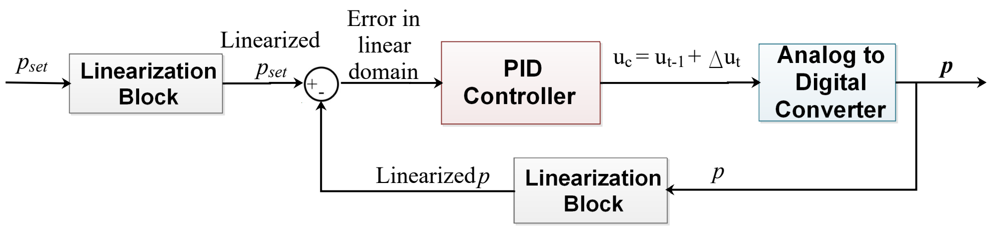
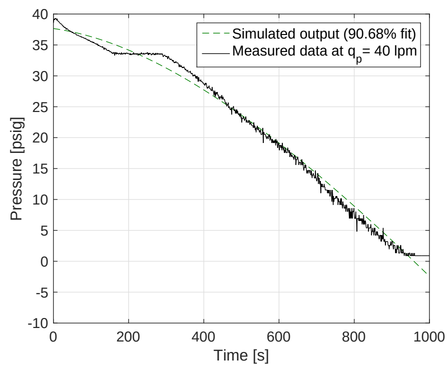
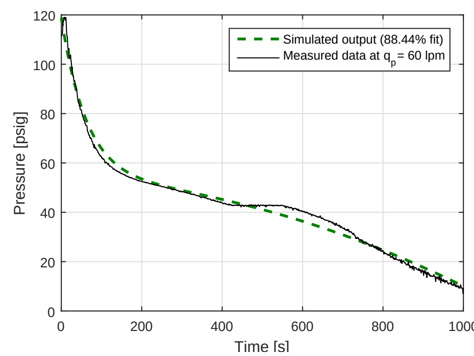


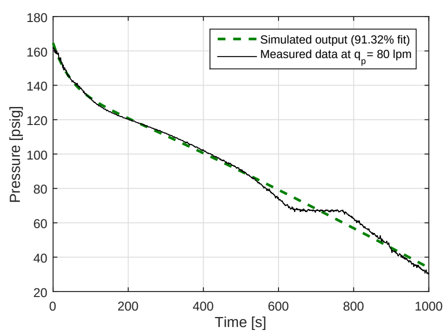
Figure 3.13: Linearized choke pressure based PI controller layout



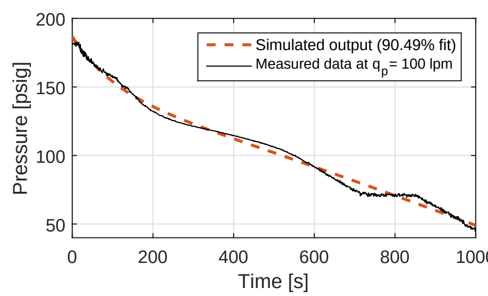
(a) Choke pressure at $q_p = 40$ lpm



(b) Choke pressure at $q_p = 60$ lpm



(c) Choke pressure at $q_p = 80$ lpm



(d) Choke pressure at $q_p = 100$ lpm

Figure 3.14: Comparison between predicted output and actual measurement

significantly. So, in order to reduce the computational effort, last two segments were merged and three controllers were implemented.

Table 3.4: Linearized plant models and controller gains

Controller	Flow range(lpm)	Linearized plant models	k_p	k_i
1	25 - 45	$\frac{1.585s^2+0.09418s-1.192*10^{-5}}{s^2+0.06442s+6.713*10^{-5}}$	0.3140	0.11
2	45 - 65	$\frac{7.162s^2+0.0118s-2.569*10^{-5}}{s^2+0.01603s+2.008*10^{-6}}$	0.0355	0.15
3	65 - 85	$\frac{6.584s^2+0.1191s-9.889*10^{-5}}{s^2+0.02415s+4.034*10^{-6}}$	0.1854	0.19
	85 - 105	$\frac{7.469s^2+0.04909s-3.861*10^{-5}}{s^2+0.01105s+1.626*10^{-6}}$	0.1914	0.2

3.6.4 Normal drilling operation

The purpose of performing experiments in normal drilling operation mode is to check the designed controller's ability in tracking predefined bottomhole pressure setpoint p_{bh}^{set}. The bottomhole pressure and choke pressure has the same dynamics, only a bias due to frictional loss in the annular flow path. In Figure 3.15 the bottomhole pressure setpoint was set to vary in every 35 secs interval ranging from 17 psi to 37 psi for constant 40 lpm pump flow rate. The controller was able to reach the choke pressure setpoint values within 25 secs. However, an steady state bias of approximately 4 psi was observed between pressure setpoint and actual values at high pressure. Throughout the pressure manipulation the flow rate remains constant as the progressive cavity pump and the non-return valve in the drill string pipe head maintains preset pump flow rate. In Figure 3.16 it can be seen that, with increase in pump flow rate the controller performance has improved; time to reach steady state and the offset between setpoint and actual bottomhole pressure value has decreased. The pressure reached new setpoint within 15-20 secs. The choke opening showed smoother change compared to choke movements at 40 lpm flow rate. The performance kept improving for

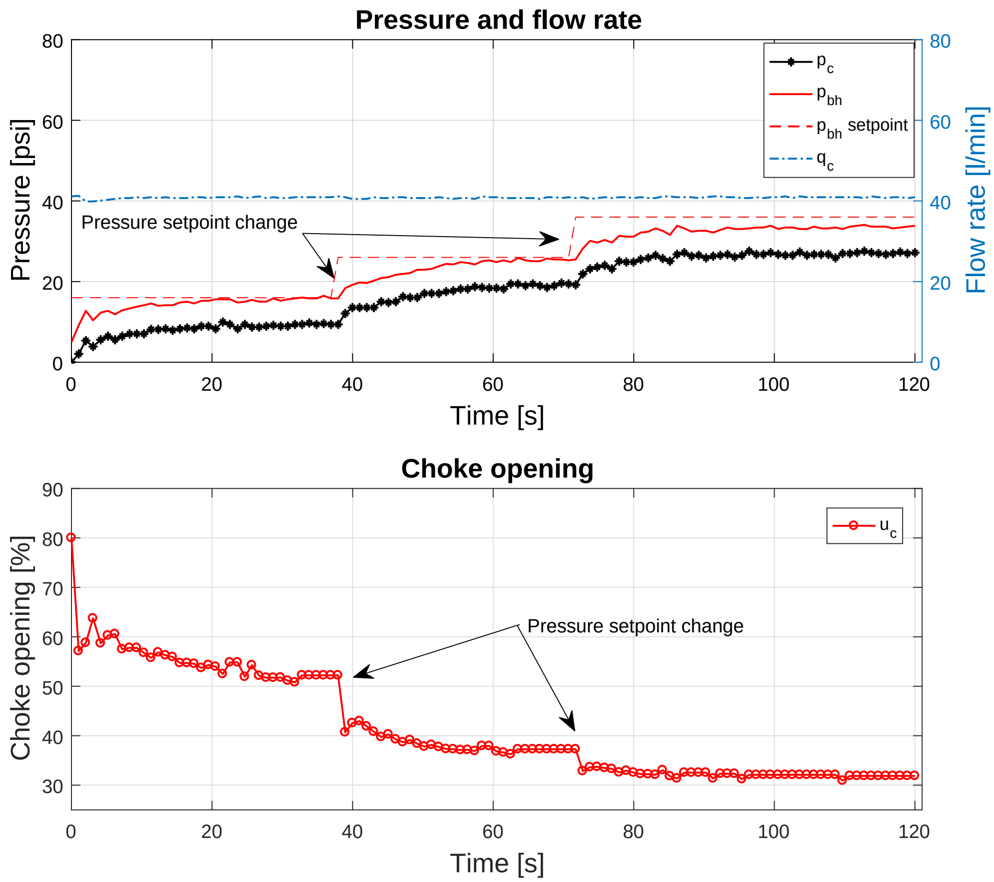


Figure 3.15: Constant bottomhole pressure at 40 lpm pump flow rate

controllers designed for 80 lpm and 100 lpm as shown in Figure 3.17 and Figure 3.18 respectively. At higher flow rates, the tracking error reduced to 1 psi range. Overall it was observed that with valve linearization technique, the controller was able to track pressure setpoint value reasonably well. For all the experiments, the flow rate remained constant irrespective of choke opening changes. The controller performed well at higher flow rate than lower flow rate as the increased circulation rate provided additional support in meeting the pressure tracking requirement which was limited in low flow operations. Moreover, the choke opening had to be reduced steadily with increasing pressure demands. All these characteristics are no different than the hy-

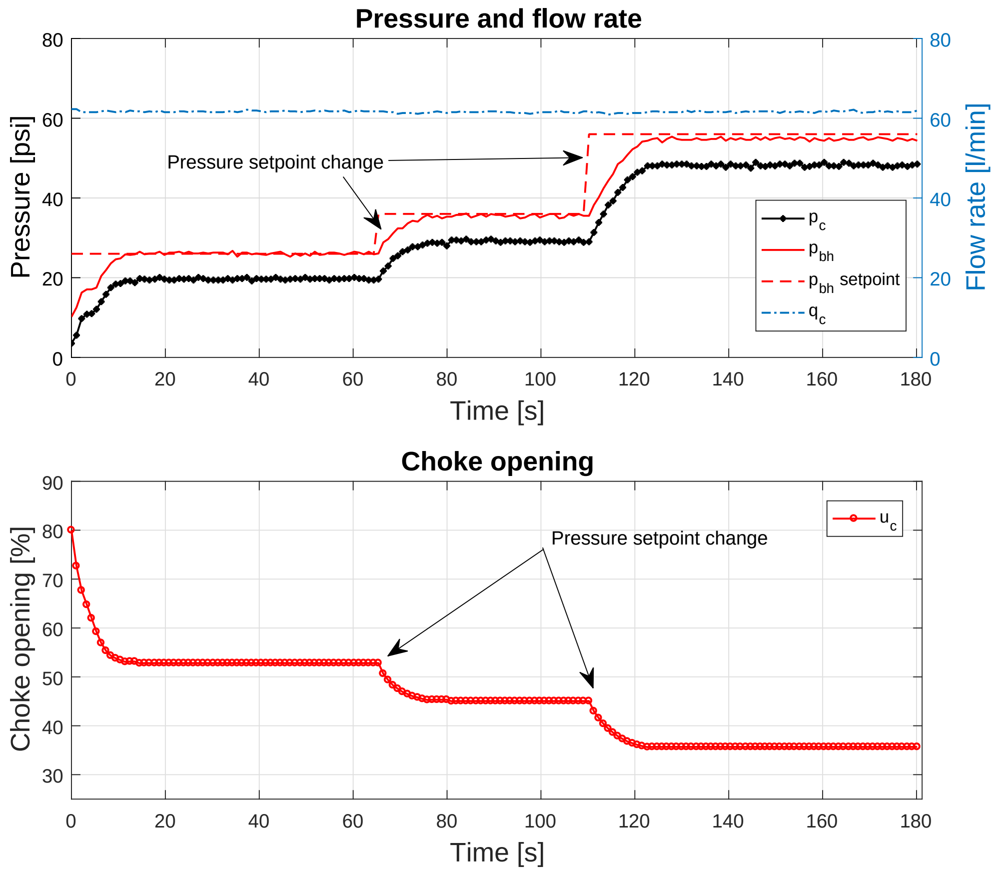


Figure 3.16: Constant bottomhole pressure at 60 lpm pump flow rate

drodynamic properties required for an MPD setup. This shows the setup's ability to further simulate different operational scenarios to understand the hydrodynamics of a MPD system.

3.6.5 Pipe extension scenario

During pipe extension scenario, the pump flow rate is ramped down to no flow condition. After stabilizing the no flow bottomhole pressure condition, the pipe change sequence is performed. Lastly, the circulation rate is ramped up again once the pipe change sequence is completed. In the overall process, it is desired to maintain down

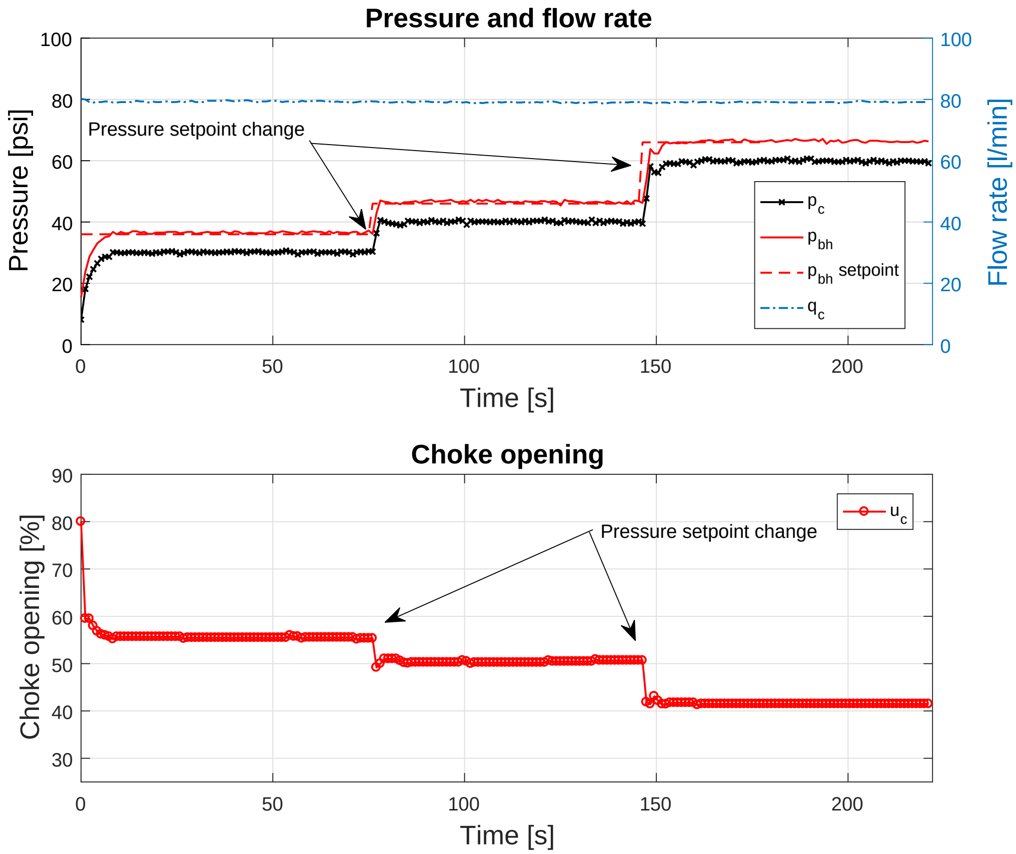


Figure 3.17: Constant bottomhole pressure at 80 lpm pump flow rate

hole pressure to a value marginally above formation pressure to maintain well integrity and avoid kick initiation. In the real life scenario mud density is increased to offset the pressure exerted by the pump. At no flow condition pump pressure goes to zero and the bottomhole pressure is maintained fully by using hydrostatic pressure. In our setup we currently do not have the ability to increase the fluid density. As such we had to circulate a minimum flow through the system to maintain the bottomhole pressure. Because of the large variation in pressure and flow rate, all the controllers of different operating ranges were active at different point to maintain the optimal performance. Figure 3.19 shows the sequences of the controllers during the entire pipe extension operation. During this sequence the choke opening were varied between

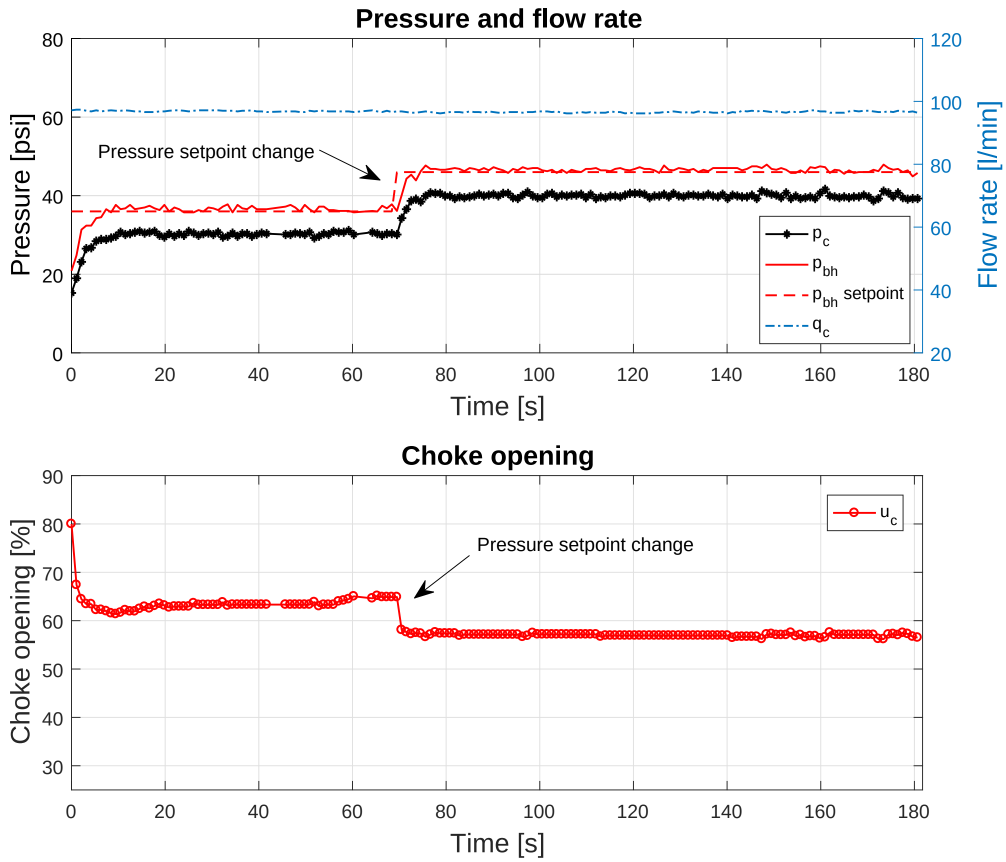


Figure 3.18: Constant bottomhole pressure at 100 lpm pump flow rate

25% and 85%. The bottomhole pressure setpoint (p_{bh}^{set}) was set to 20 psi. Initially the pump flow rate was maintained at 100 lpm. After 120 secs the flow rate was ramped down from 100 lpm to 30 lpm over 4 mins. The flow rate was kept constant at 30 lpm for next 120 secs. Lastly, the flow rate was ramped up to 100 lpm in the next 4 mins. Figure 3.19 shows that the gain switching controller is able to reach the bottomhole pressure (p_{bh}^{set}) setpoint with an offset of 3 psi. It was also observed that at low flow rate the pressure tracking offset error was higher than the higher flow rate.

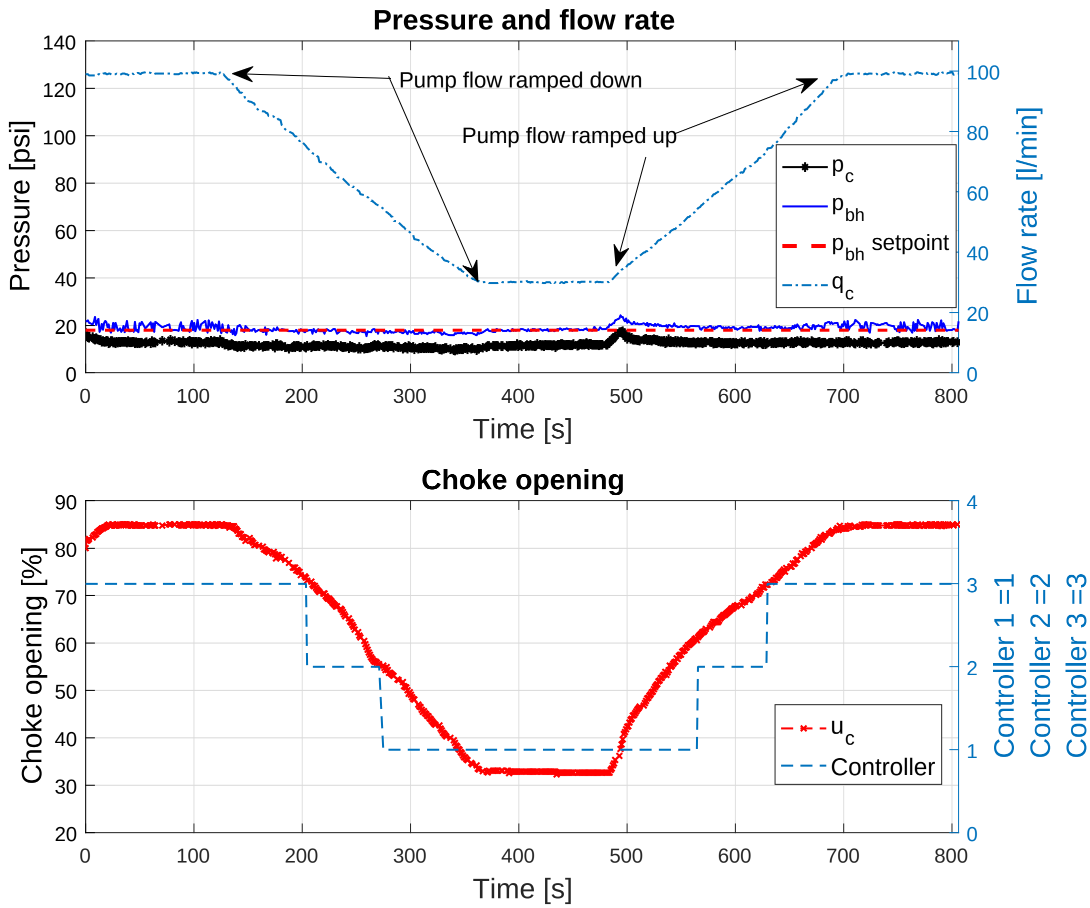


Figure 3.19: Controller performance during pipe extension scenario

3.6.6 Pump failure scenario

Pump failure cases results in a sudden drop in circulation rate to 'no flow' or to a very low flow rate. The controller must be able to maintain its predefined pressure setpoint by quickly manipulating the choke opening to compensate the pressure drop due to the sudden drop in flow rate. In this experiment, the pump flow rate was dropped from 100 lpm to 35 lpm at 70^{th} sec of normal operation. Figure 3.20 shows that, when the flow rate was changed quickly within 5 secs, the controller switched from controller 3 to controller 1 instantly to manipulate the choke opening and compensated

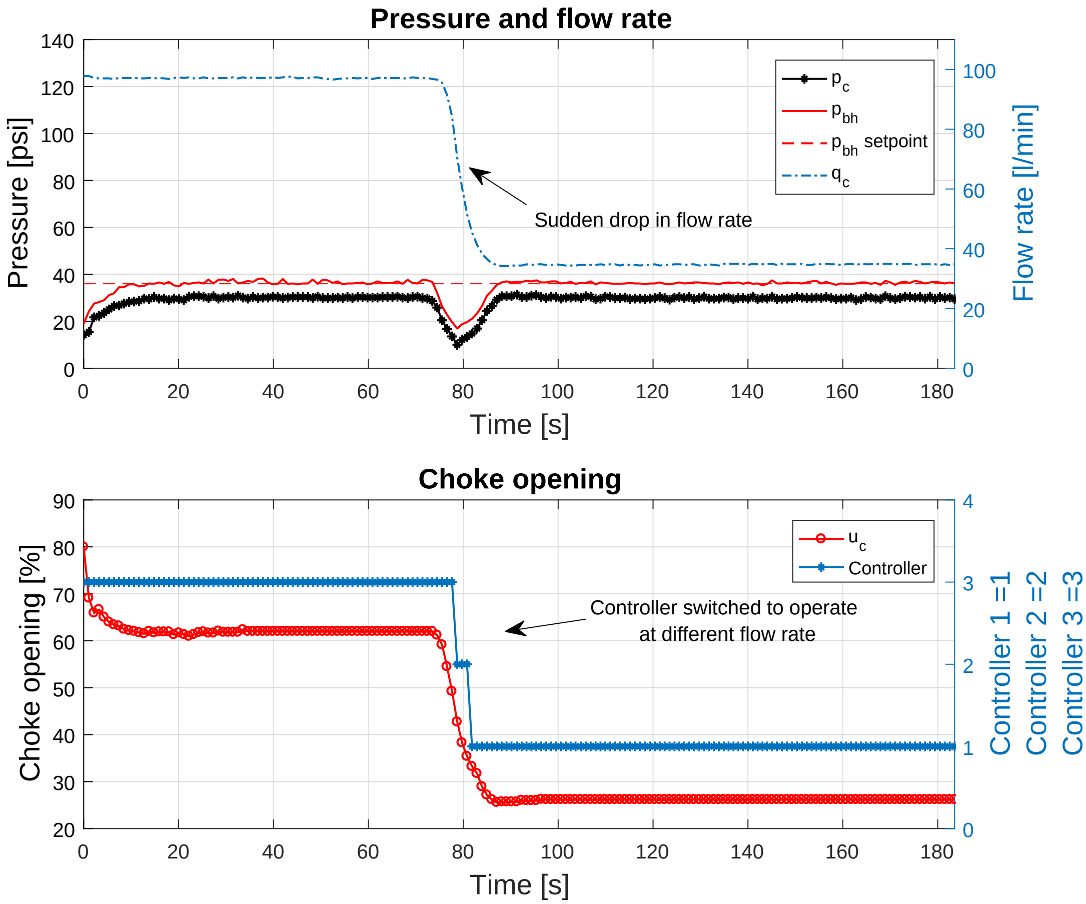


Figure 3.20: Controller performance during pump failure scenario

for the pressure loss. The bottomhole pressure setpoint was predefined at 30 psi. The controller successfully maintained setpoint pressure with a minor offset of 2 psi. Again a 'no flow' condition could not be simulated since there is no option for changing the density of the drilling fluid.

3.6.7 Gas kick scenario

A gas kick scenario was simulated in the system to observe the controller's performance in kick mitigation. During normal drilling operation the pump flow rate was maintained at 60 lpm. To simulate 'gas kick' pressurized air is injected at 110^{th} sec,

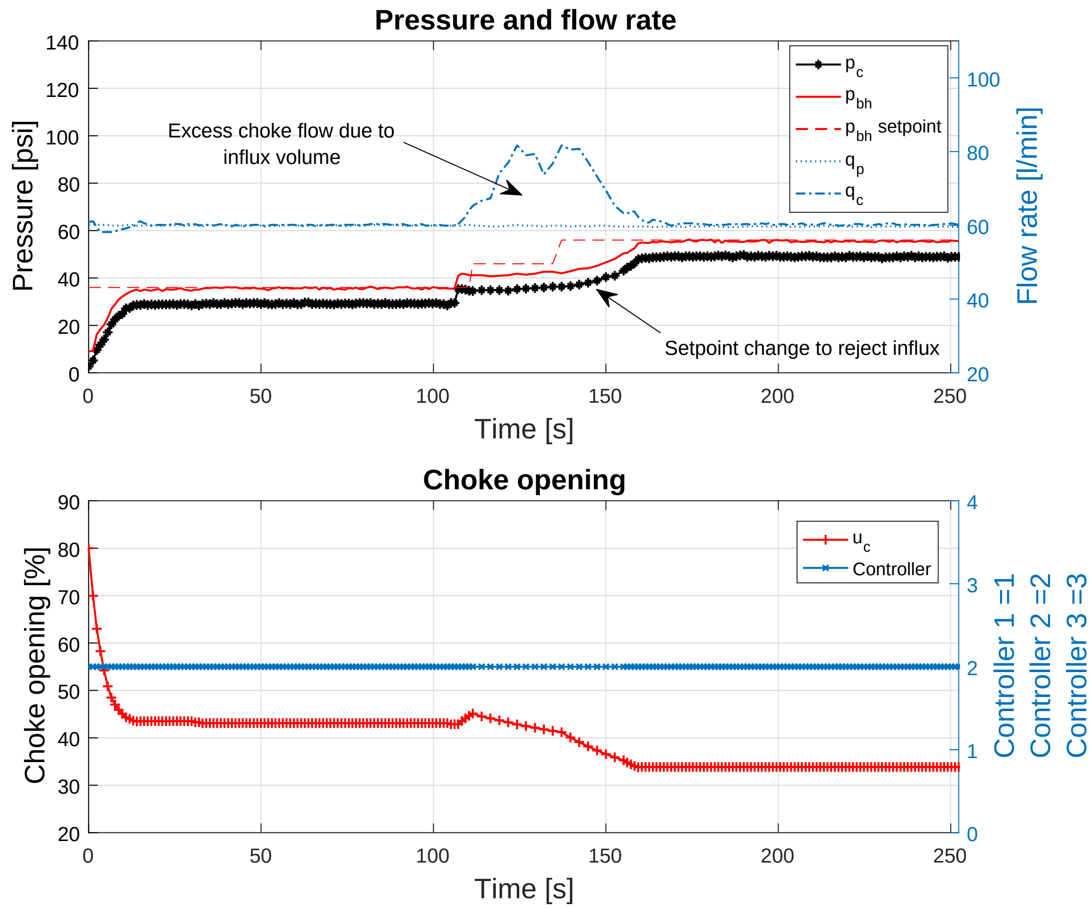


Figure 3.21: Controller performance during gas kick scenario

the choke flow rate rises sharply whereas the pump flow rate still remains constant at 60 lpm. Real-time choke flow rates are observed to detect kick situation as shown in Figure 3.21. This clearly indicates the gas kick which activates the flow control mode in the controller. The flow control mode is activated whenever the difference between pump flow rate and choke flow rate exceeds 5 lpm. The controller elevates the pressure setpoint value by 10 psi and tries to mitigate the kick by balancing pump flow and choke flow as shown in Figure 3.21. If the kick still persists after 10 secs, the bottomhole pressure setpoint is raised again by 10 psi. It can be seen that after two setpoint revisions the controller was able to stabilize the flow rate and attenuated kick. Figure 3.21 shows how the gain-scheduled PI controller has driven the choke opening to attenuate kick. The closing of choke opening increases the bottomhole pressure. As soon as the kick was detected, the setpoint pressure was increased by 10 psi. When the bottomhole pressure becomes marginally above the kick injection pressure, the influx stops and the controller returns back to constant pressure tracking mode setting the existing setpoint value as the new pressure setpoint. It took about 60 secs to mitigate the gas kick.

3.7 Conclusions and future works

The developed experimental setup is capable of replicating the hydraulics of a typical managed pressure drilling system. The hydrodynamic behaviour of the experimental setup has been compared with the theoretical correlations. A successful implementation of linearized gain scheduling PI controller has been presented. The linearized gain switching PI controller is able to handle both valve nonlinearity and nonlinearity due to flow variation. At higher flow rates the controller performance was better compared to lower circulation rates. The controller was also tested for various normal and abnormal operational scenarios. Normal drilling, pipe extension cases were emulated as normal scenarios. Experimental implementation of pump failure and gas kick attenuation cases were tested successfully as abnormal scenarios. Future work will include the setup's performance to explore predictive controllers such as NMPC controller.

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Chapter 4

Nonlinear Model Predictive Control of a Hammerstein Weiner Model based Experimental Managed Pressure Drilling Setup

Al Amin, Syed Imtiaz, Aziz Rahman & Faisal Khan

Department of Process Engineering,

Memorial University of Newfoundland,

St. John's, Newfoundland and Labrador, Canada A1B 3X5

Abstract

In this paper, we present the design and implementation of a nonlinear model predictive controller (NMPC) in a lab scale managed pressure drilling (MPD) experimental setup. The goal of the controller is to maintain constant bottomhole pressure and mitigate kick during reservoir influx scenario. Water is considered as the drilling fluid which is circulated between 20 lpm to 100 lpm. The maximum allowable system pressure is 150 psi. Under normal condition, the controller tracks bottomhole pressure to a predefined setpoint. A Hammerstein Weiner nonlinear model has been used for pressure prediction, and genetic optimization algorithm for calculating optimal control input. The optimizer uses cost function and flow constraints to generate a optimal control input trajectory. The constraint handling capacity of NMPC enables to operate with a limited number of controller configuration parameters. During reservoir influx the controller switches to flow control mode to balance the pump flow and choke

flow. After kick mitigation the controller switches back to pressure regulation mode by revising the setpoint pressure to estimated reservoir pressure. Lastly, a comparison between linearized gain scheduling PI controller and the NMPC controller has been provided. The PI controller pressure tracking was oscillatory with steady state bias of 4-5 psi. The NMPC controller delivered good performance over PI controller during normal operation, pump failure, and gas kick cases where flow demand changes frequently.

4.1 Introduction

Pressure management accounts for almost 40% of the drilling problems which makes it one of the most important task in oil and gas explorations (Weatherford, 2010). In drilling operation, drilling is performed in a narrow pressure window offered by fracture pressure p_{frac} and reservoir pressure p_{res}. For the sake of safety and efficiency in the drilling operation, bottomhole pressure p_{bh} has to be maintained within the pressure window. Managed pressure drilling (MPD) assists in achieving this objective by maintaining a marginal pressure overbalance in drilling operation. The combination of choke, backpressure pump, circulation pump, and manipulation of drilling fluid density parameters enables MPD to maintain optimal pressure and avoid an undesirable situation such as reservoir fluid influx commonly termed as kick. Abnormal situation such as kick raises drilling cost with significant non-productive time (NPT). According to Rehm et al. (2013), MPD can reduce drilling cost as much as $40 USD per foot of drilling. MPD operations need accurate hydrodynamic model and technology integration for successful implementation. It can be broadly classified into manual and automated operation mode. Due to a higher probability of error, automated MPD is preferred over human skill and expertise in handling drilling problem. The innovation in the field of MPD automation ranges from the hydrodynamic model formulation, controller design and application. The parameters such as drilling fluid rheology, multiphase flow and frictional losses induce nonlinearity in the system dynamics which makes modelling and controller design challenging.

In MPD operation controller ranges from simple PID controllers to model based advanced controllers such as nonlinear model predictive controller (NMPC). Godhavn et al. (2010) presented an ODE based PI choke pressure controller which controls system states in normal drilling, pipe extension, surge and swab operations. The controller tuning parameters were derived from a first-order transfer function model. In order to address flow demand changes, gain scheduling of PI controllers were proposed. Zhou et al. (2011) presented a novel switched control scheme for pressure regulation and kick attenuation applied to a two control volume MPD model. Under normal condition controller operates in pressure control mode and switches to flow control mode in case of reservoir kick. Reservoir kick was detected based on an observer that estimates the bit flow rate, reservoir pressure and kick flow rate. In flow control mode the controller balances the pump flow and choke flow which raises the bottomhole pressure in the casing. Once the kick is mitigated, the controller switches back to its previous pressure control mode with the revised pressure setpoint based on estimated reservoir pressure. Godhavn et al. (2011) demonstrated the use of a simplified nonlinear system of equations to estimate the bottomhole pressure and developed a feedback linearized choke controller. The controller's goal is to drive the choke pressure to desired setpoint value. Achieving accurate frictional pressure estimation also enables the system to obtain desired bottomhole pressure setpoint. The controller has been implemented experimentally and provide better performance over conventional PID controller. Siahaan et al. (2012) proposed an PID controller where the tuning parameters are selected from a set of parameters based on the realtime measurements and cost function. A high fidelity drilling simulator WeMod was used to demonstrate the effectiveness of the controller. When a PID controller tuning parameters are fixed to constant values, there is a possibility of oscillation in the states when flow demand changes and the controller tries to compensate the change. Prior to controller application, a set of candidate parameters were designed. Based on the measured data and evaluation of cost function, right candidate parameter is chosen to counteract the oscillation effect and stabilize the operation quickly. However, the computation for selecting the right setting is challenging without prior knowledge and expertise of the system. Reitsma and Couturier (2012) provided a comprehensive overview on the use of choke pressure controller in managed pressure drilling operation. The review pointed out the need of handling control valve nonlinearity which occurs due to variable flow coefficients at changing flow demands. The development of choke based controller is progressing with technological development. The nonlinear controller provided promising results over conventional PID controller in terms of response, robustness, and stability. Hauge et al. (2012) used feedback linearization technique to develop a choke controller. The controller uses an adaptive observer for estimating downhole measurements. The hydrodynamic model is a set of nonlinear ODEs based on conservation of mass and momentum across drill string and annulus control volume. Hauge et al. (2013) presented a further extension of his previous work where the controller performance was demonstrated on an experimental system and high fidelity OLGA simulator. The ultimate goal of this work was to locate the influx initiation point and estimate the magnitude of the flow. Based on the quantity, a choke opening is set and the kick is rejected by activating flow control mode in operation. A choice has to be made in selecting BHP control mode or flow control mode based on the control requirement. Nandan et al. (2014) proposed a robust gain switching scheme for automating MPD operation using constant bottomhole pressure control technique. The gain scheduling is performed based on magnitude of circulation rate and choke opening. The operating region was divided into six operating regions with H_∞ loop shaping controller designed for each region. First order transfer function models between choke pressure and choke opening has been used for designing the feedback controller. The transfer function model incorporates set of gain and time constant values to operate at different flow ranges. In normal condition the controller tracks the bottomhole pressure at different mud densities. In event of influx, the reservoir pressure is estimated from the nonlinear ODE based observers, and a new pressure setpoint is revised to mitigate kick in the system. The controller performance was simulated in normal drilling, pipe connection, pump failure and kick attenuation cases. However the experimental implementation is yet to be explored.

Nygaard and Nævdal (2006) developed an NMPC controller using a distributed mechanistic model. The optimization scheme is based on Levenberg–Marquardt algorithm. The controller was compared to a low order model based PI controller. The controller design utilized the dynamics of two phase flow phenomena. The goal of the controller is to control the choke opening based on the fluctuating flow needs in the drilling operation. The NMPC controller had better performance over PI controller because the PI controller configurations need to be changed with the change in operating parameters. Breyholtz et al. (2010) used a single-shooting multi-step quasi Newton method based solver for developing a multivariable MPC controller. The controller utilized flow rates and drill string velocity as inputs and bottomhole pressure and hook position were considered as output states. The simulation results showed successful disturbance rejection and BHP regulation. Drill pipe extension and flow control cases were not focused in the study. Carlsen et al. (2013) compared different controller algorithms which can be used to automate the sequential control operations in an influx situation. High fidelity simulator was used to evaluate the controllers' performances.

PI controller was designed to control the choke pressure during influx situation; internal model controller (IMC) and model predictive controller (MPC) were designed to control the pump flow rate and choke pressure to handle kick situations. The controller parameters were derived from first order process models. It was observed that the multivariable IMC and MPC controller performance was comparatively better than the PI controller. The MPC controller showed better performance when the control horizon was increased. However, the robustness of the controller was compromised with an increase in control horizon. Møgster et al. (2013) proposed a linear MPC controller in dual gradient drilling (DGD) operation. For using PID controller with a fixed tuning constant, multiple PID controllers must be integrated for flow and pressure control operation at the same time. A linear MPC controller is subjected to multiple flow and pressure constraints which eliminate the need of using multiple conventional PID controller. For efficient flow and pressure controller, a linear first order transfer function model is utilized for manipulating choke opening and pump flow rates for control purposes. However, the potential of this controller could be explored in influx and pipe extension scenarios. Eaton et al. (2015) combined three different MPC controller i.e. a high fidelity model based controller, a low order model controller and an empirical controller to obtain enhanced real-time performance in MPD operation. The high fidelity model is based on simulator based on SINTEF flow model. The low order model is based on nonlinear ODE hydrodynamic equation and the empirical controller relies on the measured data obtained from the simulation. The combination of these three controller delivered good pressure tracking during normal operation and pipe connection scenario. Even though this controller is successful in handling measurement inaccuracy, it requires significant computational power, expertise to design and successfully implement. Zhou and Krstic (2016) included the time delay parameter in designing an adaptive predictive control. Transient behavior is always experienced in a typical drilling operation. For the sake of simplicity time dependent behaviors are generally ignored for hydrodynamic modelling and controller design. This study presented a comparison between PI controller and predictive controller with time delay parameter. However, the full potential of this model is yet to be explored in real field application. Nandan and Imtiaz (2017) designed an NMPC control scheme which utilizes the constraint handling capacity of NMPC and automatically switches from pressure control mode to flow control mode in case of reservoir kick. An nonlinear ODE observer has been utilized to estimate the bit flow rate q_{bit} and kick volume q_{kick}. Whenever the kick volume q_{kick} goes beyond a threshold value indicated by the difference between inlet and outlet flow rate, the flow control mode is activated to drive the kick out of the system. The controller was developed and tested on a simulated ODE model proposed by Kaasa et al. (2012) which solves for optimal choke opening by optimizing the constraint values in predefined cost functions. The performance of the controller was verified simulating in normal drilling, pipe extension and flow control cases. The controller needs further experimental evaluation before it is ready for field application.

In this paper, we present an experimental implementation of an NMPC controller. The NMPC algorithm is based on a Hammerstein Weiner model. The configuration of the NMPC is similar to that presented in (Nandan and Imtiaz, 2017). The controller uses the constraint handling capability of NMPC. During normal operation the controller operates as a constant bottomhole pressure controller and switches to a flow controller in case of a flow influx from the reservoir.

Nomenclature	Type
PT	Pressure transmitter
FM	Flow meter
AF	Air flow meter
CV	Control valve
MV	Manual valve
PCV	Progressive cavity pump
NRV	Non return valve

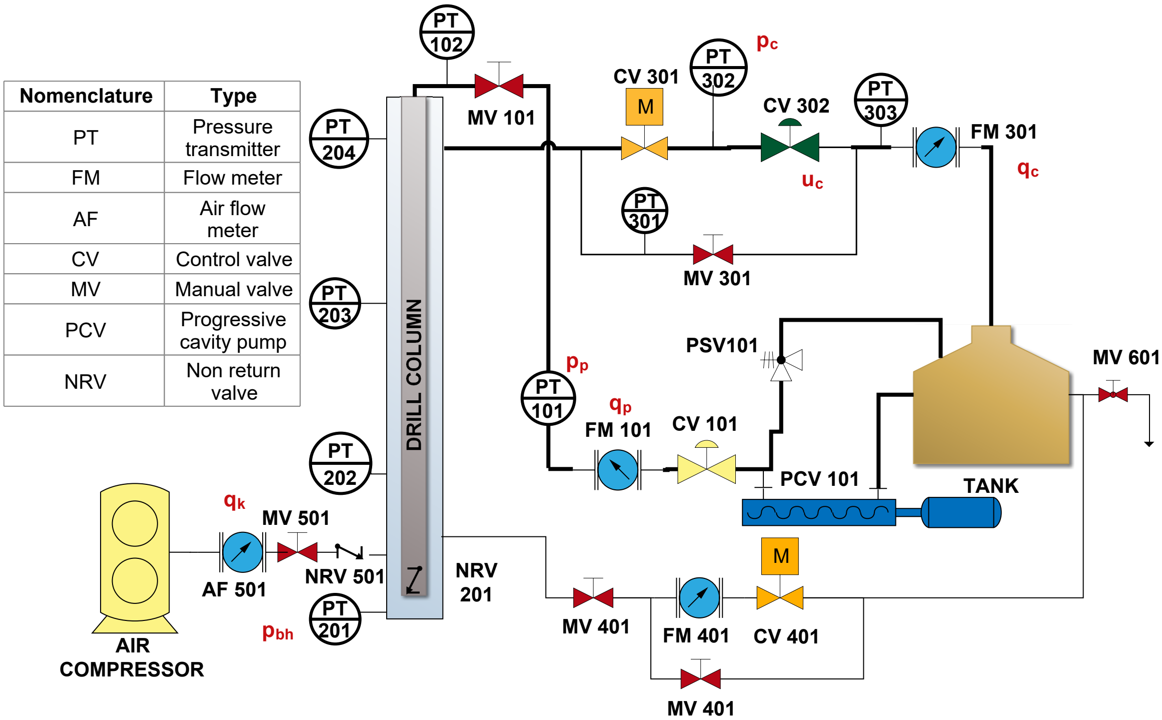

Figure 4.1: Schematic of the experimental setup

Figure 4.2: Actual experimental setup

4.2 Experimental setup

The developed experimental setup is a lab scale replica of an actual MPD wellbore system. The flow diagram and a photograph of the setup are shown in Figure 4.1 and 4.2. The core of the setup is a 1.5 inch diameter PVC pipe which is installed vertically to represent the tubular drill string pipe and a 3 inch clear PVC pipe placed concentric to the drill string pipe representing the casing. A 600 l capacity tank is constructed to supply drilling fluid to the progressive cavity pump. The drilling fluid returns back to the tank after being pumped through the flow loop maintaining a closed loop circulation system. The screw type progressive cavity pump (PCV) circulates drilling fluid with a circulation rate between 20 lpm and 200 lpm. The pump is capable to deliver drilling fluid with a discharge pressure as high as 145 psi. A variable frequency drive (VFD) is used to control the pump rpm to obtain the desired flow rate and pressure during the experiment. The VFD frequency can be regulated between 5 Hz to 60 Hz. A non return valve (NRV 201) separates the drill string and annular casing control volume by ensuring unidirectional flow in the bottomhole region. Two pneumatic choke valves has been placed in the pump outlet and wellhead outlet respectively. For ensuring safer operation during any blockage condition in the flow path, a bypass line has been created in the pump outlet region using a pressure safety valve (PSV). If the system pressure exceeds 200 psi due to blockage in the flow loop, the PSV will open the bypass line to release the excess pressure by redirecting the flow from pump outlet to drilling fluid container. A plug type pneumatic actuator is installed in the wellhead region to control the upstream system pressure. The valve stem travel in the actuator decides the choke opening between 0% and 100%. Both actuators requires a continuous air supply of 35 psi to be able to manipulate the valve opening corresponding to the current signals obtained from the control system. The choke opening can be calibrated automatically using the digital positioner equipped with the valve travel mechanism. Apart from the pneumatic control valves, two isolation valves is installed in the wellhead and loss circulation region to bypass the flow through an alternative flow path. The isolation valve can either be opened or closed completely using a physical switch placed in the control station. An air compressor has been used to supply air to the pneumatic actuators and the air injection port in the bottomhole region. The compressor can supply air to simulate the 'gas kick' in the bottomhole region with pressure between 0 to 100 psi and air flow rate as low as 2.7 lps. Manual pressure regulators has been installed to regulate the supply pressure as desired. An air flow meter (i.e. Omega FLR 6725D) has been used in the air supply line to measure the air flow rate between 0 to 25 cfm with 2% full scale accuracy. A non return valve installed in the air supply line ensures unidirectional air supply through the air injection port to emulate the 'gas kick'. 8 pressure transmitters and 3 flow meters are placed in the overall flow path as shown in Figure 4.1. The pressure transmitters provides pressure measurements in current signal ranging from 4-20 mA with an accuracy of 0.1%. The flow meters provides instantaneous flow measurements in current signals between 4-20 mA which is further converted in the control system to record data in actual physical units. For safety, it is desired to operate with a maximum system pressure of 150 psi with a flow rate ranging from 20 lpm to 100 lpm. Water is used as the drilling fluid during the experiments. The drill string pipe is stationary i.e. rate of penetration (ROP) and no rotation of drill bit. Air is used as reservoir fluid to simulate the influx situation. There is no loss of drilling fluid during circulation at zero influx condition.

4.3 NMPC design

An output feedback NMPC controller was designed and implemented on the experimental setup to achieve various operational objectives of MPD system. The NMPC utilized nonlinear Hammerstein Weinner (H-W) model similar to that presented by Al-Duwaish and Naeem (2001) for prediction, and genetic algorithm for calculating optimal control input. Pump or circulation rate and choke opening are the primary sources for pressure manipulation in the system. The state vectors are bottomhole pressure p_{bh} and pump pressure p_p. For achieving the control objective choke opening u_c is regulated to apply required backpressure to maintain desired bottomhole pressure p_{bh}. Choke flow rate q_c and choke pressure p_c are measured variables. Below we describe the two most important components of NMPC.

4.3.1 System model

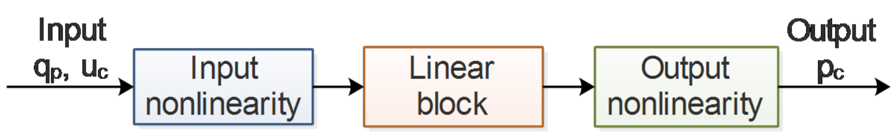

Figure 4.3: Hammerstein Weiner model

The structure of Hammerstein-Weiner model is shown in Figure 4.3. Hammerstein-Weiner model was identified using actual process data collected from system identification experiments. The collected data is fed into MATLAB system identification toolbox (Ljung, 2007). The identified H-W model was used as a prediction model in the NMPC framework. The H-W model constitute of series of static and dynamic blocks. The input nonlinearity block captures the nonlinearity in inputs (q_p,u_c) and transform it to $w(t)$ as shown in Equation 4.1a. The transformed non-measured term $w(t)$ is passed through a linear function block. The linear function projects the linear input to an output $x(t)$ using Equation 4.1b. Finally, the output nonlinearity block induces the nonlinear dynamics to provide an improved nonlinear estimate of the output $p_c(t)$ as shown in Equation 4.1e, (m, n) are the orders of the numerator and denominator of the linear functional blocks and α is a nonlinearity index.

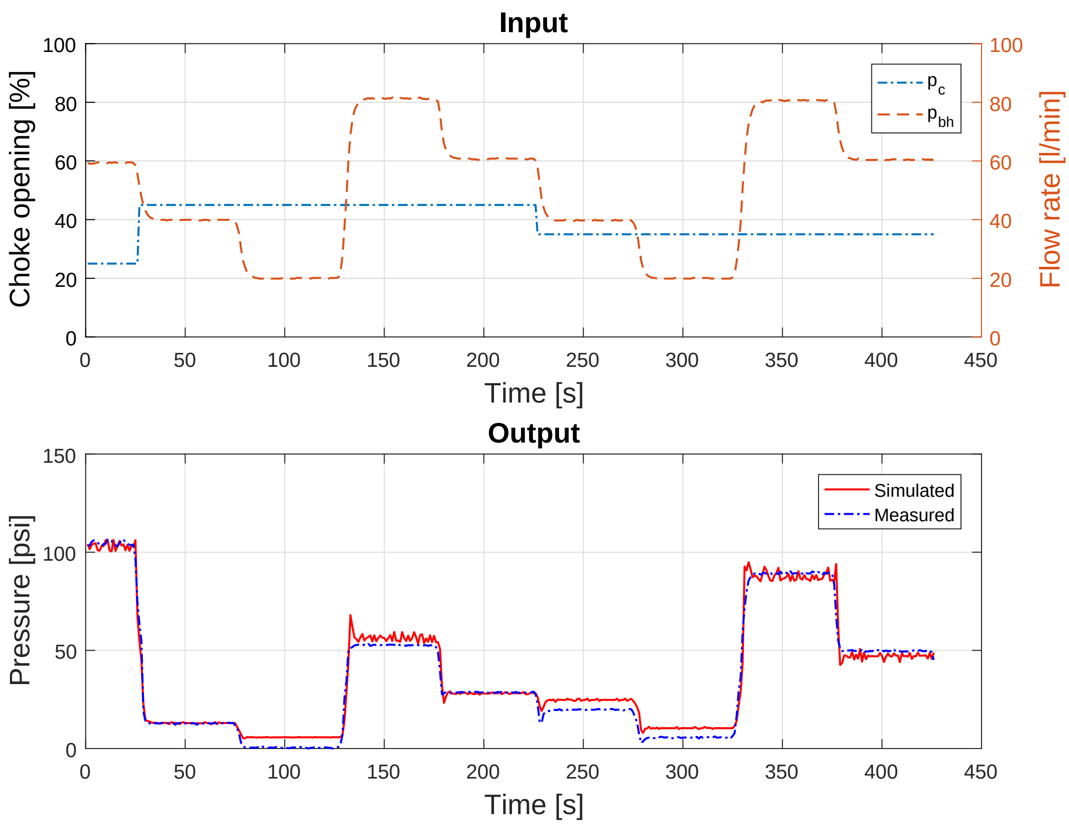

Figure 4.4: Measured pressure and predicted pressure during identification experiment.

$$w(t) = f(\alpha, q_p, u_c) \tag{4.1a}$$

$$x(t) = \frac{B(q^{-1})}{A(q^{-1})} w(t) \tag{4.1b}$$

$$B(q^{-1}) = b_o + b_1 q^{-1} + ... + b_m q^{-m} \tag{4.1c}$$

$$A(q^{-1}) = 1 + a_1 q^{-1} + ... + a_n q^{-n} \tag{4.1d}$$

$$\hat{p_c}(t) = f(\alpha, x(t)) \tag{4.1e}$$

The experiments were performed by manipulating the choke opening and pump flow rate with random step type excitations. The pump flow rate was varied between 80 lpm and 25 lpm. The choke opening ranges from 25% to 75%. Figure 4.4 shows input signals and the comparison between measured and predicted pressure. Linear model parameters of the identified model are given in Equation 4.2a to 4.2d. A fit of R = 89.2% between the measured and predicted signal was obtained. The input nonlinearity parameters were identified as a 2x1 array of nonlinearity estimator objects in MATLAB. The linear component of Hammerstein-Weiner model are given in as Equation 4.1a to 4.1e. Consequently, output nonlinearity parameters were configured using a set of 10 piecewise linear breakpoints. The reservoir kick can be considered as a disturbance in the system. In addition to the identified model we used the steady state relation as given in Equation 4.3 for bottomhole pressure prediction.

$$B_1(z) = z^{-1} - 0.9492 z^{-2} \tag{4.2a}$$

$$B_2(z) = z^{-1} - 0.9962 z^{-2} \tag{4.2b}$$

$$F_1(z) = 1 - 0.7033 z^{-1} - 0.6914 z^{-}2 + 0.6101 z^{-3} \tag{4.2c}$$

$$F_2(z) = 1 - 0.6064 z^{-1} - 0.5065 z^{-2} + 0.1182 z^{-3} \tag{4.2d}$$

$$\hat{p}_{bh} = \hat{p}_c + \rho g h \tag{4.3}$$

4.3.2 Estimation of optimal control output

The control objective is to maintain the bottomhole pressure at the desired setpoint ($r = p_{bh}^{set}$) under various disturbances (e.g. reservoir kick). In this setup, pump flow rate was not available for manipulation by the controller. Only choke valve opening (u_c) was used as manipulated variable. The cost function (Equation 4.4) minimizes the error between the target and predicted output over the prediction horizon keeping the choke valve movements to minimal.

$$J = \min_{u_c} \sum_{K=k}^{k+m} \gamma_1 (\hat{p}_{bh}(K) - p_{bh}^{set}(K))^2 \ + \ \gamma_2 \ \Delta {u_c}^2 \tag{4.4}$$

where $\hat{p}_{bh}$ is given by Equation 4.1 and Equation 4.3. γ_1 and γ_2 are weighing constants. subject to constraints

$$p_{bh}^{min} \leq p_{bh} \leq p_{bh}^{max};\ p_c^{min} \leq p_c \leq p_c^{max} \text{ and } u_c^{min} \leq u_c \leq u_c^{max}$$

The above optimization problem was solved using genetic algorithm (GA). Genetic algorithm utilizes the Darwinian concept to find an optimal solution from a set of outputs known as population (Stojanovski and Stankovski, 2012). Al-Duwaish and Naeem (2001) showed the implementation of NMPC controller using GA optimization technique. Initially the algorithm uses the Hammerstein-Weiner model to evaluate the set of possible system outputs i.e. choke pressures using pump flow rate and choke opening. The choke pressure values are used to estimate the bottomhole pressures as given in Equation 4.3. The estimated bottomhole pressure constitutes a set of new population. The genetic algorithm looks for set of possible control inputs from the population which satisfies the cost function (Equation 4.4) and constraints. During this process, the fitness for the set of potential solutions are evaluated. The optimal solution is determined which provides maximum fitness. Lastly, the control input trajectory is developed and passed to the controller hardware for control valve input. One of the major objectives of the controller is to minimize the effect of reservoir kick into the system. In order to achieve that in addition to the above constraints we also included the flow constraint given by Equation 4.4 in our minimization problem.

$$|q_c - q_p| < \epsilon \tag{4.5}$$

where ϵ is a tuneable parameter dependent on the sensor noise and disturbance within the system in Equation 4.5. This constraint is valid for this system since there is very small delay (<1 sec) between the pump flow q_p and choke flow q_c. Under normal condition the controller's priority will be to maintain the bottomhole pressure to the target setpoint and will act more like a constant bottomhole pressure controller. In case of a reservoir kick the difference between q_p and q_c will increase and as soon as the constraint gets active, the controller will give up on the bottomhole pressure target and put effort to balance the flow. In essence the controller will switch to a 'flow control mode'. Once the reservoir kick has been mitigated in order to return to the 'pressure control mode' the target bottomhole pressure has to be revised to a higher setpoint. The pressure setpoint will be little over the updated reservoir pressure, typically obtained by an observer. In this current experiment we determine the new pressure setpoint based on known air injection pressure.

$$0\ psi \leq p_{bh} \leq 100\ psi \tag{4.6a}$$

$$0\ psi \leq p_p \leq 100\ psi \tag{4.6b}$$

$$25\ lpm \leq q_p \leq 100\ lpm \tag{4.6c}$$

$$25\ lpm \leq q_c \leq 100\ lpm \tag{4.6d}$$

$$25\% \leq u_c \leq 75\% \tag{4.6e}$$

Equation 4.6a to 4.6e show the ranges of operation for the NMPC controller. The prediction horizon of the controller was 3 secs. The controller execution interval was 1 sec. The control system is built on MATLAB Simulink and Advantech ADAM 5000 controller platform. ADAM 5000 is a 8 slot distributed data acquisition and control system which can accommodate analog input or output cards for bidirectional data transmission. Communication between the MPD plant and MATLAB Simulink was established using ADAM 5000 TCP/IP, OPC Server, and MATLAB OPC toolbox. Three input cards and one output card had been used for reading the measurements and writing the control outputs. ADAM 5017 input cards were used as analog input module which can record data at 10 samples/sec with an accuracy of ±0.1%. The pressure and flow measurements are recorded through the input module with an effective data resolution of 16 bit. Sensor calibration was performed using the maximum and minimum ranges of the measuring component with corresponding current input signals obtained between 4 to 20 mA. ADAM 5024 output module was selected for sending the analog output signals with an effective resolution of 12 bit. Two pneumatic actuators wired to the output module receive current signal between 4 to 20 mA to drive the choke valve to a desired opening position between 0 to 100%. OPC server and client pairs were configured in the computer using the Advantech OPC server software. ADAM 5000 TCP/IP sends and receives data in the computer using RS-485 communication standard.

4.4 Benchmark gain switching PI controller

To compare the performance of NMPC controller, a linearized gain switching PI controller has been used. The choke pressure is nonlinearly related to the choke opening. A novel linearized PI controller with valve linearization technique has been proposed in Section 3.6.1 and 3.6.2. The linearized pressure can be obtained from Equation 3.8. The entire flow range for gain switching PI controller was divided into three sections. The proportional gains k_p and integral gains k_i for the PI controllers were calculated based on Ziegler Nichols tuning method (Xue et al., 2007). The controller configurations are shown in Table 4.1. The switching between the controllers was done based on pressure and flow values.

Table 4.1: Controller configuration for linearized gain switching PI controller

Controller	k_p	k_i	**Operating flow range (lpm)**
1	0.3140	0.11	25-45
2	0.0355	0.15	45-65
3	0.1914	0.2	65-105

4.5 Experimental results

The performance of the NMPC controller was demonstrated for various normal operational scenarios such as bottomhole pressure setpoint tracking, pipe connection; and managing abnormal conditions, such as reservoir kick and pump failure. The controller performance has been compared with a linearized gain scheduled PI controller performance. The following sections provide a brief overview of the experimental conditions and the observations.

4.5.1 Tracking of bottomhole pressure

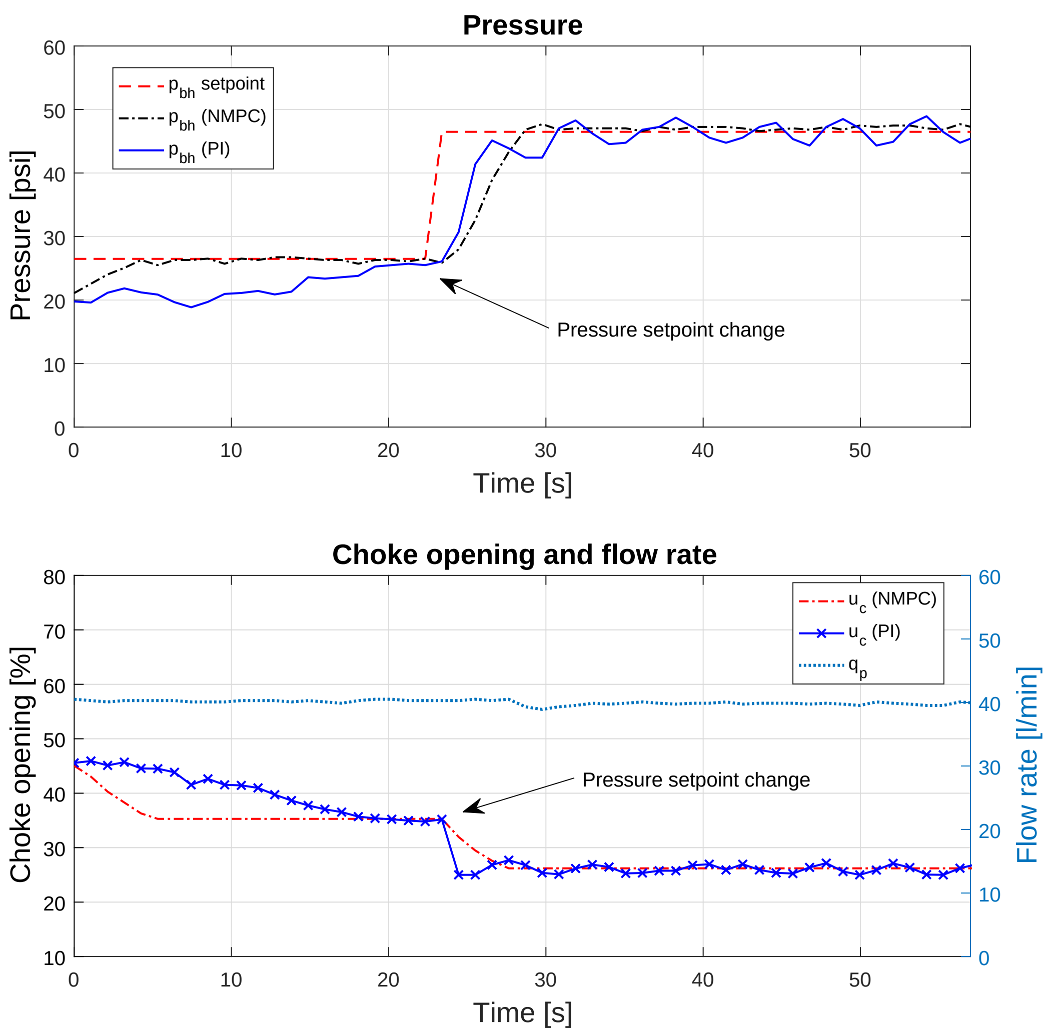

Figure 4.5: Constant bottomhole pressure at 40 lpm circulation rate

The purpose of these set of experiments is to make a performance comparison between the NMPC controller and the linearized gain switching PI controller in tracking the bottomhole pressure setpoint p_{bh}^{set}. During these experiments, the circulation rate was fixed to 40 lpm. The pressure setpoint was changed from 27 psi to 47 psi at 23rd sec. Figure 4.5 shows that initially when the controller setpoint was 27 psi, the NMPC controller closes the choke opening to achieve required setpoint value within 5 secs of operation. On the other hand, the gain switching controller tracks the bottomhole pressure after 15 secs with minor steady state bias. When the setpoint was changed after 23 secs, the PI controller responded within 5 secs to adjust the choke opening to reach the new pressure setpoint of 47 psi. Though the PI controller response was quicker, the NMPC controller reached the new setpoint within first 7 secs compared to 10 secs for the PI controller. Also, the NMPC response was smooth while PI response was oscillatory with a steady state bias. The choke opening manipulation did not have any effect on the circulation rate due to use of progressive cavity pump and non return valve at the bottomhole. Overall, it can be observed that, the NMPC controller provides closer and stable tracking performance compared to the linearized gain switching PI controller.

4.5.2 Pipe extension scenario

In a pipe extension scenario, initially the pump flow rate is gradually ramped down to no flow condition. At this point, the pipe replacement operation is performed. Once the replacement is complete, the circulation rate is ramped up back to the original value. It is desired to maintain constant bottomhole pressure above the reservoir pressure during this entire sequence to avoid kick initiation and maintain well integrity. In real life scenario mud density is increased to compensate for the loss in pump pressure at ‘no flow’ condition. As our setup does not have the ability increase mud density, a minimum flow has to be maintained to sustain the bottomhole pressure. In this experiment, the bottom pressure setpoint was fixed to 19 psi for both controllers. Figure 4.6 shows that, for the NMPC controller the pump flow rate was

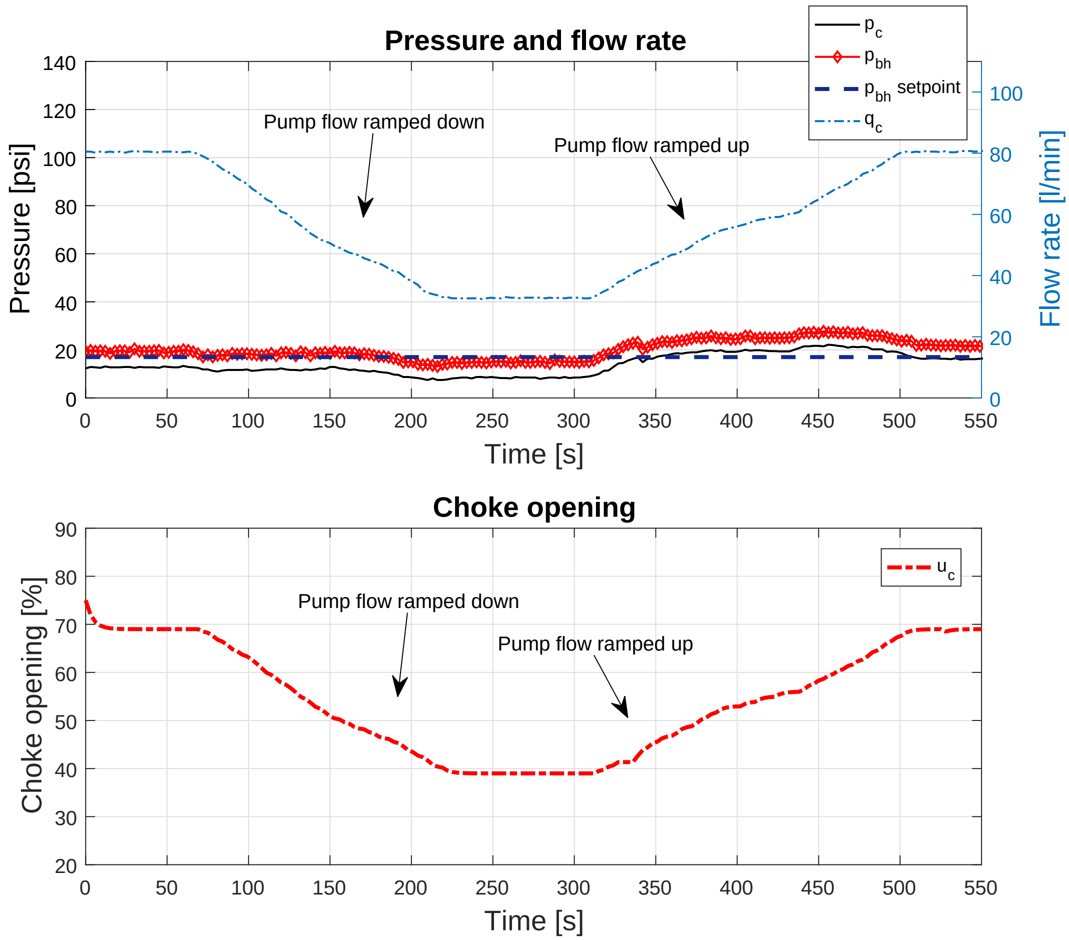

Figure 4.6: NMPC controller - Pipe extension scenario

maintained at 80 lpm for the first 1 min. After 1 min, the pump flow rate was gradually decreased from 80 lpm to 30 lpm in next 3 mins. At 30 lpm the flow rate was kept constant for 1 min. During this period the bottomhole pressure dropped 4 psi below the setpoint when the offset in bottomhole pressure was also eliminated. Figure 4.7 shows the performance of the linearized gain switching controller for pipe extension sequence. The pump flow rate was gradually ramped down from 80 lpm after 1 min. In 3 mins the flow rate was brought down from 80 lpm to 30 lpm. After reaching 30 lpm the pump flow rate was kept constant for 1 min. Lastly the flow rate was ramped up to 80 lpm in next 3 mins. Comparing the PI controller performance with

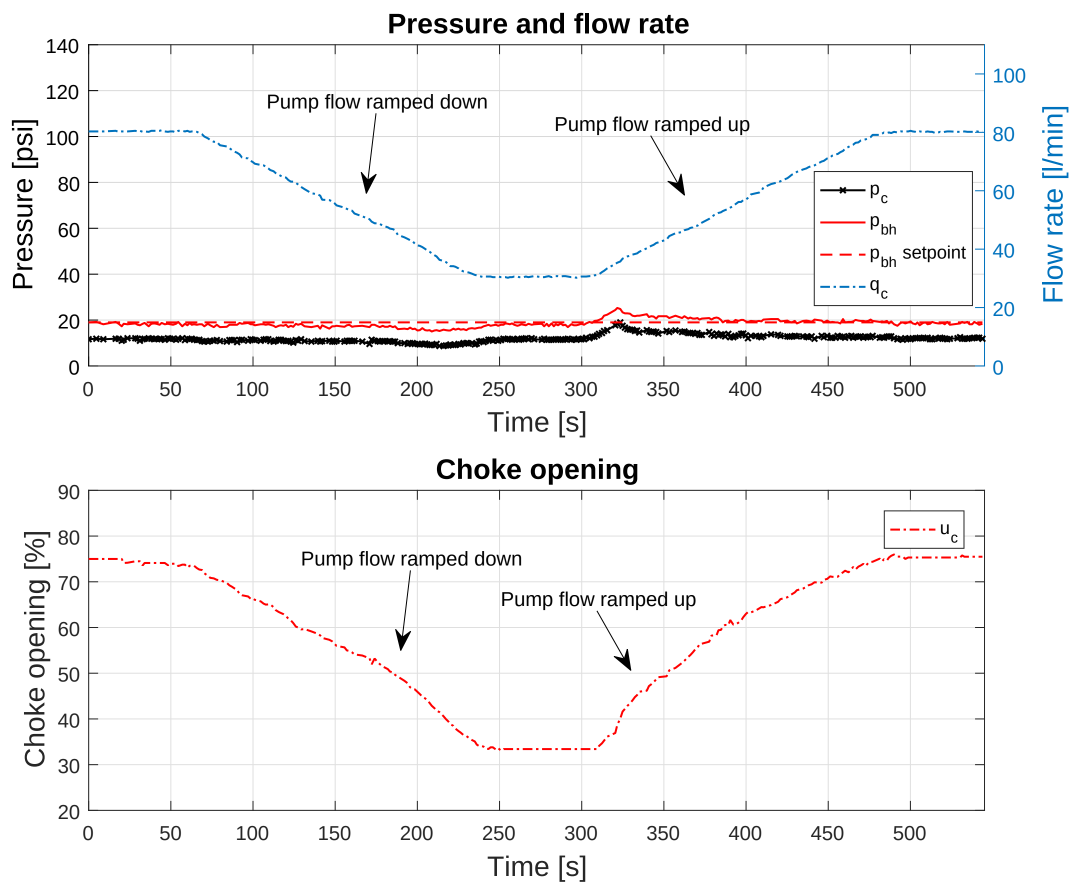

Figure 4.7: Linearized gain switching PI controller - Pipe extension scenario

the NMPC controller, the PI controller successfully tracked the bottomhole pressure within an offset margin of 3 psi. This is due to the modelling inaccuracy of the Hammerstein Weiner model used for predicting the pressure in bottomhole region for the setup.

4.5.3 Pump failure scenario

Pump failure condition is experienced due to sudden failure of the circulation rate. The controllers' goal is to quickly compensate for the pressure loss and maintain bottomhole pressure above the collapse pressure to avoid kick situation and maintain

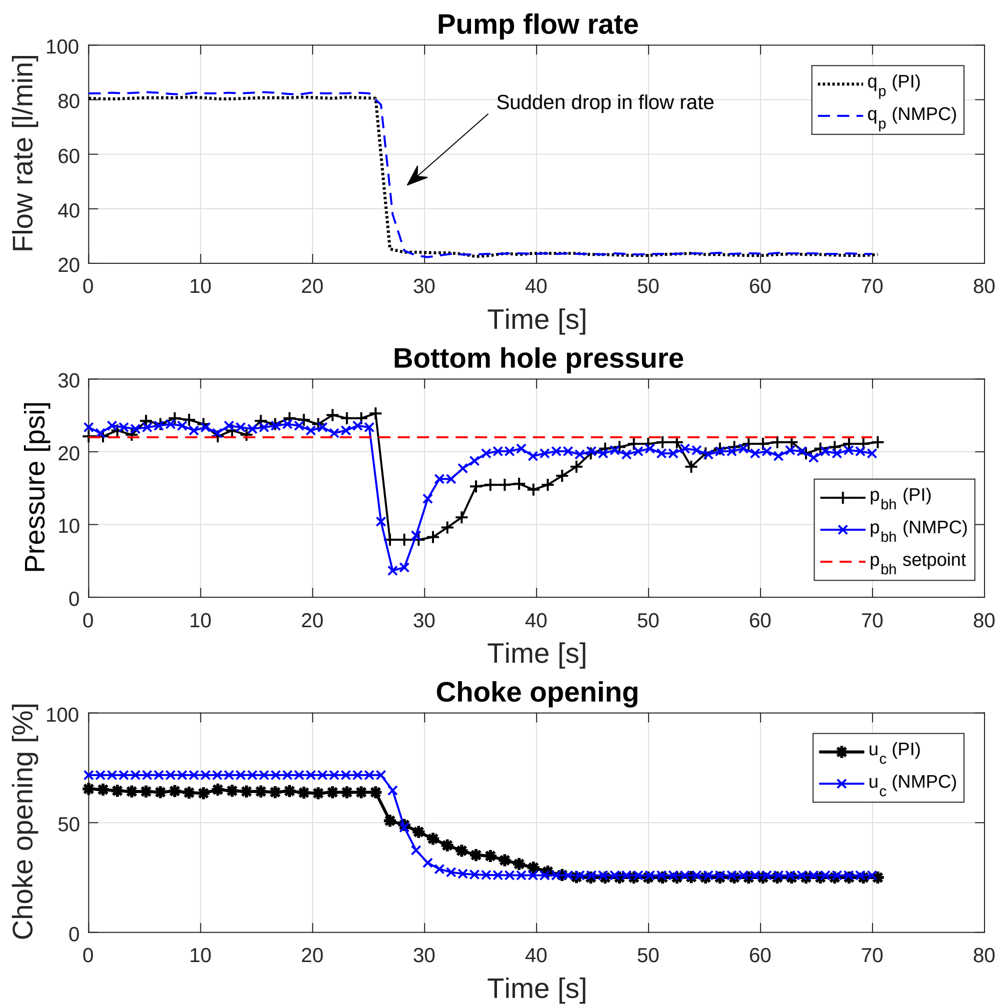

Figure 4.8: Pump failure scenario

well integrity. Figure 4.8 shows that the pump flow rate was suddenly decreased from 80 lpm to 25 lpm after 25 secs of operation. Again, the bottomhole pressure setpoint p_{bh}^{set} was set at 22 psi. Both controllers successfully tracked the bottomhole pressure with a steady state offset margin of 3 psi. The response of the NMPC was quicker compared to PI. NMPC reached within 3 psi pressure margin within 10 secs while PI took about 17 secs to reach the same level. In the experimental setup we could not test the complete loss of circulation since it require increasing the density of circulation fluid. Rather, we simulated partial loss of circulation.

4.5.4 Gas kick scenario

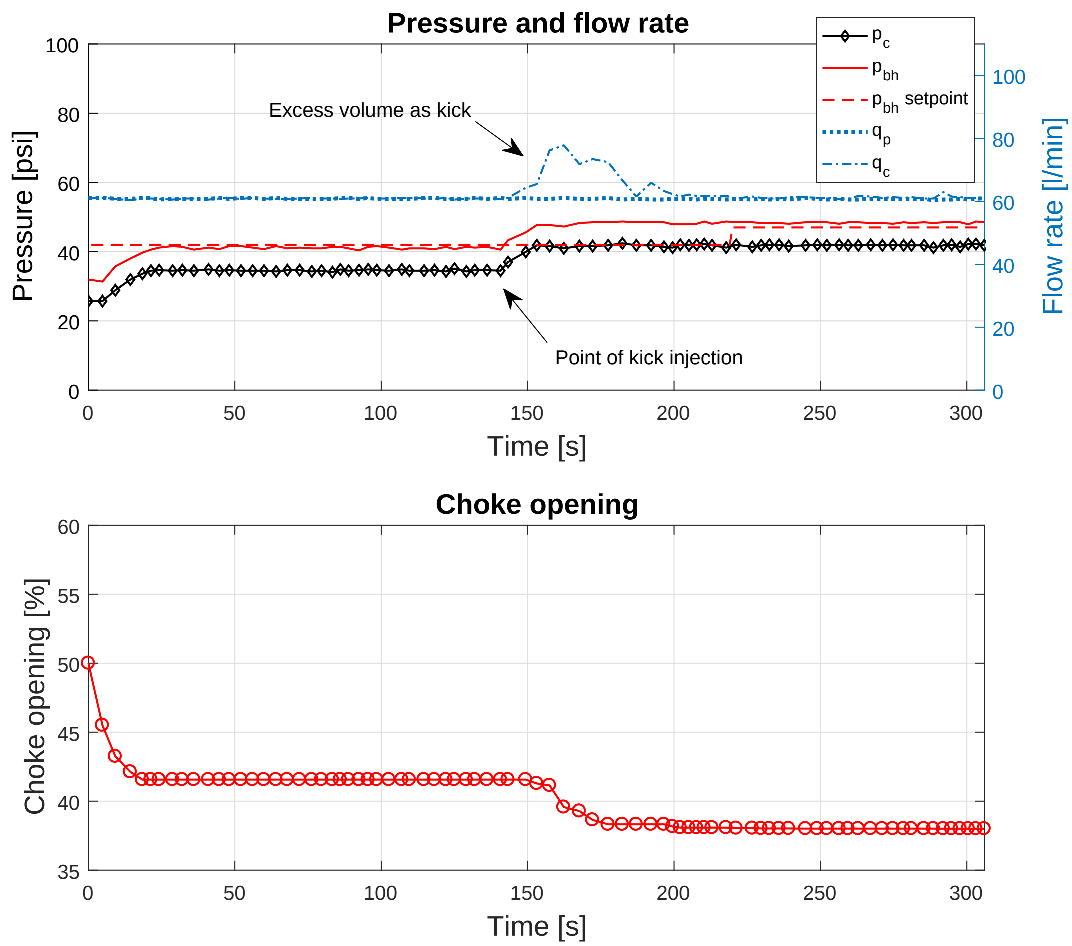

Figure 4.9: NMPC controller - Influx attenuation scenario

To simulate the reservoir influx, pressurized air at 41 psi was injected in the bottomhole region of the setup. The pump flow rate was kept constant at 60 lpm, and the bottomhole pressure setpoint was set to 40 psi. The controllers are configured to maintain kick volume below 5 lpm i.e. ϵ<5 lpm. Figure 4.9 shows that, the NMPC controller successfully tracks the 41 psi pressure setpoint till 140 secs of operation

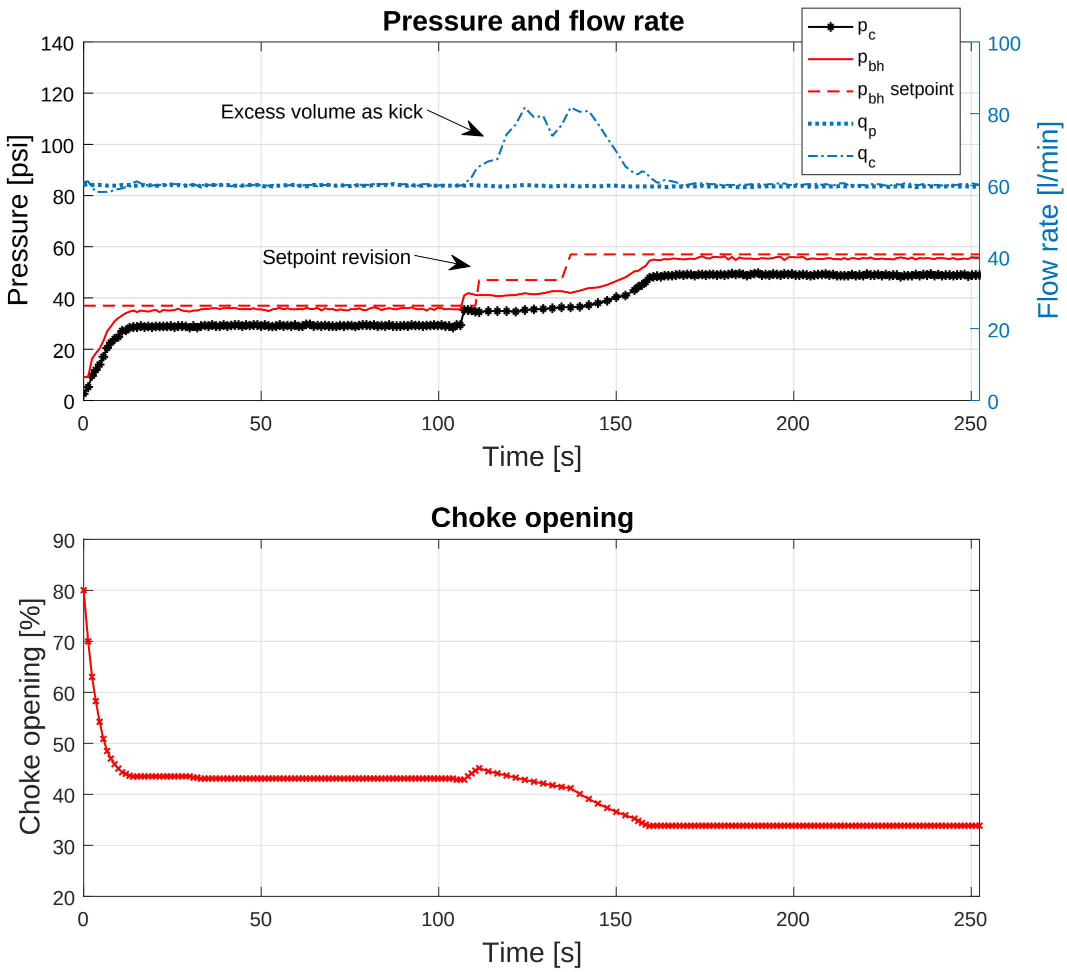

Figure 4.10: PI controller - Influx attenuation scenario

within a steady state offset of 2 psi. When a gas kick was injected after 140 secs of operation, the flow constraint specified by ϵ is violated as the excess flow exceeded 5 lpm. Since flow constraint has more priority over pressure tracking, the NMPC controller gives up on bottomhole pressure setpoint tracking and starts to reduce the excess flow by closing the choke valve. It can be observed within 50 secs the NMPC controller was successful in stopping the influx of gas into the setup, thus mitigating the gas kick condition. At 225 secs the pressure setpoint was revised to 50 psi i.e. 9 psi over the injection pressure. As the flow constraint was no longer active the controller switched back to pressure tracking mode. To simulate the gas kick scenario using the linearized gain switching controller, the pump flow rate was maintained at 60 lpm during normal operation. The controller tracked bottomhole pressure to 39 psi using the 'pressure control mode'. Figure 4.10 shows that pressurized air was injected at 110^{th} sec. Due to the gas injection the choke flow rate rises sharply which detects the kick situation. The controller switches to 'flow control' mode and elevates the pressure setpoint value 10 psi to mitigate the kick by balancing the pump flow and choke flow. It can be seen that after two setpoint revisions the controller was able to balance the flow rate and attenuated kick. When the pressure becomes marginally above the kick injection pressure, the influx stops and the controller returns back to constant pressure tracking mode automatically. It took 60 secs to mitigate the gas kick using the PI controller. It was observed that the NMPC controller tries to eliminate the gas kick with minimal setpoint revision compared to the PI controller.

4.6 Conclusions and future works

The NMPC controller was successfully implemented in the experimental setup. The NMPC controller was able to track bottomhole pressure setpoint using pressure control mode during normal operation. Moreover, the pressure tracking during flow demand changes was also observed by performing experiments replicating pipe extension and pump failure cases. On the other hand, whenever a reservoir kick was injected to the system, the flow measurements instantly indicated the abnormal situation. The NMPC activated the flow control mode of the controller to drive the flow rates to the minimum threshold kick value. The overall control action maintained the predefined pressure, flow and input constraints by minimizing the cost function. The Hammerstein-Weiner model helped in handling nonlinearity in the system states and provided accurate prediction. However, the modelling mismatch induced a steady state bias between 2 to 5 psi. The deviation in pressure values was observed more during pipe extension scenarios where the flow demands were changing over a short period of time. Comparing the NMPC controller performance with the linearized gain switching PI controller, the NMPC provided fast pressure tracking over PI controller. The PI controller required multiple setpoint revisions during flow control operation. There was no significant difference in performance during pump failure scenario. However, the pressure tracking was oscillatory with steady state bias for PI controller comparing the NMPC controller. For further improvement, the drilling fluid of different rheological properties can be tested in the system. Moreover, a multiphase flow model can be modelled and tested using the experimental facility which will provide a more realistic representation of the actual managed pressure drilling operation.

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Chapter 5

Conclusions

5.1 Conclusions

The goal of this thesis was to develop a lab-scale experimental managed pressure drilling (MPD) setup which can replicate the hydrodynamic behavior of a real MPD facility. The setup should be able to operate in pipe extension, pump failure to kick attenuation cases. In order to achieve these objectives, two controllers have been developed: (i) a linearized gain switching proportional-integral (PI) controller, (ii) a nonlinear model predictive controller (NMPC).

A lab-scale experimental facility has been built. Reynolds number and pressure drop per unit length were considered while designing the experimental setup. Based on the flow requirements, sensors and actuators were placed to get real-time data. A control station monitors the sensor measurements and sends control signals to the actuators. The control valve induced nonlinearity in the flow parameters which was addressed by linearizing the valve output. The plant model for linearized valve outputs was identified using experimental data. This simplified the controller tuning requirements and enabled the controller work flawlessly. In order to ensure smooth operation during flow demand changes, gain switching schemes have been integrated by designing three different PI controller across the overall operating range. The linearized PI controller took approximately 30 secs to reach the steady state pressure tracking value. The controller was successful to achieve constant choke pressure during pipe extension, pump failure and kick attenuation scenarios. The pressure tracking was limited to 2-5 psi steady state bias. The PI controller induced minor fluctuations while tracking the setpoint pressure at low flow rate. It was seen that the PI controller may need multiple setpoint revision to eliminate the kick from the system. Moreover, pipe extension cases can only be tested during circulation.

The NMPC controller provided superior performance over linearized PI controller. It takes the measurement from the system to decide a suitable control input based on the predefined flow constraints. The controller uses a nonlinear Hammerstein-Weiner model for predicting the states based on the real-time measurements. The constraint handling capacity of this controller helped in gaining stable control during setpoint changes. Steady state bias was lower using NMPC controller comparing PI controller. However, this error could be reduced by addressing 10% modeling mismatch in the nonlinear system identification for the plant model. The flow constraint was predefined to assist in flow control operation in the event of kick. During kick scenario, the controller rejected the influx within 10 secs of injection. No significant variation was observed while experimenting with pump failure scenario. Both controllers were able to respond to abrupt change in flow rate.

5.2 Future work

For the preliminary assessments, only water has been used as the primary drilling fluid in the experiments. The use of drilling fluid with different rheological parameter would help in obtaining in depth understanding of the challenges involved in implementing the controllers. Besides this, the rotation and rate of penetration parameter can be integrated to provide an accurate representation of the real drilling facility. Due to absence of a backpressure pump, the pipe extension scenario cannot be tested at zero circulation rate. The future work will include the use of a backpressure pump to provide efficient controller performance in MPD operation. Moreover, using a time delay parameter in the prediction model could enhance the controller's ability to deal with sudden flow changes.

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