A COMPREHENSIVE CONTROL SCHEME FOR DYNAMIC INLINE FLOCCULATION OF OIL SANDS TAILINGS

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ABSTRACT

Inline flocculation is a promising technique for the dewatering and remediation of oil sands tailings. In recent years the industry has undertaken a number of exploratory programs aimed at defining the process operating windows that will produce flocculated materials with the desired properties. The major challenges related to the process include determining flocculant dosing sensitivities, mixer operating windows, influence of pipeline shear, and development of effective instrumentation technique and process control relationships. To be applicable in a field setting, the inline flocculation process must be controllable such that process disturbances can be addressed, ensuring consistent production of acceptable material. This paper presents lab-scale evaluation of a comprehensive control scheme developed by Shell for dynamic inline flocculation. A feed forward scheme is implemented to control the mixing intensity and flocculant dosage based on the properties of the fluid fine tailings and polymer. Inline image analysis and particle size measurements performed on the flocculated product are used to add a feedback trim to the scheme, accounting for the errors in the model or unmeasured disturbances. Results from the laboratory-scale tests are presented to demonstrate the efficacy of this control strategy.

INTRODUCTION

The oil sands extraction process produces significant quantities of fluid fine tailings (FFT). Producers are required to determine effective strategies to manage the volume of these tailings throughout the life of their mines. Fine clay particles can remain in suspension over long time periods and therefore intervention is required to extract water from the tailings and allow accelerated consolidation of the solids.

Inline flocculation (ILF) is one potential tailings treatment strategy currently being evaluated by Shell. In ILF a polymer flocculant is added to the tailings stream to help bind clay particles together into larger flocs, which settle more rapidly. Dynamic inline flocculation refers to the use of a moving mixing element to blend the polymer with the tailings, ensuring effective contact between the clays and the flocculant. Two challenges involved in the implementation of an ILF scheme are maintaining an optimal flocculant dosage and an optimal level of mixing, regardless of process disturbances, such as changes in input properties or flow rates.

The required amount of additive depends on the solids content of the tailings stream as well as the clay content of the solids. Both insufficient and excessive polymer dosages result in inferior treatment performance. Also, excessive dosing results in unnecessary costs as flocculants are expensive chemicals. Similarly, the amount of mixing must be maintained at an optimal level to ensure that the additive is blended effectively, while avoiding excessive shear which can be undesirable for the deposition strategy. The required mixing intensity varies with flow rate as well as the solids and clay content of tailings.

Unfortunately these challenges can be difficult to overcome using standard instrumentation and control techniques. Determination of the tailings clay content can be particularly challenging, and while the use of a dynamic mixer allows easy variation of the amount of mixing, finding the optimum level is non-trivial. Other elements of the ILF process also require attention, such as selection of the mixer design, and the polymer and tailings delivery systems. This paper presents a comprehensive control system developed by Shell to optimize the commercial implementation of the ILF process.

FLOCCULATION APPARATUS

In this study a laboratory apparatus operating around the 10 m^3/h scale was used. However the control strategies that have been developed should also be applicable at much larger scales. In the current laboratory setup, FFT was fed into a 5" pipeline equipped with an inline mixer. Polymer was injected just upstream of two hydrofoil impellers as shown in
Figure **1**. Samples were collected at the discharge from the pipeline several meters downstream of the mixer. Various sensors were placed upstream and downstream of the mixer, as described in the following section.

Figure 1. Photograph of an inline mixer with a polymer injector directly upstream of dual hydrofoil impellers.

CONTROL SYSTEM

Two standard control architectures are feedforward and feedback control. In feedforward control, input disturbances are measured and a model is used to determine the required control action to compensate (see Figure 2 (a)). Feedback control does not require a model, and instead measures an output parameter and adjusts the controlled variable based on the deviation from the desired setpoint (Figure 2 (b)). An advantage of feedforward systems is that they can compensate for upstream disturbances before they have a chance to impact performance. However they require an accurate process model to respond appropriately and therefore it is inevitable that there will be some discrepancy between the desired and actual results due to deficiencies in the model. Feedback systems can achieve a target setpoint regardless of unexpected behaviors, provided an appropriately accurate measurement of the performance metric can be made.

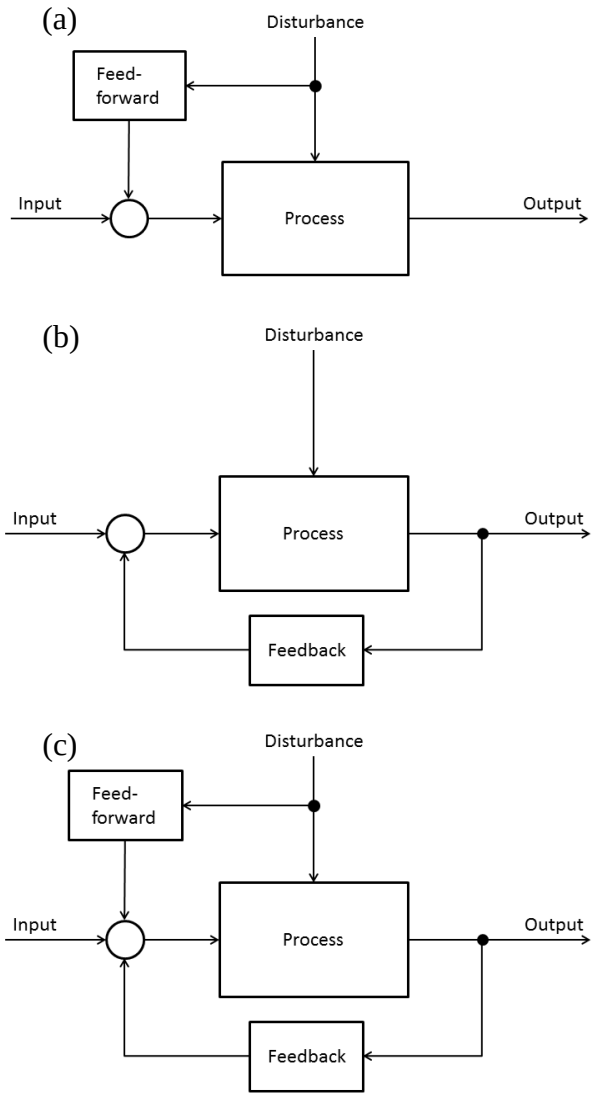

Figure 2. Block diagrams for (a) feedforward, (b) feedback, and (c) feedforward with feedback trim control systems.

Feedforward and feedback control can also be combined, where the feedback signal is used to

"trim" the control action after the feedforward adjustments are made (Figure 2 (c)). This combined scheme has been selected for the Shell ILF process to control the impeller speed of the dynamic mixer. A feedforward-only system is used to control the polymer dosage on a tailings stream standardized to a desired density.

Polymer Delivery

Flocculant dosages are typically quoted in terms of grams of polymer per tonne of solids in the tailings, where the optimal solids based dosage depends on the clay content of those solids. The required polymer flow rate therefore depends on the flow rate of the tailings stream as well as its properties and the properties of the polymer solution (1):

$$Q_{poly} = f(Q_{FFT}, \rho_{FFT}, \beta, \phi_{poly}) \quad (1)$$

where Q_{poly} and Q_{FFT} are the flow rates of polymer and FFT respectively, ρ_{FFT} is the FFT density, ϕ_{poly} is the solid polymer fraction, and β is the polymer dosage. With a known FFT flow rate, the FFT density, polymer concentration and desired dosage need to be determined to control for the appropriate amount of polymer delivery.

FFT Density

The density of the tailings was measured using an Endress and Hauser Gammapilot nuclear densitometer with a Cs-137 source. The source container was placed on one side of the FFT feed pipe and the detector on the other, allowing the absorption of the gamma rays to be used to measure the density of the material in the pipe. A first principles estimation of the calibration coefficient, combined with a pure-water calibration under-reported the density by 1-2.5%. An in-situ calibration with FFT across the range of expected densities was performed to further improve the accuracy.

Polymer Concentration

As the polymer concentration can vary with some preparation techniques, we infer the value through a measure of the solution viscosity. An Anton Paar L-Vis 510 inline viscometer was calibrated for this purpose. Figure 3 shows a photograph of the viscometer. Internally the viscometer consists of a partially open tube containing a rotating cylindrical shaft, which is inserted into the polymer pipeline. The inner bob rotates and draws fluid into the gap. The outer cylinder is split and a sensor measures a deflection caused by the fluid flowing in the gap that depends on the viscosity. Polymer solutions with varying concentration and temperature were measured and a calibration was developed to yield the concentration as a function of measured viscosity and temperature.

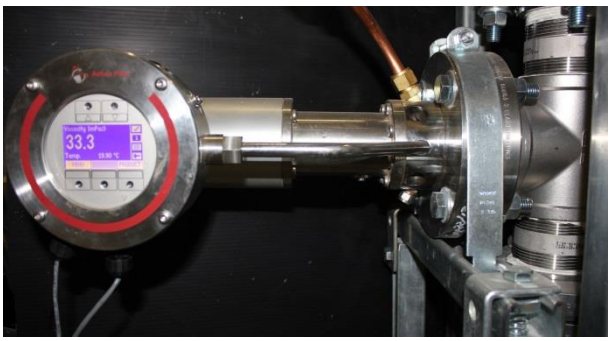

Figure 3. Anton Paar L-Vis 510 inline viscometer.

Desired Optimal Polymer Dosage

The desired polymer dosage is directly correlated to the feed FFT. A Bruker Matrix-F near-infrared (NIR) spectrometer was used to measure the clay content of the FFT. NIR reflection spectra were obtained for a series of calibration samples with varying clay content, prepared by blending several master sources in varying ratios. Example spectra are shown in Figure 4. A chemometric analysis using the partial least squares approach was performed to develop a calibration relating the spectra to the clay content of the tailings, as represented by the methylene blue index (MBI). The NIR region between 4200 and 7500 cm^{-1} (1.3 to 2.4 µm) was used for the calibration. This analysis allowed an effective calibration to be found despite the fact that the clay peaks are relatively weak and obscured by strong water interactions. Figure 5 shows example validation results for the calibration performed with two data-preprocessing techniques. The validation procedure steps through each sample spectra and removes it from the calibration set before calculating the estimated value based on the data from the rest of the samples. Good agreement is achieved, demonstrating that the NIR system is capable of measuring the MBI of the samples.

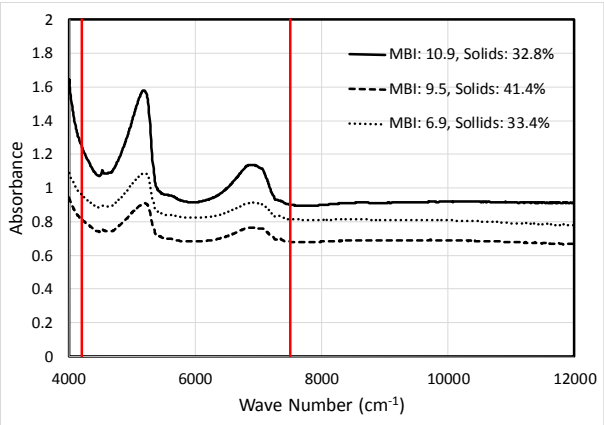

Figure 4. Example NIR reflectance spectra for three FFT samples. The region between the red lines was used for the calibration analysis.

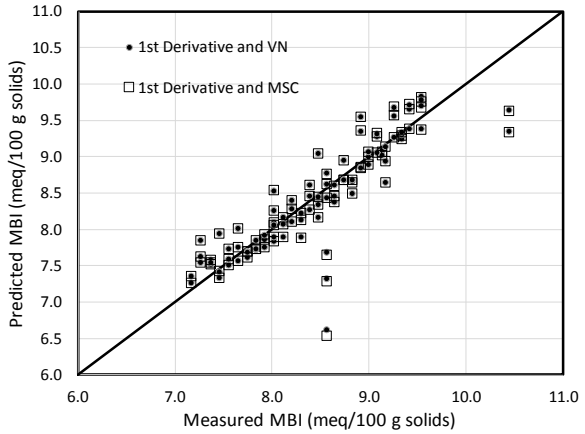

Figure 5. Example validation results for the NIR calibration for data pre-processing methods two methods: 1st deverivative with vector normalization (VN) and 1st derivative with multiplicative scatter correction (MSC).

A pipe spool was fabricated with a sapphire window to allow optical access to the FFT flowing in the feed pipeline. A Bruker emission head was used to illuminate the window and collect the reflectance spectra as shown in Figure 6. The Bruker software was set to automatically perform an analysis once every 20 seconds and the resulting MBI value was transmitted to the control system using an analog output card.

Figure 6. Custom pipe spool with NIR sensor head attached.

To determine the optimal dosage a series of approximately 150 laboratory flocculation experiments were conducted using several FFT feeds with different MBI and density. The dosage and mixer speed were varied and an optimal value for dosage was selected for each feed material based on an analysis of dewatering and rheology metrics. An optimal mixing intensity was also selected, as described in the following section. Once the optimal values were determined, the optimal dosage was fitted as a function of density and MBI:

$$\beta = f(\rho, \mathrm{MBI}) \qquad (2)$$

With this we now have all of the data required to calculate Q_{poly} using equation (1) and can program the control system to implement feedforward control.

MIXER SPEED

The feedforward aspect of the mixer speed control was developed similarly to the system described above for polymer delivery. The desired mixer speed was calculated using the following functional relationship (3):

$$N = f(K, Q_{FFT}, Q_{poly}, D) \qquad (3)$$

where N is the impeller speed, D is the impeller diameter and K is proportional to the amount of

mixing required and is a function of density and MBI. This dependence was established by prior work (Gomez 2016). In the current work we added an additional functional dependence (4) for *K*:

$$K = f(\rho, \mathrm{MBI}) \qquad (4)$$

Again the data on the optimal levels of mixing for each feed were fitted to establish this relationship.

Feedback Trim

Equation (4) enables feedforward control of the mixer speed, however the optimal mixer speed is difficult to predict accurately. Therefore a feedback trim element is desirable to bring the level of mixing to an optimal level based on the measured flocculation results. Two instruments were investigated to provide online measurements of the properties of the flocculated tailings stream: the Particle Vision and Measurement (PVM) system and the Focused Beam Reflectance Measurement (FBRM) system, both from Mettler-Toledo.

The PVM is essentially an in situ microscope, capturing close-up images of the tailings flowing in the pipe. A sapphire window located at the end of a shaft that protrudes into the pipe allows the recording of images of the process material. Illumination is provided by six pulsed lasers behind the window. We operated the camera at a framerate of 5 Hz, the maximum rate which provided consistent timing. The 1360×1024 pixel greyscale images correspond to a ~ 1075×825 µm area, for a nominal resolution of ~ 0.8 µm/pixel. Figure 7 shows a photograph of the PVM head. Figure 8 shows sample images of untreated and flocculated FFT, with much more structure apparent in the flocculated example.

Figure 7. PVM V819 instrument head.

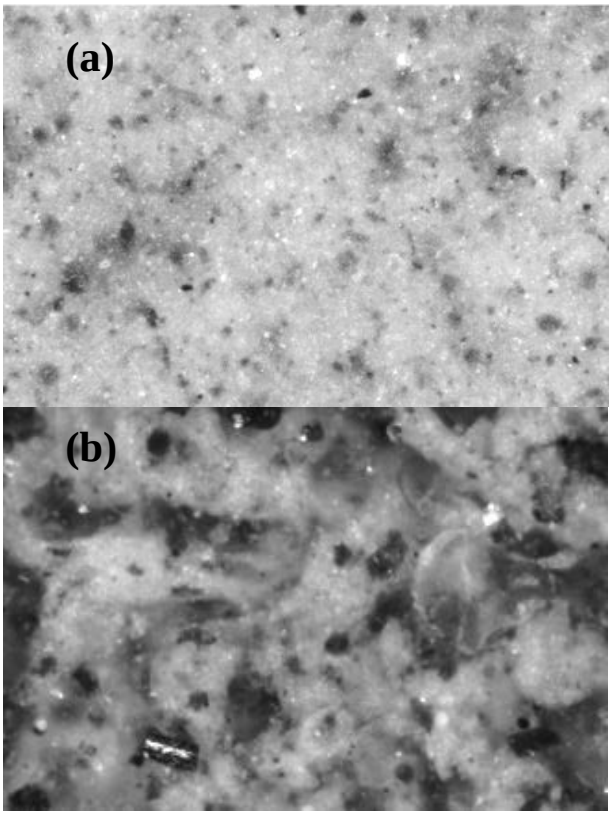

Figure 8. Example PVM images of (a) untreated and (b) flocculated FFT.

The FBRM system also uses a cylindrical probe that is inserted into the process pipeline. A miniature air motor sweeps a focused laser spot around a circular pattern through the sapphire window and measures reflectivity as a function of time. By analyzing changes in this reflectivity signal the FBRM deduces a “chord-length distribution” for particles in the process fluid, returning one distribution every 2 seconds. The chord length distributions are very similar to particle size distributions, in that they give a particle count as a function of “length” but the chord length corresponds to the distance traversed across the particle by the laser, which is not necessarily the true size of the particle. Figure 9 shows an example chord length distribution from flocculated FFT.

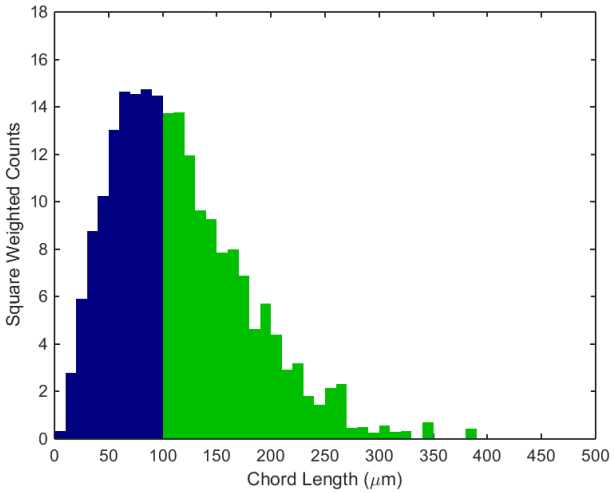

Figure 9. Example FBRM chord length distribution. The number of counts above a threshold of 100 µm (green area) has been identified as being correlated with the flocculation quality of the material.

To control the mixer, the ideal feedback measurement would give a signal that is monotonic with mixer speed, and has a well-defined optimal value to use for the controller setpoint. There are many ways to process the data from the PVM and FBRM instruments. Unfortunately it appears that most simple metrics can suffer from a lack of a universal optimal setpoint across multiple types of feed and can also exhibit non-monotonic behaviour. For example, one image metric is the coefficient of variation (CoV): the standard deviation of the image brightness divided by the mean brightness. The CoV can be observed to increase during the flocculation process. However, for certain tailings feeds a value of around 0.2 might be optimal, while for another feed type a value of 0.3 would be superior. Additionally, the CoV has been observed to saturate at high levels of mixing.

Similarly for the FBRM, one possibility is to monitor the number of counts for chord lengths above some threshold size, possibly corresponding to the presence of flocs. However, the desirable absolute value of these counts similarly seems to depend on the feed material. This FBRM metric exhibits a peak at a certain degree of mixing and for increased mixing intensity the number of counts can decrease. While this can make sense intuitively as flocs may break down and become smaller at high mixer speeds, the position of this peak does not appear to be universal and implementing a peak finding algorithm in the control system would be more complicated than a traditional simple feedback controller.

We have chosen to explore the concept of evaluating the "mixing state" of the material in order to address these difficulties. Figure 10 shows a schematic diagram illustrating the relationship between the integrated mixing intensity or "amount of mixing" and the dewatering and strength properties of the flocculated material. Four mixing states have been identified. At low levels of mixing the flocculant is not distributed properly resulting in poor dewatering and strength for the treated material (state 1, undermixed). Increased mixing improves both dewatering and strength with the region of the peak in material strength denoted as state 2, well-flocculated. With further mixing the dewatering remains high and possibly increases slightly, while strength declines (state 3: sheared). With excessive mixing the strength continues to decrease while dewatering remains similar or declines slightly (state 4, oversheared).

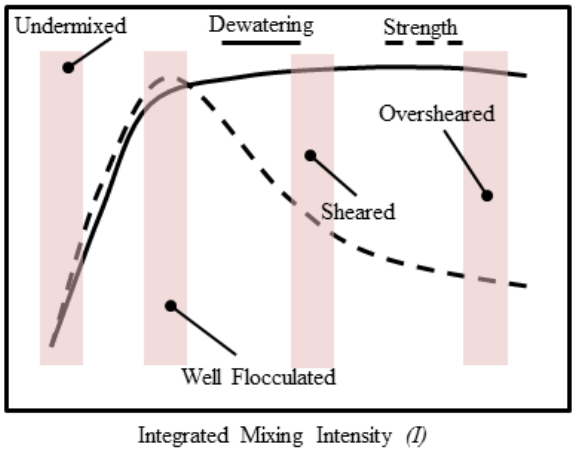

Figure 10. The relationship between the integrated mixing intensity and the mixing state. Dewatering (solid line) increases with mixing intensity before levelling off at high levels of mixing. Material strength (dashed line) increases to a maximum and then declines for excessive mixing. Four generic mixing states have been identified: undermixed, well flocculated, sheared, and oversheared.

While the actual dewatering and strength properties that are achieved can vary significantly for different tailings materials, the trends in mixing state are consistent for varied levels of mixing

intensity. If we can use the feedback instruments to estimate a mixing state for the material then we can select a desired setpoint value for our controller. The mixing state should be monotonic with mixer speed. The optimal setpoint can be selected based on operator requirements, perhaps at a value of 2 for well flocculated, or 3 if more shear is desirable. Fractional values such as 2.5 are also possible.

The algorithms used to estimate the mixing state based on the instrument outputs are the subject of previous work (Veenstra et al. 2016). An "eigenface" analysis technique (Turk and Pentland 1991) was used to process the PVM images and a maximum likelihood classifier was used to match the results with one of the mixing states. Additional information from the FBRM and even the instruments can also be incorporated into the classification routine to improve results.

The estimate of the mixing state from the feedback system can now be used to trim the feedforward output. A simple feedback controller uses the estimated mixing state for the measured variable and compares that to the mixing state setpoint. The resulting control action is summed with the feedforward signal and sent to the mixer speed controller. The result is a system that uses the instrument feedback to reach the desired setpoint, but responds quickly the feed disturbances in flow rate, clay content, or density without having to wait for the material to go off-specification. Additionally, keeping the speed close to optimal with the feedforward system should make it easier for the feedback system to perform correctly by avoiding wildly varying conditions.

LABORATORY TEST RESULTS

We present results from preliminary laboratory testing. The feedforward system was implemented along with feed standardization. The feedback system was not used to actively adjust the mixing speed, but data was recorded and post-processed to provide information about how the system would have responded.

Two experiments are described here. For the first test, the system was started with one batch of FFT and the control system was enabled. After the system was stable, data was recorded for approximately 100 s and then the FFT feed source was manually changed to a different tank containing a second batch of FFT with higher density and clay content. Figure 11 shows data recorded during the experiment. The top pane shows the standardized FFT flow rate, which was held constant during the experiment. The measured MBI value jumped up shortly after the feed tank was switched. This resulted in immediate increases in the mixer speed, *N*, and polymer flow rate, though the later had a slower control loop response. The density of the FFT feed also increased at the tank switchover, resulting in an increase in the feed standardization dilution water, which eventually brought the density back down to the target of 1190 kg/m^3. The feed standardization implementation used here had a slow response time. The polymer flow rate and impeller speed declined slightly from their peak as the density dropped to its final value.

Samples were collected during the steady state periods just before the tank change and at the end of the test. The capillary suction time (CST) dewatering metric rose slightly from 8 s to 36 s and the peak yield fell from 99 Pa to 39 Pa. Results from a permeability index test remained constant. The results for the second set of samples from the high MBI material were not as good as those for the initial samples, however the feedforward system had not been tuned for the materials used in the experiment, and additionally it was not necessarily expected to achieve the same absolute results for the different feed types. The goal was to achieve the best possible results for the given feed and to at least maintain acceptable performance.

The bottom pane of Figure 11 shows the estimated mixing state from the feedback system. The results changed in character after the switch in feed tank, delayed by the time it took for the material to make it through the mixer to the discharge instruments. The estimated mixing state value became more variable and dropped slightly. The variability can be handled by a smoothing algorithm. In this case it appears that if the target mixing state were the initial value of "3" then feedback trim would have slightly increased in mixer speed after the feed change.

The results of a second control test are shown in Figure 12. Again the experiment was started with one type of FFT and allowed to reach a steady state. This time, before switching to a different FFT tank, the feedforward control system was disabled at the 125 s point and the feed tank was switched (the feed standardization system was manually adjusted to maintain a constant density). This time

there was no immediate response in polymer flow rate or mixer speed when the MBI increased. The sample CST worsened from 8 s to 20 s and the peak yield dropped from 96 Pa to 38 Pa. The permeability index test result dropped dramatically. Feedforward control was re-enabled at the 300 s point, causing an immediate increase in polymer flow rate and mixer speed. The final sample had a slightly lower CST of 14 s, a much higher peak yield of 125 Pa, but the permeability value did not recover to the previous value, likely due to the higher MBI of the material.

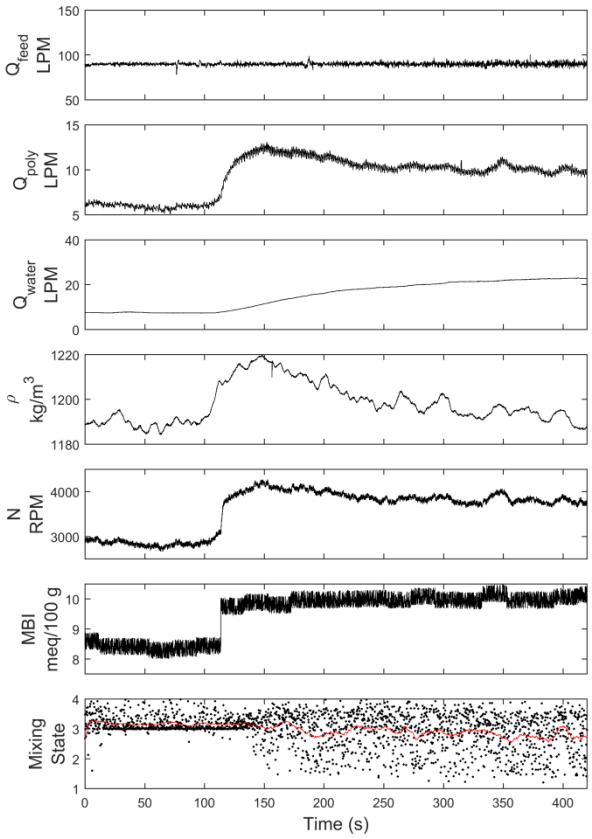

Figure 11. Results from the first feedforward control test. The FFT feed tank was switched at around the 100 s point. From top to bottom the charts show Q_{feed} (standardized), Q_{poly}, ρ_{FFT}, N (mixer speed), MBI, and the estimated mixing state from the feedback system (not used for control). The red line in the bottom mixing state plot is a moving average.

The estimated mixing state results started at slightly above 3, perhaps indicating that the material was being mixed somewhat excessively. After the tank was switched with control disabled the mixing state dropped significantly, as expected because the higher MBI material should require more mixing. When control was re-enabled the estimated mixing state returned close to the previous value, indicating that the feedforward system had acted appropriately. In this case it appears that the feedback system would not have been required to trim to final mixer speed.

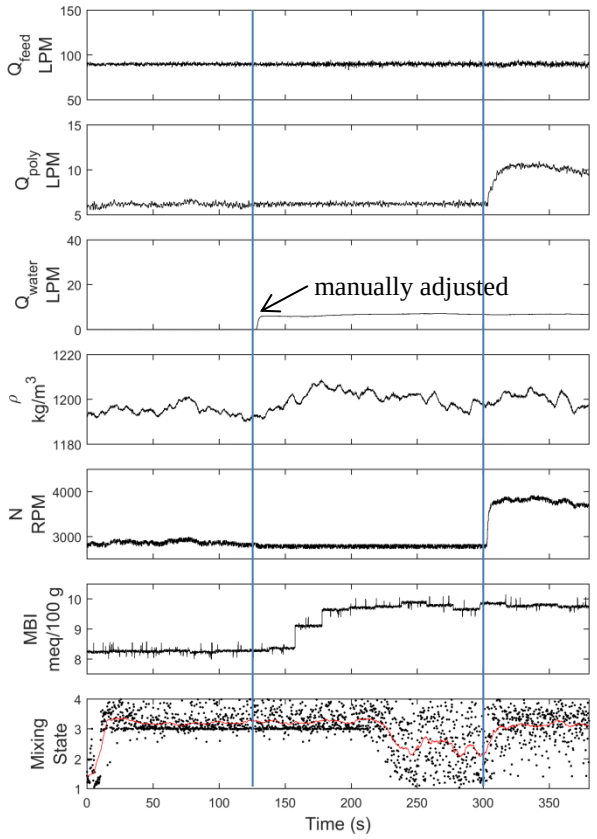

Figure 12. Results from the second feedforward experiment with the same charts as shown in Figure 11. Control was disabled at the 125 s and the FFT feed tank was switched. After a second steady state was reached, control was re-enabled at the 300 s point.

CONCLUSION

This paper presents a scheme that provides feasible solutions to many of the control issues that can affect commercial success of the inline

flocculation process, including adjusting polymer dosage and mixing intensity based on FFT feed properties, compensating for polymer concentration fluctuations, and providing an online estimate of flocculation quality.

Future trials are planned at the pilot scale to further evaluate and adjust the scheme, including implementation of the real-time feedback trim component.

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