AES/PE/12-36 Design of an automatic drilling fluid measurement setup and closed-loop pH control

22-Nov-12 I.L. van der Sluijs





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Abstract

This thesis concerns the design and construction of an automatic drilling fluid measurement setup and the use of such setup to control the drilling fluid pH.

The construction of the experimental setup include modifications to the acquired rheometer to obtain reliable batch rheology measurements within the typical viscosity range of a shear-thinning drilling fluid ([0.02-0.15]Pas).

A model-based control approach is taken to control the drilling fluid pH. With help of a static model we have defined a new scaling method which enables us to get an estimate of the required control fluid to shift the pH up to a mud volume of 32L. Implementation of the model shows that the pH can be maintained within the desired operating window if the quantity of control fluid is adjusted properly. The right quantity of control fluid is achieved by adjusting the estimated quantity of control fluid with help of a tuning parameter *a*. Results of this thesis show that to be able to control the pH at rig-scale, which is a dynamic process, closed-loop pH control based on the flux in and out of the mud tank should be implemented. The closed-loop pH control utilizes two pH sensors, the new scaling method and the signal from the Coriolis flow meter to add the right quantity of control fluid to stabilize the pH of the drilling fluid into the well.

Based on the results that show the advantages of measuring both incoming and outgoing fluid properties at the active mud tank, a twin skid construction for rig-scale implementation is proposed.

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1. Introduction

Most future drilling activities will take place in remote and environmentally harsh areas. Shell and other oil- and gas operators envision drilling automation to reduce human exposure to significant health, safety and environmental (HSE) risks in those areas, achieve operational efficiency and consistency in tight margin environment. In this thesis, we focus on the automation of drilling fluid management, which plays a critical role in drilling since it contributes up to 10% of the total well cost.[1]

Drilling fluids perform several critical functions to ensure a smooth and safe drilling operation. These functions are, among others: pressure control, suspend and transport of cuttings, drag reduction and many more. Drilling fluid properties must be monitored and maintained or modified in order to perform these functionalities properly.

Nowadays, drilling fluid properties are still largely monitored and optimized manually by mud engineers. Samples are taken from the shaker and mud tank three times a day and fluid properties such as viscosity, pH and density are measured manually and noted in reports. Mud engineers make decisions on the required treatment(s) by observing the trend of the properties.

In this project we will focus on the drilling fluid pH which generally has to be controlled in the pH range of 8 to 10 (slightly basic) to facilitate the performance of additives such as viscosifiers, organic thinners, biopolymers, to maximize the solubility of toxic gases like hydro sulfuric acid (H₂S) and/or carbon dioxide (CO₂) and to prevent corrosion.[2] Drilling fluid chemistry will change as drilling progresses because the fluid comes into contact with different formations each with their own chemical compositions.

Prior to drilling, mud engineers perform a small scale experiment (titration) to determine the amount of acidic or alkali control fluid that needs to be added to maintain the desired pH range. The mud engineer employs a-rule-of-thumb scaling factor to determine the required amount of acidic or alkali control fluid for the mud tank. As pH has a highly nonlinear dynamics around the pH range of 6 to 10, a simple volumetric scaling of the small scale experiment will likely be unsuitable for rig-scale implementation. In this thesis we show how a nonlinear static model can be used to design a better pH control system.

The current practice that relies heavily on the varied skills of mud engineers obviously lacks consistency and efficiency. Therefore a pilot project was initiated by several oil companies which successfully demonstrated the feasibility of automatic mud monitoring in a large flow loop. Five years ago the project showed that it is possible to measure and control properties of drilling fluid remotely by looking at real-time data.[3] In this thesis we would like to build on the previous project and try to make a step forward by automating pH control.

<u>Objective</u>

The objective of this thesis is therefore to design a low cost, modular prototype of an automatic mud system that can easily be up-scaled to the rig system and allows real time monitoring of drilling fluid properties and application of model-based control techniques to control drilling fluid pH.

<u>Outline</u>

The outline of this thesis is as follows. At first the design and modifications of a small-scale laboratory setup will be discussed. Secondly, the implementation and validation of a first principle static pH model will be presented. Thirdly, system analysis and controller design are discussed. Conclusions and recommendations for future work are given in the last section

2. Experimental setup

The goal of the experimental setup is to automatically measure different drilling fluid properties and control the fluid pH. Before we start to design an experimental setup we take a look at the rig circulation system, see Figure 1 below:



Figure 1: illustration of a rig circulation system

There are three main elements of the rig circulation system which we want to mimic:

- The time delay before the mud returns to the mud pit
- Contact of the drilling fluid with the formation and the formation fluids
- Mud-mixing hopper to change drilling fluid properties

An important component in the rig circulation system which we will not take into account is the shale shaker because we will not work with particles.

Our experimental design is based on the three main elements which we want to mimic and the result can be seen in Figure 2.



Figure 2: illustration of the experimental setup and a description of the main components

Similar to the rig circulation system components, we have a mud pit (nr. 1), a mud pump (nr. 3), a combined borehole and annulus represented by a large diameter tube (nr. 5), a reserve pit in case the mud pit overflows (nr. 9), a combined discharge line, stand pipe and drill pipe (nr. 4), a mud return line (nr. 6) and couple of tanks with control fluid which represent the mud mixing hopper (nr. 8).

Three main elements

We wanted to mimic the time delay with one large diameter tube and some small diameter tubes. At first we wanted to connect and construct some components with RVS tubes. However, this was not necessary because calculations indicated that pressures below 1 bar are expected (Appendix section 8.1). Instead the components are connected with garden hoses and some components are constructed out of PVC material including component nr. 5 and the housing for the sensors.

To simulate the contact of the drilling fluid with the formation and formation fluids, an outflow point(nr. 11) and an injection point(nr. 10) are attached to the large diameter tube. The inflow and outflow of formation fluids can be simulated with a syringe pump respectively a valve. The volume balance for the experimental setup is shown in Appendix section 8.1.2/

Instead of a mixing-hopper, tanks with control fluid are placed on top of a balance. With a balance and control valves the quantity of acidic and alkali control fluid can be remotely controlled via a computer program.

<u>Sensors</u>

We included several sensors which had to meet the following three general requirements:

- 1. Capability of performing measurements in the operating range of interest
- 2. Capability of performing real-time measurements
- 3. Easy interface to data acquisition tools.

Given these requirements, only instruments measuring pH, conductivity, density and flow rate could be covered by available sensors in the market. A rheometer was also added although only batch measurements could be obtained. Density and flow rate can be measured with a Coriolis flow meter. The Coriolis flow meter is based on a special case of the momentum balance. Tubes inside the flow meter are oscillated with constant amplitude and its resonant frequency. Whenever a medium passes through the tubes these twist slightly because of the Coriolis effect. The quantity of tube deflection registered as a phase shift is directly proportional to the mass flow. The period of oscillation of the flow tubes at its resonant frequency is related to the density of the fluid in the flow tubes.[4]

Placing the Coriolis flow meter at the outlet of the well enables us to measure hole cleaning problems and to quantify fluid loss and inflow to the well.[5]

We bought conductivity sensors because they could possibly enhance our knowledge for pH and rheology control.[6, 7] To realize closed-loop control, conductivity and pH sensors are placed at the inlet and outlet of the mud pit.

The best location of the rheometer is close to the mud pit because otherwise thixotrophy would affect the measurement and also gel particles would build up in the rheometer.[8] A bypass loop is constructed to the mud tank to create a circulation path between the mud pit and the rheometer(nr. 12) with help of two pumps. Before each rheology measurement, the pumps are switched off after which the rheometer needs several minutes to conduct a decent rheology measurement after which the pumps are turned on again and a new sample enters the rheometer.

After designing the experimental setup, some modifications were required to optimize the setup. First the syringe pump was exchanged with two tube pumps because its injection rate was below the error (1L/hr) of the Coriolis flow meter and below what is to be expected in reality. Secondly, a series of modifications had to be made to the acquired rheometer, see section 2.1.

2.1. Rheometer

2.1.1. Introduction to rheology

We introduce some basic rheology concepts before we start analyzing the rheometer.

Rheology is a study of the deformation and flow of matter which plays a critical role in hole cleaning and is thereby an important parameter in drilling.

Most drilling fluids used in the industry have a non-Newtonian rheology. These fluids exhibit a shearstress/shear-rate relationship which is not constant; hence do not have a single or constant viscosity. In fact these fluids exhibit a "shear-thinning" behavior such that the effective viscosity decreases with increasing shear rate. Most drilling fluids also have to overcome a certain yield point (YP), a shear stress required to overcome internal inertial forces, before it starts deforming.

The shear rate versus shear stress behavior of a typical drilling fluid can be described best with the Herschel-Buckley equation[2]:

 $1 \tau = \tau_0 + K \dot{\gamma}^n$

Where τ_0 = yield stress, τ = shear stress, K = consistency, \dot{y} = shear rate and n = flow behavior index.



In Figure 3 below the typical behavior of a drilling fluid is compared to other fluid rheology profiles.[2]

Figure 3: illustration comparing the different fluid behaviors

The behavior of a typical drilling fluid has some important implications:

- At high velocities(nozzle) a shear thinning fluid thins to a low viscosity, reducing circulating pressure and pressure losses. Shear rate range [5.000-100.000]s⁻¹
- At lower velocity as in the annulus, the mud has a higher viscosity that aids in hole cleaning. Shear rate range [5-100]s⁻¹
- At ultra-low velocities like static conditions the fluid reaches its highest viscosity and becomes a gel which aids in suspending weight material and cuttings. Shear rate range [0.1-1]s⁻¹.

The ideal shear stress versus viscosity curve of a drilling fluid is shown in Figure 4 below.[9]



Figure 4: illustration of the ideal drilling fluid rheology

We are primarily interested in the lower shear rate region because of the hole cleaning and suspension which are a very important because we drill more and more horizontal wells. Now that we have some basic rheology knowledge we start analyzing the rheometer.

2.1.2. Rheometer modifications

The Haake rheometer, from Thermofisher, has been attained because of:

- simple interface
- accuracy in the lower shear rate region
- stress controlled which makes it easier to get reliable yield point measurements.

The Haake rheometer utilizes different geometries to measure the viscosity. An accompanied flow cell (Figure 7(a)), utilizing a magnetic bearing, was employed to get viscosity measurements at different temperatures and pressures in a flow loop.

Viscosity is typically measured as a function of the shear rate. The flow cell measurements start oscillating when shear rates $<\approx 50 \text{ s}^{-1}$ and shear stresses $<\approx 20 \text{ Pa}$ are applied as can be seen in Figure 5. The friction of the magnetic bearing which cannot be entirely compensated likely causes this.





Due to the oscillations in the low shear rate region using the flow cell, rheology measurements were carried out with two other geometries that follow the German measurement standard (DIN): a cylindrical bob/cup geometry (Z40) and a double gap bob/cup geometry (DG41), see Figure 7(b) respectively below and above.

As we wanted a geometry which was able to measure the viscosity of water up to the viscosity of an oilbase mud for shear rate range of $[0-1020]s^{-1}$ we tested the geometries in the range of [0.001-0.35]Pas. When testing the upper limit with an oil sample with a viscosity of 0.360Pas, both geometries did not meet the requirements:

- DG41 was unable to measure the oil at higher shear rates because at 50% of the maximum torque, the system gives a temperature error and stops measuring. The more viscous a fluid is, the higher the required torque to achieve a certain shear rate
- Z40 was unable to measure oil at shear rates >1000s⁻¹ because of turbidity (sudden increase in viscosity due to vortices in the sample)(Figure 6, left).

When testing the lower limit with water, both geometries did not meet the requirements either:

- DG41 showed large variations in the lower shear rate region (Figure 6, right)
- Z40 was able to measure water in the lower shear rate region but failed at higher shear rates due to turbidity.



Figure 6: illustration of two rheology test, a test with Z40 geometry on an oil sample of 0.36Pas (left) and a test with DG41 geometry on a water sample (right)

Because of the failure of both the DG41 and Z40 geometries we decided to design a new cup. In this design we wanted to improve the higher shear rate readings. The new cup is based upon the geometry of the Z40, due to the ease of cleaning and the bigger sample size to get an appropriate representative elementary volume (REV). To improve the higher shear rate readings the gap between bob and cup is reduced by 0.5mm, see Figure 7(c) for the result.



Figure 7: stepwise modification process to the rheometer

The newly designed cup, from now on called "Z40mod", deviates from DIN standard and has "dead zones" in the flow path for viscous fluids that will influence future viscosity measurements. A silicon cover was created to get rid of these "dead zones", see Figure 7(d).[10]

The newly designed cup is tested against other cylindrical cups (Z20 and Z40) and a plate-to-plate configuration (PT41) using calibration fluids with different viscosities: 0.001, 0.032, 0.098 and 0.323Pas. The measurements were carried out in steps, from the highest to the lowest, comparable to the way rheology is measured with the Fann. The Fann is the brand of the manually operated rheometer which is standard on most rigs. See Figure 8 for the result.



Figure 8: evaluation of different geometries for different calibration fluids

The plate-to-plate measurements (black dashed lines) are taken as the reference measurement. Ideally, the measured viscosity of a Newtonian fluid should stay constant as the shear rate changes. The following observations can be made:

- Error of the readings, due to turbulence, decreases the more viscous the fluid
- The height of the bob from the bottom of the cylinder (gap is 28mm or 53mm) has an effect on the readings
- Z40mod is less affected by turbulence than Z40
- Z40mod has an overall reproducible trend whereas the Z40 and Z20 geometries show a decrease in viscosity at higher shear rates
- Z20 and Z40 are inaccurate for fluids with a viscosity around 0.1Pas
- Z40mod is inaccurate for viscosities close to 0.3Pas
- All configurations show good results in the lower shear rate region [5-20]s⁻¹ which is of great importance for hole cleaning purposes.

Before we jump to any conclusion, the same experiments are repeated with cylindrical geometries comparable to the Fann rheometer currently utilized in practice. This time we use a constant shear rate ramp for more data points and a smoother curve, see Figure 9 below for the result.



Figure 9: evaluation of different geometries/devices for different calibration fluids

The following observations can be made:

- The accuracy of the Fann meter readings are very poor in the lower shear rate region [0-20]s⁻¹
- For shear rates higher than >30s⁻¹ the DG41 gives the overall most accurate results
- The more viscous the fluid the more inaccurate the DG41 gets in the lower shear rate region [0-20]s⁻¹. This is likely caused by the very low bob speed
- DG41 and Z40 are inaccurate for fluids with a viscosity around 0.1Pas
- Z40mod is inaccurate for viscosities around 0.3Pas
- Z40 and Z40mod show good results in the lower shear rate region [5-20]s⁻¹ for fluids more viscous than water
- Fann rheometer cannot measure a fluid with a viscosity of 0.323Pas.

Up to this point Newtonian fluids have been analyzed and the Z40mod performs satisfactorily compared to the various manufacturer's geometries. Since a typical drilling fluid is shear-thinning, similar experiments are repeated with laponite. The measurement results on a sample with 3% laponite and a plastic viscosity of 0.075Pas are shown in Figure 10.



Figure 10: 3% Laponite solution measured with different geometries in Haake and the Fann35SA

The following observations can be made:

- Fann35SA rheometer has been designed for shear thinning fluids
- DG41 is inaccurate at shear rates below <30s⁻¹
- Z40mod is more accurate in higher shear rate region $>200s^{-1}$ because of the reduced gap.

Conclusion, there is except for the plate-to-plate not a single geometry which is capable of accurately measuring any viscosity in the range of [0.001-0.35]Pas within a 10% error over the entire shear rate range [0-1020]s⁻¹. The region in which the Z40mod is accurate can be narrowed down to [0.02-0.15]Pas which is the typical viscosity range for a shear thinning fluid at shear rates >100s⁻¹. Z40mod is ready to provide reliable viscosity measurement for typical shear thinning drilling fluids in the experimental setup.

Now that we have optimized the experimental setup we proceed to pH control such that in the end we can run a test experiment (Appendix section 8.4) to check whether the experimental setup is ready to investigate the effect of the pH and additives on the rheology.

3. pH control

3.1. Introduction

pH control is important to maintain the desired rheological properties of drilling fluid. The drilling fluid pH affects the effectiveness of additives used to control the viscosity and must therefore be kept between 8-10.[2] The drilling fluid pH will be altered during drilling due to interaction with different formations and formation fluids.

As explained in section 1, pH is a difficult property to control due to its non-linearity. In many operating units, the desired pH range is typically set between 8-10. In this project we would like to set the desired pH range tighter, namely between 8-9. Within this pH range, a small addition of control fluid ($V_{a,b}$) will result in a very large pH change. A typical example of an alkali titration curve from pH 6 to 12 can be seen in Figure 11.



Figure 11: nonlinearity of the pH as a function of the added volume of acidic or alkali control fluid (V_{a,b})

In practice, titration experiments are used to control the drilling fluid pH. A mud engineer collects a mud sample from the mud tank at irregular intervals and carries out the titration experiments. From this titration experiment the mud engineer estimates how much alkali or acidic control fluid is required to shift the pH. The estimation from the mud engineer is based on the multiplication of the titration volume by the volume ratio between the mud tank and the mud sample.

There are several drawbacks of the current practice:

- pH measurements are obtained at scarce and irregular intervals
- The pH of the drilling fluid flowing into the well is not constant
- Inaccuracy of the volumetric scaling factor.

To improve the current practice, we want to automatically neutralize the drilling fluid that flows out of the well into the mud tank. This is possible if we have two pH sensors, one at the inlet of the mud tank to measure the effect of the disturbance on the drilling fluid pH and one at the outlet of the mud tank to check the effect of addition of control fluid ($V_{a,b}$). How we vision the automated pH neutralization process is shown in Figure 12.



Figure 12: illustration of neutralizing the inflow of altered drilling fluid in the mud tank. $Q_{out,m}$ = measured flow rate out of the well, Q_{in} = pump rate into the well, pH_1 = pH of the drilling fluid into the well, pH_2 = pH of the drilling fluid out of the well, $V_{a,b}$ = quantity of control fluid added, pH = pH of the drilling fluid inside the mud tank, Φ = flux from the valve and V_{tot} = quantity of altered drilling fluid flowing into the mud tank at a certain interval Δt

To be able to control the pH automatically we have built up our process of controller design and thereby this chapter in steps. First a process model is built to understand the physics behind the pH control process. Secondly, this model is validated against titration experiments. Thirdly, system analysis of a heuristic experiment. Finally a controller is designed and simulations are carried out.

3.2 Build a process model

Before we built our process model we will go over the basic concept of a system and show how a model can improve our knowledge of this system.

3.2.1 Definition of a system

A system can be defined as a black box where an input signal produces an output signal which is the result of interactions between variables related to the system. A system can be operated in either an open-loop or closed-loop configuration, the difference between the two is shown in Figure 13.



Figure 13: illustration on the difference between an open-loop and closed-loop system where G is the system relating the input to the output

3.2.2 pH control system

We want to tackle the pH control in the mud tank using a system and control approach. Therefore we introduce some system control theory notions. The drilling fluid pH that flows into the well (pH_1) is the variable we would like to control, the output. The pH is affected by:

- A manipulated variable or input V_{spr} which is the volumetric set point to the valve which determines the quantity and type of control fluid that needs to be added to the mud tank from t = 0. t = 0 is defined as the first point in time that control fluid is added to the system.
- Inflow of altered drilling fluid with pH_2 . The drilling fluid is altered in the well because of additional ions and influx of formation fluids. However, we are not able to predict or estimate the potential change in the pH and therefore we need to measure it.

The conceptual static process system and control model in accordance to Figure 12 is shown in Figure 14:



Figure 14: conceptual static pH process system and control model, with pH_1 = the pH of the drilling fluid going into the well, pH_2 = pH of the drilling fluid out of the well, V_{sp} = volumetric set point given to the valve to add a certain quantity of control fluid, $V_{a,b}$ = quantity of control fluid added and G_1 , G_2 and H_1 = system relation between the input and output

We would like to design a model such that pH_1 can be kept within the desired pH range. To design such a model, we need to understand the physics behind pH control i.e. system G₂. Therefore a static pH model (stirred tank) is designed in MATLAB.

Before we go into the theory behind the model, an overview of the parameters used in the pH model is given in Table 1:

	<u>unit</u>	Description	
State variable			
y 1	[-]	pH of the mud flowing into the well (pH $_1$)	
Parameters			
V _{tot}	[mL]	Quantity of altered drilling fluid flowing into the mud tank at a certain interval Δt	
C _{a,ini}	[mmol/mL]	Initial acid concentration of mud	
C _{b,ini}	[mmol/mL]	Initial base concentration of mud	
C _{a,tank}	[mmol/mL]	Acid concentration of acidic control fluid	
C _{b,tank}	[mmol/mL]	Base concentration of alkali control fluid	
V _{a,b}	[mL]	Added volume of acidic(a) or alkali(b) control fluid	
y _{ref}	[-]	Target pH	

The pH in this thesis is from now on denoted by "y."

In general, the pH of a fluid system can be described as follows:

2 $y = f_1(V_{tot}, C_{a,ini}, C_{b,ini}, C_{a,tank}, C_{b,tank}, y_1, V_{a,b})$

where f is a nonlinear function describing system G_2 and which is based on the electro-neutrality balance. This can be re-written as a static 'control law':

3 $V_{a,b} = f_2(V_{tot}, C_{a,ini}, C_{b,ini}, C_{a,tank}, C_{b,tank}, y_1, y_{ref})$

where $V_{a,b}$ (either V_a or V_b depending on whether acidic(a) or alkali(b) control fluid is added) is the quantity of control fluid added to the mud tank. Function f_2 calculates the quantity of acidic or alkali control fluid that needs to be added to shift the pH from y_1 to a certain target/reference pH (y_{ref}). For more details about the static pH model see Appendix section 8.1.2.

We can validate this model by comparison to experimental data and utilize it to estimate the required quantity of control fluid at any system volume V_{tot} .

3.3 Model validation

Equation 3 from section 3.2.2 can be used to quantity of either acidic or alkali control fluid that is required to control the pH to a certain target. But how much does the model behind the equation deviate from reality? We use a graphical comparison between experimental and modeled values of $V_{a,b}$ (the added volume of control fluid), by taking the "Titration curve" approach: stepwise reduction or increase of pH by gradually adding control fluid.

The experimental data is obtained from two titration curve experiments: one for a mud volume of 0.25L and one for a mud volume of 32L (the volume in the experimental setup). A small scale titration is a test which mud engineers typically do in the field. The objective of carrying out a big titration experiment in our case is to validate the modeling result and investigate a better scaling method.





The experimental and modeled titration curves are compared in Figure 15. As can be observed, the models do not match the experiments. One source of this mismatch are the dissociation coefficients, which are kept constant in the model. [11, 12] A dissociation coefficient is used in the equilibrium equation of a chemical reaction (equation 33 in the Appendix). McMillan et al. state that: "some tweaking of the dissociation constants is inevitable for a complex mixture." [11] In this project, we do not tweak the dissociation constants in the model to match the actual pH response because there are other uncertainties that affect the response of the drilling fluid pH which we cannot measure directly.

Nevertheless, the titration curves seem to have a similar trend. We analyze the trend around each titration step further in section 3.3.1.

3.3.1 Analyzing the model inaccuracy

The titration curves from the model and titration experiments seem to have a similar trend. To analyze the titration responses, we linearize the titration curves from the model and experiments at every titration step. We represent the titration curve with a simplified function $f(y, V_{a,b})$, which describes the nonlinear relation between $V_{a,b}$ and y neglecting all other variables in equation 2, see Figure 16.



Figure 16: illustration of the nonlinear static relation f(), which gives y^{i+1} , the pH, which is obtained when a quantity of control fluid ($V_{a,b}$), the input, is added to the system knowing y^{i} , the initial pH or the state

Linearizing the nonlinear relation around V_0 and y^i with help of the Taylor expansion can be described according to:

4

$$y^{i+1} \approx f(y^{i}, V_{0}) + f'(V_{0}) \cdot V_{a,k}$$
$$\hat{y}^{i+1} = f(y^{i}, V_{0}) + f'(V_{0}) \cdot V_{a,k}$$
$$\frac{\hat{y}^{i+1} - y^{i}}{V_{a,k}} = f'(V_{0}) = K_{p}$$

 $\mathbf{v}^{i+1} = f(\mathbf{v}^i, \mathbf{V}_0 + \mathbf{V}_{a,b})$

Where the slope $f'(V_0)$ can be replaced by K_p , which we refer to as the static process gain. The process gain K_p relates an addition of control fluid to a change in y the pH. Now for every titration step, we can approximate the resulting pH from the model and experiments, using the following linear approximation:

5
$$\widehat{y}^{i+1} = y^i + K_p^i \cdot V_{a,b}^i$$

Where \hat{y}^{i+1} =estimated pH after an addition of control fluid, y^i =pH at the ith titration step, K_p^i =static process gain corresponding to the ith titration step and $V_{a,b}^i$ =quantity of control fluid added at the ith titration step.

We are interested in the static process gains from pH 6.0 up to 8.5 and from pH 12.0 down to 8.5 i.e. the static process gains for alkali control fluid respectively acidic control fluid. With help of $\frac{\hat{y}^{i+1}-y^{i}}{V_{a,b}}$ we can compute the static process gains for the titration steps of importance for both the modeled and the experimental titration curves.

For clarity, we denote the static process gain at each titration step K_p^{i} from the model $K_p^{i_model}$ and from the experiments $K_p^{i_exp}$.

Figure 17 shows a graphical comparison between the static process gains from the model $K_p^{i_model}$ and the experiments $K_p^{i_model}$, where "i" denotes the corresponding titration step. There is almost no data in the pH range 8 to 9 because it is the steepest range and data points are therefore scarce.



Figure 17: trend comparison between modeled and experimental process gains for two mixtures with identical composition but different V_{tot} namely 0.25L and 32L

Figure 17 confirms that the static process gains of both the model and the experiment follow a similar trend for different mud volumes. We impose a hypothesis to check the accuracy of the modeled static process gains with respect to the experimental static process gains.

3.3.1.1 Hypothesis testing

Successful implementation of a model-based control approach depends highly on the quality of the model. In this section, we will check whether the static pH model is adequate for our control purposes. To do so, we check the accuracy of the modeled static gains using a hypothesis.

The deviation d_i between the modeled and experimental gains at every titration step *i* is defined as:

$$\boldsymbol{6} \qquad \boldsymbol{d}_{i} = \frac{\left(K_{p}^{i_model} - K_{p}^{i_exp}\right)}{K_{p}^{i_exp}}$$

Where $K_p^{i_model}$ = modeled static process gain and $K_p^{i_exp}$ = experimental static process gain.

The average absolute deviation \overline{D} is defined as:

$$\overline{\mathbf{D}} = \frac{\sum_{i=1}^{n} |d_i|}{n}$$

Where n is the total number of titration points and $|d_i|$ denotes the absolute value of d_i .

We set the following hypothesis, H_0 : "*The modeled static gains give an adequate estimate of the experimental static gains.*" We reject this hypothesis if the average absolute deviation \overline{D} >0.2 and we accept if \overline{D} <=0.2.

Figure 18 below shows the deviation d_i of the modeled static gain from the experimental gains obtained from titration experiments carried out for a small volume (0.25L) and the volume in the experimental setup (32L).



Figure 18: deviation of the modeled static gain from the corresponding experimental gain for V_{tot} = 0.25L and 32L

Table 2: statistics on the deviation for V	tot = 0.25L and 32L	with σ = absolute standard	deviation of K _p ⁿ	^{nodel} from k _p ^{exp}
--	---------------------	-----------------------------------	--	---

\overline{D} for V_{tot} =0.25L	1.17
σ for V _{tot} = 0.25L	1.14
$\overline{\mathrm{D}}$ for V _{tot} =32L	1.26
σ for V _{tot} = 32L	0.84

We reject the hypothesis because the modeled gains are about 2 times higher than the actual gains $(d_i >>2)$ and $\overline{D} >0.2$, as can be observed from Figure 18 and Table 2. We noticed however that the modeled and actual gains exhibit similar trends for different volumes (Figure 17) and we can exploit these trends to scale the modeled gains better. How this is accomplished is explained further in subsection 3.3.1.1.1 of this paragraph.

3.3.1.1.1 Utilizing ratio equation to minimize the deviation

Figure 19 shows the ratios *F_i* between the static gains for the two mud volumes, which is defined as:



Figure 19: illustration of the ratio between $K_p^{i_model}$ and $K_p^{i_exp}$ for V_{tot} = 0.25L and 32L

From Figure 19 we can conclude that the ratio F_i is generally constant between the two mud volumes. With a constant ratio we can estimate the static process gain $K_p^{i_est_Vtot}$ at any mud volume V_{tot} using the following expression:

9
$$K_p^{i_est_Vtot} = \frac{K_p^{i_exp_small}}{K_n^{i_model_small}} \cdot K_p^{i_model_Vtot}$$

Where $K_p^{i_exp_small}$ and $K_p^{i_model_small}$ are the static process gains from respectively the modeled and the experimental small scale titration curve and $K_p^{i_model_Vtot}$ = static process gain from the modeled titration curve at any V_{tot}.

Figure 20 shows the deviation of both the modeled and estimated gain from the experimental gain for a large mud volume.



Figure 20: deviation of the estimated static gain K_p^{i-est} from the corresponding experimental gain for $V_{tot} = 32L$ Table 3: statistics on the deviation with K_p^{est}

\overline{D} with $K_p^{i_est}$ for V_{tot} = 32L	0.19
σ for V _{tot} = 32L	0.13

We accept the hypothesis because \overline{D} < 0.2, as can be observed from Figure 20 and Table 3. From this section and appendix section 8.3 we conclude that a small scale titration test in combination with the model can be used to get a good approximation of the real static gain for any volume V_{tot} up to 32L.

3.3.2 Final result from modeling part

Instead of multiplying the quantity of control fluid added to the small scale titration test by the volume ratio, we propose a new scaling method based upon a static model.

The new scaling method multiplies the gain from the small scale titration test $K_p^{i_exp_small}$ by the ratio K_p^{large}/K_p^{small} obtained from the model (Appendix 8.1.2). With the new scaling method we obtain an adequate approximation of the real gain for any volume V_{tot} up to 32L.

In the previous section, we showed that with $K_p^{i_est_Vtot}$ we can get an estimate of the quantity of control fluid $V_{a,b}^{i}$ required to shift y to the next titration step for any volume V_{tot} up to 32L. For ease of notation, we refer to $K_p^{i_est_Vtot}$ as $K_p^{i_est}$.

By transforming equation 5 we obtain an estimate of the quantity of control fluid $V_{a,b}^{i}$:

$$10 V_{a,b}{}^i = \frac{\widehat{y}^{i+1} - y^i}{K_p^{i} - st} \approx \frac{y^{i+1} - y^i}{K_p^{i} - st}$$

For n titration steps we can sum up the quantity of control fluid $V_{a,b}^{i}$ with their corresponding $K_p^{i_est}$ at each side of the window of operation to obtain the volumetric set point V_{sp} to shift the pH from any y^i to y^{n+1} which is set to 8.5.

11
$$\mathbf{V}_{\mathrm{sp}}(\mathbf{y}^{i}) = \sum_{i=1}^{n} V_{a,b}^{i} \approx \sum_{i=1}^{n} \frac{1}{K_{\mathrm{b}}^{i,\mathrm{est}}} \cdot \left(\mathbf{y}^{i+1} - \mathbf{y}^{i} \right)$$

Where y^i = initial pH, y^{i+1} = the pH of the next titration step, $V_{sp}(y^i)$ = volumetric set point of required quantity of control fluid to go from y^i to y^{n+1} which for control purposes is set at 8.5, K_p^{i-est} = approximated static process gain belonging to y^i , n = number of titration steps.

With help of a curve fit through the points in the graph y versus V_{sp} we obtain a nonlinear static function f_3 where the quantity of control fluid V_{sp} becomes a function of y. The process of deriving f_3 is shown in Figure 21:



Figure 21: illustration of converting the approximated K_p^{est} (figure 1 left) to $V_{sp}(y^i)$ (figure 2 middle) to f_3 where V_{sp} becomes a function of y the pH (figure 3 right) for V_{tot} equal to 32L

In the following sections and chapters we will use function f_3 , which corresponds to a certain V_{tot} , to calculate the required volumetric set point of control fluid to shift y from any point to the window of operation.

3.4 System analysis

Up to now we have defined a new scaling method which on the basis of a small scale titration curve and equation 3 gives us a nonlinear function f_3 for any V_{tot} up to 32L. Function f_3 gives us the quantity of control fluid V_{sp} as function of y (the pH) to control the pH in one step into the window of operation.

The mud tank in the experimental setup and on a rig cannot be considered as a static system with water where the transient response is negligible.[6] The components of the experimental setup and the drilling fluid properties introduce delays and therefore a transient response into the system. Some components and properties that contribute to the delays are:

- Viscosity and the flow rate of the drilling fluid
- Mixing efficiency of the mixer installed in the mud tank
- The flux of control fluid that can flow through the control valves
- Mud tank size
- Location of the sensors.

The process model in the continuous-time domain is shown in :



Figure 22: process model in time with G_1 , G_2 and H_1 are the transfer function, $y_1 = pH_1$, $y_2 = pH_2$, $V_{a,b}$ =quantity of added control fluid and V_{sp} = volumetric set point obtained from function f_3

Before we move on to the analysis of the transfer functions G_1 , G_2 and H_1 we will explain what a transfer function is and how it can be mathematically justified in section 3.4.1.

3.4.1 Transfer function explanation

The transfer functions G_1 , G_2 and H_1 are known as the system functions. It is a mathematical representation of the relation between the input and output of a LTI system describing the control system.[13]

In general, $\Delta y_1(t)$ is obtained through convolution:

12
$$\Delta y_1(t) = G_2(t) * V_{a,b}(t)$$

Where $G_2(t)$ = unknown impulse response function.

By approximating the systems with a linear time-invariant (LTI) system and transforming the LTI system with Laplace the convolution becomes a multiplication problem.

13
$$\Delta y_1(s) = G_2(s) \cdot V_{a,b}(s)$$

As an example we will linearize the signals $\Delta y_1(t)$ and $V_{a,b}(t)$ according to [13]:

14
$$\sum_{k=0}^{n} a_k \frac{d^k \Delta y_1(t)}{dt^k} = \sum_{k=0}^{m} \mathbf{b}_k \frac{d^k \mathbf{V}_{a,b}(t)}{dt^k}$$

Where a, b are the linearization coefficients, k = summation index and n, m = highest order of linearization.

Now we can transfer equation 14 with help of the Laplace transform to the s-domain:

15
$$\mathcal{L}\{y^{(n)}(t)\} = \int_0^\infty e^{-st} \cdot y^{(n)}(t) dt = s^n y(s) - s^{(n-1)} y(0) - \dots - y^{(n-1)}(0)$$

In the s-domain we can characterize the transfer function $G_2(s)$ according to:

16
$$G_2(s) = \frac{\Delta y_1(s)}{V_{a,b}(s)} = \frac{\left\{\sum_{k=0}^m b_k s^k\right\}}{\left\{\sum_{k=0}^n a_k s^k\right\}}\Big|_{initial \ conditions \ = \ 0}$$

 $G_2(s)$ in the s-domain can be obtained from the static equation 5 according to:

17
$$\Delta y_1 = K_p \cdot V_{a,b} \rightarrow \Delta y_1(s) = K_p \cdot \widetilde{G}_2(s) \cdot V_{a,b}(s) = G_2(s) \cdot V_{a,b}(s)$$

Where K_p is the real process gain and $\tilde{G}_2(s)$ = transfer function describing a nth order process with a certain time constant τ and time delay T_d . An example of a typical first order process with time delay is shown in Figure 23.



Figure 23: illustration of a typical first order system where after a certain time delay T_d the process starts reacting. When t equals the time constant τ , 63% of the steady-state value of the process gain K_p has been achieved. With t_{ss} = time to steady-state.

Now that we have explained the fundamentals behind the transfer functions we proceed to the analysis of the transfer functions.

3.4.2 Analysis of transfer function G₁

In section 3.3.2 we have defined the static relation between V_{sp} and y_1 . In our experimental setup $V_{a,b}(t)$ is depending on the flux through the valves which is a function of h (the height of the fluid level in the control fluid tank). We can show the dependence of Φ on h in Figure 24:



Figure 24: illustration of the flux (Φ) through the control valve (valve) defined by the height of the fluid column (h) in the control fluid tank and the diameter of the control valve (d)

The flux can be calculated according to the law of Torricelli:

18
$$\Phi = A_{v} * v = \frac{\pi}{4} d^{2} \cdot \sqrt{2 * g * h}$$

Where A_v = surface of the opening of the valve, d = diameter of the valve, g = gravity, h = height of the fluid column.

 $V_{a,b}(t)$ depends primarily on the flux, which is a function of the valve dynamics which we cannot control because the control fluid tank has fixed dimensions and is filled manually. We can only define a set point V_{sp} . As we cannot control the valve dynamics, the valve dynamics G_1 need to be combined with the transfer function G_2 , which is shown in Figure 25:



Figure 25: illustration giving the updated characteristics of transfer function G(s), where $\Phi(t)$ = the flux in time which changes according to h, $V_{sp}(t)$ = volumetric set point of control fluid that needs to be added, $V_{a,b}$ =quantity of control fluid added and $\Delta y_1(t)$ = change in y_1 due to the addition of control fluid in time

The valve has a maximum capacity, so if the set point V_{sp} is higher than its maximum capacity there will be additional time delay to the system. Figure 26 illustrates this problem: when V_{sp} is small, the required volume can be achieved within a very short time and when V_{sp} is large, additional time delay is introduced to the system.



Figure 26: illustration of the effect of the size of the set point on the flux in time, with T_{d_valve} = additional time delay due to the valve capacity

We can conclude that if $\frac{v_{sp}}{\phi}$ equals 1, G₁(s) is purely a time delay due to the opening and closing of the valve.

3.4.3. Analysis of transfer functions H₁ and G₂

Before we can analyze the transfer function G_2 and H_1 we conduct an experiment based upon a heuristic approach.

3.4.3.1. Heuristic experiment

19

With this heuristic experiment we want to test and check the transient response of $y_2(t)$ and $y_1(t)$ if control fluid is added while altered drilling fluid flows into the mud tank.

Because we do not know the transfer functions, the computer in Figure 14 consists of an if-else statement:

$$\label{eq:spectral_states} \begin{split} \text{if } 8 &\leq y_1(t), y_2(t) \leq 9 \ \& \ t < t_{cycle} \\ V_{sp} &= 0 \\ else \\ V_{sp} &= a^{a,b} \cdot f_3\left(\frac{y_1 + y_2}{2}\right) \end{split}$$

Where t_{cycle} = controller execution frequency, $a^{a,b}$ = a tuning parameter which is different for acidic a and alkali b control fluid and f_3 = nonlinear function for V_{tot} = 32L.

We want to keep $y_1(t)$ from equation between 8< $y_1(t)$ <9. This is possible by changing t_{cycle} to avoid instability and more frequent control executions and by correcting V_{sp} with help of a tuning parameter $a^{a,b}$.

The initial parameters for the open loop heuristic approach are listed below:

Parameters	Description	Value
a ^{a,b}	Tuning parameter for acidic (a) and alkali (b) control fluid	[0.5-1] [-]
y ₁	pH of mud flowing to the well	[1-14] [-]
y ₂	pH of the mud coming from the well	[1-14] []
t _{cycle}	Execution frequency of controller	2.5 [min]
f ₃	A nonlinear static function f3	Fitted curve for V _{tot} =32L

 Table 4: parameters for the heuristic approach

Figure 27 is the result of the open-loop heuristic experiment and shows six graphs with four drilling fluid property responses against the time.



Figure 27: result of an open-loop experiment, applying a heuristic approach. Graph 1 depicts the transient response of y_1 and y_2 to additions of control fluid and disturbance; Graph 2 depicts the transient response of $Q_{out,m}$; Graph 3 depicts the transient response of conductivity sensor 1 and 2; Graph 4 depicts the transient response of the density; Graph 5 depicts the added volume of control fluid in time and graph 6 depicts the transient response of the temperature.

Observations:

First we let an alkali disturbance flow into the well and y₂ starts increasing.

Acidic control fluid is added when both y₁ and y₂ are outside the window of operation. y₁ continues to rise before the control fluid lowers the pH which takes approximately 15s. At first the tuning parameter *a* was 1, however we see that y₁ dropped below the window of operation. Therefore to minimize the overshoot we set the tuning parameter a^a to 0.8.

After the system has returned to steady-state conditions, an acidic disturbance is injected in the well. The inflow of the disturbance into the well can be seen in the increase in $Q_{out,m}$ in graph 2 of Figure 27. Now we can observe how well y_1 is stabilized for an acidic disturbance.

Alkali control fluid is added when both y₁ and y₂ are outside the window of operation. For alkali control fluid, the tuning parameter a^b set at 0.8 is too large, indicated by an enormous overshoot of pH₁. For the second step we set the tuning parameter a^b to 0.6 to reduce the overshoot in y₁.

Conclusion

We did not manage to reduce the overshoot by applying this approach, however we did manage to keep y_1 close to the window of operation. y_1 has only been above 9.5 for 1.5min during the whole experiment. As we mentioned before, the heuristic approach is not the ideal solution but just to get information on the systems G_2 and H_1 .

3.4.3.2. Analysis of transfer functions H₁

For the analysis of H_1 we look at a close up of the first 300s of graph 1 and 2 from Figure 27.



Figure 28: illustration of the first 300s of graph 1 and 2 of Figure 37 with $T_{d_sensors}$ = time delay between the sensor locations after a change in y_2 is seen $Q_{out,m}$ = measured flow rate out of the well and $Q_{in,d}$ = inflow of disturbance

From Figure 27 (graph 1) and Figure 28 we can observe the following:

- The inflow of disturbance in the experimental setup is a summation of impulses
- When we have inflow of formation fluids in the well, we register an increase in Q_{out,m} because of Q_{in,d} see Appendix 8.1.2 for the volume balance
- It seems that $y_2(t)$ correlates to $y_1(t)$ through a first order transfer function with a gain approximately 1, a small time constant τ and a time delay $T_{d \ sensors}$ of 52s
- T_{d_sensors} is a function of the pump rate *Q_{in}*, the mixer speed *N_s* and the viscosity μ of the drilling fluid.

3.4.3.3. Analysis of transfer function G₂

For the analysis of G_2 we look at a close up on the interval t=[200-700]s of graph 1 and 5 from Figure 37.



Figure 29: illustration of time interval t=[200-700]s of graph 1 and 2 of Figure 41 with $T_{d_{mudtank}}$ = time delay before a change in $y_1(t)$ is seen after addition of control fluid.

From Figure 29 we can observe the following:

- Too much control fluid is added at each execution cycle because we experience oscillations. To reduce or prevent the oscillations control fluid must be added in small quantities in time
- Likewise to H_1 , it seems that an addition of control fluid correlates to $y_1(t)$ through a first order transfer function with a gain K_p , a small time constant τ and a time delay $T_{d \ mudtank}$ of 20s
- $T_{d_{mudtank}}$ is a function of the pump rate Q_{in} , the mixer speed N_s and the viscosity μ of the drilling fluid
- $\Phi = 2$ ml/s and it takes some milliseconds to close/open the valve.

3.4.4. Conclusion system analysis

 $G_2(s)$ and $H_1(s)$ are dynamic transfer functions which can be characterized with a gain, time constant and time delay. However we can simplify the transfer functions such that it contains only a time delay and gain based on the following assumptions:

- $\tau << T_{d_mudtank}$. Because in pH systems like a tank, the rate of neutralization is so fast that it completes in less than a second and no secondary reactions occur[6]
- T_{d_valve}<<T_{d_mudtank}. The time delay imposed by the valve due to V_{sp} needs to be smaller than the residence time in the mud tank.

3.5. Controller design

From section 3.4.2 we determined that if we can set the flux Φ or if $\frac{Vsp}{\phi} = 1$, G₁ is purely the opening and closing of the valve which we considered negligible. From section 3.4.4 we concluded that given the assumptions, G₂ and H₁ can be approximated by a pure time delay and a gain. An updated version of the process model neglecting the time delays can be described according to:

20
$$\frac{dy_1(t)}{dt} = K(y_2(t) - y_1(t)) + K_p(y_2)\phi(t)$$

Where K is the gain relating $y_2(t)$ to $y_1(t)$, $K_p(y_2) =$ process gain, depending on y_2 due to the nonlinearity of the titration curve, relating a quantity of control fluid to a change in the pH and $y_2(t) =$ measured effect of the disturbances on the drilling fluid pH.

Transforming the process model in the Laplace domain gives us

21
$$y_1(s) = \frac{1}{s+K} \Big(K y_2(s) + K_p(y_2) \phi(s) \Big)$$

Now we can update Figure 14:



Figure 30: illustration of the updated process model in the s-domain neglecting the time delays. K = gain relating y_2 tot y_1 , $K_p(y_2)$ = process gain, depending on y_2 , relating Φ to a change in y_2 , Φ = flux of control fluid, y_2 = pH of drilling fluid altered by disturbances, y_1 = pH of the drilling fluid into the well and $Q_{out,m}$ = measured flow rate out of the well.

The input $\Phi(t)$ from the computer can be defined as:

22
$$\phi(t) = -\frac{K}{K_p(y_2)} (y_2(t) - y_{ref}(t))$$

Function f_3 with y_{ref} = 8.5 reduces equation 22 to

23
$$\int_0^{\Delta t} \phi(t) dt = V_{sp} = f_3(y_2(t))$$

Where $[0-\Delta t]$ = time interval over which control fluid is added to the mud tank

The nonlinear function f_3 corresponds to a certain V_{tot} which changes in time according to:

24
$$V_{tot} = \int_0^{\Delta t} Q_{out,m}(t) dt$$

Where Q_{out,m} = measured flow rate out of the well

Our model is adequate up to a mud volume of 32L. If $\frac{Vsp}{\phi}$ =1, meaning Δt =1, $Q_{out,m}$ is equal to a flow rate of 2000L/min which is a typical pump rate in reality.

3.5.1. Closed-loop control

The process model in Figure 30 is an ideal case where there is no time delay. In reality when we measure y_2 the corresponding V_{tot} does not flow into the mud tank directly but after a moment which equals T_d . So after T_d seconds, V_{tot} flows into the mud tank and at that moment we need to add control fluid. After we added the control fluid it takes several seconds equal to $T_{d_mudtank}$ until we measure the effect of the neutralization in y_1 by sensor 1. See Figure 31 for a graphical representation of the time delays.



Figure 31: illustration of the time delay experienced in reality because of sensor locations, fluid properties and etc.. $y_2 = pH$ of the drilling fluid flowing into the mud tank, $y_1 = pH$ of the drilling fluid flowing out of the mud tank, $\Phi =$ flux of control fluid, $y_{ref} =$ reference or target pH, $T_d =$ time delay before altered drilling fluid enters the mud tank, $T_{d_sensors} =$ time delay before a change in y_1 is measured after a change in y_2 , $T_{d_mudtank} =$ time delay before a change in y_1 is measured after an addition of control fluid.

With help of y_1 we can correct or update our nonlinear function f_3 . When we apply f_3 for the first time we do not know the accuracy of the model. We can be careful and add only a certain percentage of the volumetric set point V_{sp} by applying a trust level y according to:

25
$$\int_0^{\Delta t} \phi(t) dt = V_{sp} = \gamma \cdot f_3(y_2(t))$$

Where γ = trust level i.e. a multiplication factor.

After $T_{d_{mudtank}}$ we can start updating our model. There are two possibilities of correcting the quantity of control fluid:

• We correct the quantity of control fluid by changing the reference or target pH y_{ref}. The quantity of control fluid depends on y_{ref} if we change equation 25 to

26
$$\int_0^{\Delta t} \phi(t) dt = V_{sp} = f_3(y_2(t)) - f_3(y_{ref}(t))$$

Where y_{ref} = reference or target pH and update y_{ref} according to

if
$$\hat{y}(t) \neq y_1(t)$$

27
$$y_{ref}(t) = (\hat{y}(t) - y_1(t)) + y_{ref}(t)$$
else
$$y_{ref}(t) = y_{ref}(t)$$

Where $\hat{y}(t)$ = predicted pH from the model. We can obtain \hat{y} graphically from f_3 see Figure 32.



Figure 32: illustration of graphically deducing the predicted pH \hat{y} from the nonlinear function f₃. With Vsp = volumetric set point and y is the trust level.

• We correct the quantity of control fluid with a tuning parameter a(y₂). To be able to do this we change equation 25 to

28
$$\int_0^{\Delta t} \phi(t) dt = V_{sp} = a(y_2) \cdot f_3(y_2(t))$$

Where $a(y_2) = tuning parameter which can be different for each <math>y_2$.

The multiplication factor can be obtained with help of the nonlinear function f_3 . For example, from f_3 we obtain V_{sp} to go from $y_2(t=0) = 6$ to a pH of 8.5. If instead $y_1(t)$ at $t=t_{d_sensors}$ equals 8, we can obtain $a(y_2)$ according to:

29
$$a(y_2) = \frac{f_3(y_2(t=0)) + f_3(y_1(t=t_{d_sensors}))}{f_3(y_2(t=0))}$$

If $y_2(t=0)<8$ and $y_1(t=t_{d_sensors})>9$ then $y_1(t=t_{d_sensors})$ is negative and an identical approach if $y_2(t=0)>9$ and $y_1(t=t_{d_sensors})<8$. The next time $y_2(t=0)$ equals 6 we know the tuning parameter we have to apply.

For both methods to work we require two separate nonlinear functions for both acidic and alkali control fluid. A combined one from which we can deduct the quantity of alkali control fluid up to y is 8 and the quantity of acidic control fluid down to y is 9 is not suitable. Reason being the fact that the quantity of acidic control fluid to go from 10 to 8.5 is not equal to the quantity of alkali control fluid to go from 8.5 to 10.

Implementing this strategy in Labview without MATLAB would take quite some time because we need to program the nonlinear static model (equation 3, Appendix section 8.1.2). Instead we use signal y_2 from the heuristic experiment and use it in a simulation which will be explained further in subsection 3.5.2.

3.5.2. Simulation of open-loop pH control

We apply equation 25 to time interval t=[0-800] of signal y₂ from section 3.4.3.1 in MATLAB to show the result of applying the open-loop pH control presented in Figure 30. For application of the control diagram in MATLAB we utilized the following parameters:

Properties	Value and	Description
	unit	
К	1 [-]	Static gain relating y_2 to y_1
Q _{out,m}	178 [L/hr]	Measured flow rate out of the well into the mud tank
Δt	0.5 [s]	Time interval over which control fluid is added which is equal to the
		sampling time of the sensors
t	[s]	Time
y ₂	[-]	pH response of the drilling fluid flowing into the mud tank from the heuristic
		experiment
γ	[0.8-1.0] [-]	Trust level of function f ₃
Va	40[ml]	Total volume of acidic control fluid added to control the alkali disturbance
		from heuristic experiment
\widehat{V}_a	[ml]	Sum of the quantity of acidic control fluid added each Δt

Table 5: parameters for control diagram

With equation 25 implemented in MATLAB we can check the effect of different trust levels on the error $(\hat{V}_a - V_a)$ which should be equal to zero if we want to neutralize the alkali disturbance. By applying different trust levels we can determine the trust level which we should apply in practice for acidic control fluids and with the trust level we know the accuracy of the right part of the nonlinear function f_3 . We use $V_a = 40$ ml, based upon graph 5 (Figure 27), which is the total volume of acidic control fluid that has been added to control the alkali disturbance.

The effect of different trust levels on the error and the calculated control fluid per element of pH_2 can be seen in Figure 33.



Figure 33: : illustration showing the required quantity of control fluid for three different trust levels Table 6: result of three different trust levels on the error

Trust level(γ)	Error[ml]
1	7
0.9	2.2
0.8	-2.5

From Table 6 we can determine that if we apply γ =0.85 the error is the smallest and therefore the alkali disturbance is completely neutralized resulting in a stabilized γ_1 . A likewise procedure can be applied to time interval t=[800-2000] to determine the best trust level for neutralizing an acidic disturbance. With the above simulation however we have proven that the control model in Figure 30 and equation 25 can be applied and due to time constraints we stop here.

4. Proposed skid construction

For implementation on a drilling rig, two identical skids should be built in order to measure the effect of a control step. The required size of the skids is determined by the representative elementary volume (REV). The REV is provided to the fluid testing system by a small bypass line which is attached to the pipeline at the inlet and the outlet of the active mud tank. Inside these skids a smart assembly of instruments analyzes the fluid properties, see Figure 34 for the proposed skid construction.



Figure 34: 3D proposed skid construction where instead of a rectangular mud tank, we have two hexagonal tanks where the measurement skid is attached to

With these skids and a Coriolis flow meter and Toroidal sensor placed before the ditch/shaker the entire fluid process including the shaker efficiency can be analyzed and controlled for a dozen of rigs by a group of specialists in a real time operating center (RTOC).

5. Conclusion and recommendations

In this chapter, conclusion are drawn based on the work of this project. Also several recommendations are made for further research.

Conclusions

- We have defined a new scaling method enabling us to get an estimate of the required quantity of control fluid for any mud volume V_{tot} up to 32L. If the required quantity of control fluid can be added within a second a mud volume of 32L corresponds to a flow rate of 2000L/min in reality.
- Two pH sensors, one at the inlet of the mud tank and one at the outlet of the mud tank allow us to create a closed-loop pH control system. By measuring the pH of the altered drilling fluid at the inlet of the mud tank and using that pH as input to the nonlinear function f₃ we get an estimate of the required quantity of control fluid to neutralize the altered drilling fluid pH. Adding the control fluid while altered drilling fluid enters the mud tank enables us to stabilize the pH of the drilling fluid flowing into the well.
- With a stabilized pH the drilling process is one step further to become an enhanced and fully automatic process. Several important aspects that make this approach successful: a model, the speed of pH reactions, large residence time in the mud tank, a high capacity valve and a feedback loop.
- The drilling process is subject to lots of different disturbances in time due to the geology. This makes
 drilling a dynamic process which requires continuous optimization of the nonlinear function f₃ and
 other fluid property models. For continuous optimization of the fluid property models two identical
 skids at the in- and outlet of the active mud tank are required.
- From section experimental setup we can conclude that, it is not possible to accurately measure the entire viscosity range with one cup/bob configuration. However with the current modifications made to the Z40 cylindrical cup of Thermofisher, decent results are obtained for the viscosity range [0.02-0.15]Pas over the entire shear rate range [0-1020]s⁻¹. The results for a shear thinning fluid are comparable to results obtained with the Fann35SA. With the modified cup inside our experimental setup every 8min a rheology measurement can be obtained without human interaction. With more data points a change in the plastic viscosity and yield point can be detected earlier, allowing us to take early countermeasures.

<u>Recommendations</u>

- We have only looked into model-based-control of a mixture consisting of purely sodium hydroxide and citric acid. If we want to apply this in the field, the model-based control needs to be tested on more complex mixtures by adding disturbances with different chemical compositions.
- The experimental setup needs to be modified on a couple of points: first the mixer needs to be
 replaced by a shear mixer and secondly a MATLAB license should be installed on the computer. Also
 some signal filtering of the Coriolis flow meter is needed to remove noise such that it can be utilized
 to update the nonlinear function. After these modifications the experimental setup is ready to start
 investigating the effect of complex mixtures on the pH and the effect of multiple additives and
 different types of viscosifiers on the rheology.
- Additives used to change the rheology most likely also have an effect on the drilling fluid pH, the relation between these two properties needs to be defined for each additive.
- There are many additives used to control the viscosity as there is lot of deviation in the geology around the world. It is not possible to make a fit for all rheology controller however this can be done regionally. Therefore a regional survey should be conducted to make a list of additives per region.
- Two things which are related to each other should be investigated, first what is the smallest representative elementary volume of the mud volume that enters the mud tank every second and secondly how to combine the measurement instruments into a compact skid. With a compact skid, after thoroughly testing, implementation of this skid can be done worldwide without requiring a lot of rig space.
- A similar approach as to how rheology properties are obtained in the experimental setup could be applied in practice. However, we would recommend investigating the design of a closed system. The preference for a closed system is primarily because of safety but secondly because of the capability of measuring the rheology at higher temperatures and pressures. With real-time rheology data at elevated temperatures and pressures we can more accurately predict the conditions at the bit.
- The concentration of certain ions in the drilling fluid like sulfide, potassium, chloride and either calcium or magnesium are important because these ions give valuable information allowing us to prevent HSE and stuck pipe incidents. An investigation should therefore be conducted to see whether concentrations up to 100.000mg/L (the concentration in reality) can be measured for these ions.

6. Nomenclature

Abbreviations

Avg	=	Average	РТ	=	Plate and plate
DG	=	Double gap	PV	=	Plastic viscosity [Pas]
DIN	=	Deutsches institut für Normung	REV	=	Representative elementary volume
HSE	=	Health, safety and environment	rpm	=	Rotations per minute
HSSE	=	Health safety security and environment	RTOC	=	Real time operating center
HTHP	=	High temperature high pressure	YP	=	Yield point [Pa]
			Z	=	Cylindrical bob/cup geometry

<u>Symbols</u>

$K_{a,b,w}$	=	Dissociation constants	f _{1,2,3}	=	Nonlinear functions
У	=	рН	Q _{in} , Q _{out,m}	=	pump rate in and measured flow rate out of the well
K _p	=	Process gain	Q	=	Flow rate
τ	=	Shear stress in Herschel-Buckley or time constant	k _h	=	Prediction horizon
T _d	=	Time delay	γ	=	Trust level
$V_{a,b}$	=	Volume of acidic/alkali control fluid	К	=	Consistency in Herschel- Buckley or process gain of H ₁
Μ	=	Molarity [mol/L]	t _{ss}	=	Time to steady-state
$C_{a,b}$	=	Concentration acidic/alkali control fluid [mmol/mL]	t_{cycle}	=	Execution frequency controller
β	=	$f_{H_2A^-}(pH) + 2f_{HA^{2-}}(pH) + 3f_{A^{3-}}(pH)$	di	=	Deviation
α	=	f _{Na} +(pH)	$\overline{\mathrm{D}}$	=	Absolute average deviation
Y _{ref}	=	Target or reference pH	i	=	titration step
Ns	=	Mixer speeds [rev/min]	V_{tot}	=	Total mud volume
A _v	=	Surface opening valve	δ	=	Unit impulse
t	=	Time	C _{a,b,ini}	=	Initial acidic/alkali concentration
а	=	Tuning parameter	$C_{a,b,tank}$	=	Concentration of acidic/alkali control fluid
V_{sp}	=	Volumetric set point of control fluid	Y 1,2	=	Drilling fluid pH into (pH_1) and out of the well (pH_2)
ý	=	Shear rate	Y 1,d	=	y1 affected by disturbances

τ_0	=	Yield stress	μ	=	Viscosity
n	=	Flow behavior index in Herschel- Buckley or number of titration step	Φ	=	Flux from control valve
h	=	Height fluid column	d	=	Diameter control valve
Δ	=	delta	H ₁ , G _{1,2}	=	Transfer functions
T_{d_valve}	=	Time delay until the last drop of control fluid is added	$T_{d_mudtank}$	=	Time delay between a drop of control fluid and pH sensor 1
$T_{d_sensors}$	=	Time delay between the two pH sensors	σ		Absolute standard deviation

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8. Appendix

8.1. Experimental setup

8.1.1. Calculations



Figure 35: illustration of the excel sheet which we utilized to calculate the time delay by changing the length and diameter of the tubes and the flow rate

8.1.2. Volume balance

An overview of the components of the experimental setup contributing to the volume balance is given in Figure 36 below.



Figure 36: overview of main experimental setup components contributing to mass balance, with $Q_{out,w}$ = fluid loss to the formation, $Q_{in,d}$ = inflow of disturbance (could be zero in reality but still change y_1) which has an effect on pH_1 which is measured with pH_2 , Q_{in} = pump rate into the well, $V_{mudtank}$ = volume in mud tank, $Q_{out,m}$ = measured flow rate out of the well, $V_{components}$ = volume in the experimental setup other than the mud tank, V_{sp} = volumetric set point given to the valve, $V_{a,b}$ = total quantity of control fluid added to the system and Φ = flux i.e. the flow rate of control fluid

Because $V_{components}$ is constant (fixed dimensions), the volume balance in the mud tank $V_{mudtank}$ can be described according to:

30
$$\frac{dV_{mudtank}}{dt} = (Q_{out,m} - (Q_{in} + Q_{in,d} - Q_{out,w}) + \phi)$$

In this project we do not look at fluid losses and therefore equation 30 reduces to:

31
$$\frac{dV_{mudtank}}{dt} = (Q_{out,m} - (Q_{in} + Q_{in,d}) + \phi)$$

8.2. Theory behind static pH model

Before we start a set of assumptions is made to simplify the model:

- Electro-neutrality balance applies here.
- The sum of all ion concentrations is below <10⁻³M, so all activity coefficients in chemical reactions are negligible.
- Dissociation constants are applicable to a mixture.
- A disturbance is either acid or base not a combination of both.
- Mixture of one acid and one base.
- In an aqueous solution, a salt consisting of a strong acid and a strong base will have no tendency to combine with hydrogen [H+] and hydroxide [OH⁻] ions.[14]

In this thesis, the goal is to maintain the pH between pH=8 and pH=9. A typical base used in the field is NaOH(sodium hydroxide a strong base) and a typical acid is $C_6H_8O_7$ (citric acid a weak acid).[15] Within aqueous solutions, citric acid will release [H⁺] ions in steps by following equation 32(a) to equation 32(c). Sodium hydroxide will release a negative ion [OH⁻] and disassociate according to equation 32(d). Water dissociates according to equation 32(e).

a) $C_6H_8O_7 + H_2O \leftrightarrow H_3O^+ + C_6H_7O_7^$ b) $C_6H_7O_7^- + H_2O \leftrightarrow H_3O^+ + C_6H_6O_7^{2-}$ 32 c) $C_6H_6O_7^{2-} + H_2O \leftrightarrow H_3O^+ + C_6H_5O_7^{3-}$ d) NaOH \rightarrow Na⁺ + OH⁻ e) $2H_2O \leftrightarrow H_3O^+ + OH^-$

Dissociation constants are used to define the relationship between the activities of the components in equilibrium with each other. As we consider the activity coefficients to be negligible and by assuming that the dissociation constants hold, those constants can be used to rewrite equations 32 into the following relationships:

33
$$K_{a1} = \frac{[H^+][H_2A^-]}{[H_3A]}; K_{a2} = \frac{[H^+][HA^{2-}]}{[H_2A^-]}; K_{a3} = \frac{[H^+][A^{3-}]}{[HA^{2-}]}; K_b = \frac{[OH^-][Na^+]}{[NaOH]}$$

34
$$K_w = [H^+][OH^-]$$

Where $A=C_6H_5O_7$ the non-reacting part of citric acid.

Table 7 shows the dissociation constants for each chemical reaction in equation 32.[14]

Dissociation constant	Value[K _{a,b}]	Log scale[pK _{a,b}]
K _{a1}	7.4*10 ⁻⁴	3.1
K _{a2}	1.7*10 ⁻⁵	4.8
K _{a3}	4.0*10 ⁻⁷	6.4
K _b	0.63*10 ⁰	0.20
K _w	$1.00*10^{-14}$	14

Table 7: reaction dissociation constants at 25C^o

Depending on the concentration of $[H^{+}]$, a reaction goes to the right or left. With the following fundamental logarithmic function we can relate y(pH) to the concentration of $[H^{+}]$ ions and thereby obtain an idea of the direction of the reaction:

35
$$y \cong -\log[H^+]$$

As the total concentration of acid(C_a) is the sum of all $[H_nA]$ concentrations with (A=C₆H₅O₇) and the total concentration of base(C_b) is the sum of [NaOH] and $[Na^{+}]$:

36
$$C_a = [H_3A] + [H_2A^-] + [HA^{2-}] + [A^{3-}]$$

 $C_b = [NaOH] + [Na^+]$

We can solve for each part of the acid concentration by replacing the other with help of the relationships defined by the dissociation constants (equation 33). The hydroxide term [OH-] can be replaced with help of the water dissociation equation 34. For example, we can solve for $[H_3A]$ and [NaOH]:

 \downarrow

$$C_{a} = [H_{3}A] + \frac{K_{a1}[H_{3}A]}{[H^{+}]} + \frac{K_{a1}K_{a2}[H_{3}A]}{[H^{+}]^{2}} + \frac{K_{a1}K_{a2}K_{a3}[H_{3}A]}{[H^{+}]^{3}}$$

$$C_{a} = [H_{3}A] \frac{[H^{+}]^{3} + K_{a1}[H^{+}]^{2} + K_{a1}K_{a2}[H^{+}] + K_{a1}K_{a2}K_{a3}}{[H^{+}]^{3}}$$

$$B_{b} = [NaOH] \left(1 + \frac{[H^{+}]}{K_{w}}K_{b}\right)$$

By assuming that the concentrations of $acid(C_a)$ and $base(C_b)$ consist purely of citric acid and sodium hydroxide, we can derive dimensionless functions(f_x) for each component in the mud tank depending on concentration [H⁺]:

39

$$\begin{split} f_{H_{3}A}(H^{+}) &= \frac{[H^{+}]^{3}}{[H^{+}]^{3} + K_{a1}[H^{+}]^{2} + K_{a1}K_{a2}[H^{+}] + K_{a1}K_{a2}K_{a3}} \\ f_{H_{2}A^{-}}(H^{+}) &= \frac{[H^{+}]^{3} + K_{a1}[H^{+}]^{2} + K_{a1}K_{a2}[H^{+}] + K_{a1}K_{a2}K_{a3}}{[H^{+}]^{3} + K_{a1}[H^{+}]^{2} + K_{a1}K_{a2}[H^{+}] + K_{a1}K_{a2}K_{a3}} \\ f_{HA^{2-}}(H^{+}) &= \frac{[H^{+}]^{3} + K_{a1}[H^{+}]^{2} + K_{a1}K_{a2}[H^{+}] + K_{a1}K_{a2}K_{a3}}{[H^{+}]^{3} + K_{a1}[H^{+}]^{2} + K_{a1}K_{a2}[H^{+}] + K_{a1}K_{a2}K_{a3}} \\ f_{A^{3-}}(H^{+}) &= \frac{K_{a1}K_{a2}K_{a3}}{[H^{+}]^{3} + K_{a1}[H^{+}]^{2} + K_{a1}K_{a2}[H^{+}] + K_{a1}K_{a2}K_{a3}} \\ f_{NaOH}(H^{+}) &= \frac{1}{1 + \frac{[H^{+}]}{K_{W}}K_{b}} \\ f_{Na^{+}}(H^{+}) &= \frac{1}{\frac{K_{W}}{[H^{+}]K_{b}} + 1} \end{split}$$

40

We have now defined all the components of a mixture of citric acid and sodium hydroxide in dimensionless variables depending only on $[H^+]$. When we fill this into the electro-neutrality equation, we obtain:

41
$$[H_2A^-] + 2[HA^{2-}] + 3[A^{3-}] + [OH^-] = [Na^+] + [H^+]$$
$$[H_2A^-] + 2[HA^{2-}] + 3[A^{3-}] + \frac{K_w}{[H^+]} = [Na^+] + [H^+]$$

We are left with two unknowns C_a and C_b:

42
$$C_b \cdot (f_{Na^+}(H^+)) - C_a \cdot (f_{H_2A^-}(H^+) + 2f_{HA^{2-}}(H^+) + 3f_{A^{3-}}(H^+)) = [H^+] \cdot (\frac{1 \cdot 10^{-14}}{[H^+]^2} - 1)$$

If we replace the concentration $[H^{\dagger}]$ with y the pH according to the inverse of our logarithmic function, the differences in ionic concentration X as function of pH can be written as:

43
$$X = 10^{-y} \left(\frac{1 \cdot 10^{-14}}{(10^{-y})^2} - 1 \right) = C_b \cdot \left(f_{Na^+}(y) \right) - C_a \cdot \left(\frac{f_{H_2A^-}(y) + 2f_{HA^{2-}}(y)}{+3f_{A^{3-}}(y)} \right) \downarrow$$
$$X = \alpha \cdot C_b - \beta \cdot C_a$$

Where $\alpha = f_{Na^+}(y)$ and $\beta = f_{H_2A^-}(y) + 2f_{HA^{2-}}(y) + 3f_{A^{3-}}(y)$ are called the charge coefficients. The effect of the dissociation constants and the pH on the charge coefficients explain the non-linear behavior of the pH as can be seen in Figure 37.



Figure 37: effect of pH on charge coefficient citric acid and sodium hydroxide

Using the charge balance we can compute the new concentration of acid and base if a disturbance, a quantity of acidic or alkali fluid, has entered the well:

$$\text{if } X_{new} < X_{old} \rightarrow C_{a,new} = \frac{c_{b,old} \cdot \left(\alpha_{new} \frac{V_{old}}{V_{new}} - \alpha_{old}\right) + \beta_{old} C_{a,old} - (X_{new} - X_{old})}{\beta_{new}}, C_{b,new} = C_{b,old} \cdot \frac{V_{old}}{V_{new}}$$

$$\text{if } X_{new} > X_{old} \rightarrow C_{b,new} = \frac{(X_{new} - X_{old}) + \alpha_{old} C_{b,old} - C_{a,old} \cdot \left(\beta_{old} - \beta_{new} \frac{V_{old}}{V_{new}}\right)}{\alpha_{new}}, C_{a,new} = C_{a,old} \cdot \frac{V_{old}}{V_{new}}$$

44

well.

if $X_{new} > X_{old} \rightarrow C_{b,new} = \frac{(v_{new} + v_{old}) + v_{old} + v_{old} + v_{old} + v_{new}}{\alpha_{new}}$, $C_{a,new} = C_{a,old} \cdot \frac{v_{old}}{v_{new}}$ Where: "old" represents the initial conditions and "new" the conditions after a disturbance entered the Likewise by rewriting the above formula we can compute the volume which we need to add to bring the pH back to a certain set point:

$$45 \quad \text{if } \mathbf{y} > \mathbf{9} \to \mathbf{V_a} = \frac{V_{old} \left(-C_{a,old} \left(1 - \frac{\beta_{old}}{\beta_{new}} \right) - C_{b,old} \left(\frac{\alpha_{old} - \alpha_{new}}{\beta_{new}} \right) - \frac{X_{new} - X_{old}}{\beta_{new}} \right)}{C_{a,tank} + \frac{C_{b,old} \alpha_{old} - \beta_{old} C_{a,old} + (X_{new} - X_{old})}{\beta_{new}}}{\beta_{new}}$$

$$46 \quad \text{if } \mathbf{y} < \mathbf{8} \to \mathbf{V_b} = \frac{V_{old} \left(C_{b,old} \left(\frac{\alpha_{old}}{\alpha_{new}} - 1 \right) + C_{a,old} \left(\frac{\beta_{new} - \beta_{old}}{\alpha_{new}} \right) + \frac{X_{new} - X_{old}}{\alpha_{new}} \right)}{C_{b,tank} + \frac{C_{a,old} \beta_{old} - \alpha_{old} C_{b,old} - (X_{new} - X_{old})}{\alpha_{new}}}$$

So given the molar concentrations of citric acid and sodium hydroxide and initial pH, the quantity of acidic and alkali control fluid that is required to control the pH to a certain target can be simulated. Figure 38 shows the volumetric amount of 0.25M citric acid and 0.5M sodium hydroxide that have to be added to shift the pH to 8.5 given a certain initial pH.



Figure 38: ideal steady state model for pH control, $C_{a,ini}$ = 0.042M, $C_{b,ini}$ = 0.129M

8.3. Graphical validation of model

We can also look at the difference between the two titration curves by utilizing the modeled static gain $K_n^{i_model}$ instead of $K_n^{i_exp}$.

The estimated pH, $\hat{y}_1^{i+1_model}$ can be approximated by changing Equation 5 according to:

47 $\hat{y}_1^{i+1_model} = y_1^{i_exp} + K_p^{i_model} \cdot V_{a,b}^{i_exp}$

Where $K_p^{i_model}$ = static modeled process gain, $y_1^{i_exp}$ = pH value at the ith titration step and $V_{a,b}^{i_exp}$ = experimental volume of control fluid added at the ith titration step.

The error between the estimated and measured pH can be described by the following relationship:

48 error = $\hat{y}_1^{i_model} - y_1^{i_exp}$

Now we can set another hypothesis, H_0 : *"The modeled static gains are good estimate of the reality."* We reject if error >0.5, we accept if error <=0.5.

In Figure 39 the pH measured in the titration experiment is graphically compared to the estimated pH utilizing $K_p^{j_model}$.



Figure 39: error imposed by utilizing the modeled gain instead of the experimental gain for a mud volume of 0.25L and 32L From Figure 39 we can observe and conclude that we reject our hypothesis.

As mentioned in section 3.3.1.1.1, we can utilize the model and the small scale experiment to reduce the error. In Figure 40, equations 47 and 48 are utilized again to compare the pH measured in the titration experiment($y_1^{i_exp}$) to the pH calculated with $K_p^{i_est}$.



Figure 40: result of utilizing the scaled gain instead of the modeled gain

From Figure 40 we can observe and conclude that we accept the hypothesis.

8.4. Steady-state error analysis V_{tot} = 32L

By looking at the steady-state error analysis of $V_{tot} = 32L$, the operators can obtain knowledge of the real quantity of control fluid that is required to control such a mud volume. To analyze the steady-state response, we neglect the contribution of H₁ by setting Q_{in,d} to zero (equation 31) and use y₁(t=0) as input to our nonlinear function f₃.

The steady-state pH, denoted $y_1(t_{ss})$ can be described according to:

49
$$y_1(t_{ss}) = \lim_{t \to \infty} y_1(t)$$

Where a certain quantity of control fluid V_{sp} has been added at t = 0.

Then we can update the static equation 5 according to:

50 $y_{1}(t_{ss}) = y_{1}(t = 0) + K_{p} \cdot V_{sp}(t = 0)$ $y_{1}(t_{ss}) - y_{1}(t = 0) \triangleq \Delta y_{ss} = K_{p} \cdot V_{sp}(t = 0)$ $\Delta y_{ss} = K_{p} \cdot V_{sp}(t = 0)$

Where K_p is the process gain belonging to y_1 at t = 0 and V_{sp} = volumetric set point of the total quantity of control fluid that is required to shift $y_1(t=0)$ to $y_1(t_{ss})$.

The steady-state open loop control diagram is shown in Figure 41:



Figure 41: static control diagram with $y_1(t=0) =$ the initial pH, $V_{sp} =$ volumetric set point of control fluid to shift pH $y_1(t=0)$ to $y_1(t_{ss})$, $\Delta y_{ss} =$ difference between y(t=0) and $y(t=t_{ss})$, $f_3 =$ nonlinear function relating y(t=0) to V_{sp} and G = static process gain relating the input V_{sp} to a change in pH

Because we want to control the pH back into the window of operation in one step we need to know the volumetric set point V_{sp} from any $y_1(t=0)$ to y_{ref} set at 8.5. We obtain V_{sp} from the nonlinear function f_3 which for $V_{tot} = 32L$ is presented in Figure 42.



Figure 42: illustration showing the nonlinear function f_3 which relates y to V_{sp} , where y_0 = initial pH and y_{ref} = target or reference pH

The volumetric set point V_{sp} can be obtained from the nonlinear function f_3 according to:

51
$$V_{sp} = f_3(y_1)$$

Thus when the transient behavior and any other inflow of disturbances are neglected, true process gain is known and our function f_3 is the inverse of K_p . However we know that $\overline{D} = 0.19$ and therefore the volumetric set point V_{sp} is given by:

52
$$V_{sp} = a(y_1) \cdot f_3(y_1(t=0))$$

With $a(y_1)$ the tuning parameter for a particular y_1 .

The multiplication factor can be obtained with help of the nonlinear function f_3 . For example, from f_3 we obtain V_{sp} to go from y(t=0) = 6 to a pH of 8.5. If instead y at $t=t_{ss}$ equals 8, we can obtain $a(y^i)$ according to:

53
$$a(y_1(t=0)) = \frac{f_3(y_1(t=0)) + f_3(y_1(t=t_{ss}))}{f_3(y_1(t=0))}$$

Where if $y_1(t=0)<8$ and $y_1(t=t_{ss})>9$ then $y_1(t=t_{ss})$ is negative and an identical approach if $y_1(t=0)>9$. So the next time $y_1(t=0)$ equals 6 we know the correction we should apply. With this approach we can continuously update our nonlinear function f_3 . For this approach to work we require two nonlinear functions, one for acidic and for alkali control fluid instead of a combined one.

8.4.1. Steady-state experiment

The set point V_{sp} of the total quantity of control fluid that is added to the system depends on the error between y_0 and y_{ref} and is obtained from equation 52 $V_{sp} = a(y_1) \cdot f_3(y_1(t=0))$

Where $y_1 = pH$ at t=0, $a(y_1) = tuning$ parameter related to y_1 and f3 = nonlinear function relating y to V_{sp} . The initial parameters for the open-loop steady-state control approach are listed below:

Parameters	Description	Value
а	Tuning parameter	1 [-]
Y 1	pH of mud flowing to the well	[1-14] [-]
t_{cycle}	Execution frequency of steady-state controller depends on $V_{\mbox{\scriptsize sp}}$	5 [min]
f ₃	the nonlinear static function f3	Fitted curve

Table 8: parameters for steady-state open loop control approach

With this approach we check the accuracy of the nonlinear function f_3 for V_{tot} =32L. The pH correction is done during steady state conditions and in one step from any pH straight back into the window of operation.



Figure 43: steady-state open loop control approach



Figure 44: close up of graph 1 and 5 of Figure 43

The way we judge our nonlinear function f_3 is depicted in Table 9.

Table 9: the way our nonlinear function is judged

Error	Judgment
<0	Underestimating
0-0.5	Effective
0.5-1.0	Aggressive
>1.0	Too aggressive

Observations:

First we observe how good the nonlinear function f_3 is for the acidic control fluid:

- The first controller step from 11.4 to 8.5 is underestimating the process. pH₁ instead of 8.5 goes to 10.6 by adding 150ml with the tuning parameter *a* set to 1.
- The second controller step from 10.6 to 8.5 is underestimating the process. pH₁ instead of 8.5 goes to 9.55 by adding 58ml with the tuning parameter *a* set to 1.
- The third controller step from 9.55 to 8.5 is effective. pH₁ goes to 8.5 by adding 15ml with the tuning parameter *a* set to 1.
- In total 223ml was required to control the pH back to the window of operation.

After controlling the pH back to the window of operation an acidic disturbance is injected in the well which brings pH_1 down to 6.37. The inflow of disturbance into the well can be seen in the increase in flow rate *Q* in graph 2 of Figure 43. Now we can observe how good our model is for alkali control fluid.

- The first controller step from 6.37 to 8.5 is too aggressive as pH₁ instead of 8.5 goes to 10.74 by adding a 765ml with the tuning parameter *a* set to 1.
- Now our pH₁ is >10 so now acidic control fluid must be added to control the pH back to 8.5, for this again two steps are required because we did not change the tuning parameter *a*.

From manual experiments we know that 600ml of alkali control fluid was required to control pH_1 from 6.4 to 8.5. From this experiment we know that 223ml of acidic control fluid was required to control pH_1 from 11.4 to 8.5. With this knowledge we can compute the tuning parameters $a(y_1)$, the required tuning parameters are presented in Table 10.

pH value	V_{sp} calculated [ml]	V _{sp} actual [ml]	Tuning parameter a
6.37	765	600	0.78
9.55	15	15	1
10.6	58	73	1.26
11.4	150	223	1.48

Table 10: tuning parameter a defined as the ratio between V_{sp} (actual) and V_{sp} (calculated)

Conclusion

Our nonlinear model f_3 with a tuning parameter a set to 1 is unable to control the pH in one step back except for $y_1 = 9.55$. Whenever pH₁>10 the added acidic control fluid is too little whereas for an acidic pH (pH₁<7) the added alkali control fluid is too much. The required tuning parameter a for acidic control fluid seems to be increasing linearly with 0.025 per 0.1 increase in pH.

8.5. Initial test of experimental setup with batch rheology measurements

With the heuristic pH approach and the optimized rheometer an experiment is conducted to see the effect of the pH and addition of xanthan on the viscosity. Batch rheology measurements are obtained utilizing the modified cup in an open-loop experiment. Figure 45 depicts the effect of xanthan and a change in the pH on the viscosity:



Figure 45: effect of xanthan and pH on the different fluid properties



Figure 46: close up of graph 1, 7 and 8 of Figure 45

Observations

Time[s]	Observations
0	Xanthan (162gr) to achieve a 0.5% xanthan fluid is added to the mud tank until approximately t=1500s.
1872- 2011	Base flows into the well and the controller was shut off to see the effect of increased pH on the viscosity
1995	A viscosity sample shows an increase in yield point(YP) even though the pH sensors have not registered any change in pH yet. Are we seeing the effect on viscosity by pH earlier or some yet unmixed grams of xanthan, called fisheyes, which create a higher YP?
2150	pH2 starts increasing and pH1 after another 50s
2480	A viscosity sample taken, with both pH sensors at 10.82, shows the identical results as the previous sample however this time also a higher plastic viscosity(PV) is observed. This measurement is also the most viscous sample during the whole experiment. Yet another fisheye could be the case.
2751	Controller was turned on and acid was added to the mud tank
2953	A viscosity sample taken, shows identical results as at t=1513 where no disturbance was added yet
3885- 3998	Base flows into the well but this time the controller is not turned off.
4144	pH2 starts increasing and pH1 after another 202s
4393	A viscosity measurement taken shows no increase in YP/PV. Is this due to bad mixing in the mud tank or is the previous sample with pH 8 bringing down the pH in the mud tank after which again we have an average pH around 9 to which xanthan is insensitive?
4593, 4759	Acid is added to the mud tank by the controller since both pH_1 and pH_2 are outside the window of operation, the proportional controller needs to be tuned because the pH ends below 8.

In order to check the accuracy of the batch rheology measurements we compared them to the rheology measurements done with the Fann rheometer and the DG41 geometry. Results of the comparison are depicted in Figure 47 and Figure 48.



Figure 47: batch rheology measurements from Haake in time against DG41 and Fann





From Figure 47 we observe that the rheology measurements before t=2474s deviate significantly from the rheology measurements later on. From both Figure 47 and Figure 48 we can observe that the rheology measurements done with the Fann rheometer and the DG41 geometry in Haake rheometer match the last measurements done with the Z40mod geometry in the Haake rheometer.

From Figure 48 we observe that the yield point measurements do not match the yield point measurement with the DG41 geometry.

Conclusion

Xanthan was not yet completely mixed throughout the entire experimental setup until t=2474s. Without xanthan it takes 50s to measure a change in pH₁ after a change in pH₁. With xanthan it takes 201s to measure a change in pH₁ which tells us that xanthan increases the time delay between the two sensors $T_{d_sensors}$. An increase in viscosity should be taken into account because our feedback loop utilizes the pH measurement of pH₁ to change the reference pH to add the right quantity of control fluid.

Xanthan is known for its pH stability up to a pH of 10.[16] Whether the increase in YP and PV for the viscosity measurement at t=2480 was because of an increase in pH or yet another fisheye can be argued about.

Z40mod(modified Z40 geometry) fits the readings from the Fann pretty accurately. This proves that the Z40mod can be used to get reliable batch measurements for a shear-thinning fluid in the range of [0.02-0.15]Pas.