Dynamic modeling of a paper machine, part II: evaluation of wet-end model dynamics

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ABSTRACT: Dynamic models that can predict the performance of a paper machine are a valuable asset both to industry and to the research community. This study evaluated the performance of a simulator package developed in Matlab® with Simulink® for modeling the wet-end of a pilot paper machine. The data produced by the model were compared to data collected during the operation of a pilot-scale paper machine.

The model was able to simulate the process dynamics with reasonable accuracy. The average errors of the simulated values of lithium concentration in the headbox, mixing chest, and white water trough, were calculated as 2.6%, 5.1%, and 9.3%, respectively, after step addition of lithium chloride (LiCl) solution; 3.7%, 4.4%, and 38.6%, respectively, after pulse addition of LiCl solution; and 2.2%, 4.6%, and 1.6%, respectively, after step reduction of LiCl solution.

Application: This study presents a useful method for evaluating the dynamic capabilities of a paper machine mass balance simulation, as well as verifying the practical benefits of the simulation.

Stronger competition and increased pressure to reduce emissions have led to leaner manufacturing and tighter controls on wastewater release within the paper industry. To facilitate the necessary increases in efficiencies and decrease waste, it is important to have a dynamic model capable of predicting the effects of disturbances within the system. A dynamic model can describe the intermediate system behavior that occurs during a disturbance, rather than the result only, as with steady-state models.

In this work, we tested the capabilities of a model we previously developed [1] for a pilot-scale paper machine to simulate wet-end dynamics (see **Fig. 1** for a wet-end schematic). The model was used to simulate three disturbances to a paper machine, and the modeled results were compared to those measured for a lithium tracer during a pilot-scale run.

METHODS AND MATERIALS

To obtain the data for testing the dynamic model, lithium chloride (LiCl) was introduced into the paper machine during a pilot run and samples were taken at various points to analyze the lithium concentration. Lithium was chosen for two primary reasons: (1) the addition of a small amount of lithium would not impact the results of the run and interfere with the objectives of the trial, and (2) lithium can be easily detected at low concentrations using inductively-coupled plasma (ICP) spectrometry. The lithium source was lithium chloride dissolved in water.

The LiCl solution was added as a step increase, a pulse, and then a step decrease. To facilitate a precise step increase and decrease, a metering pump was used to add the LiCl. The LiCl solution was fed into the mouth of the thick stock line leaving the stuff box. Before and after the start of the metering pump, samples were taken from three points on the paper machine: (1) the recirculation line from the headbox, which has the same concentration as the headbox stock, (2) the mixing chest, and (3) the white water trough, close to the mouth of the line which leads to the mixing chest.

With the metering pump still running, the start of the experiment was delayed to allow the process to reach equilibrium. A pulse input of 100 g of lithium chloride solution was then added to the thick stock line leaving the stuff box. After the pulse input, additional samples were collected at the three sampling points. Samples were taken until the machine reached steady state with respect to lithium concentrations.

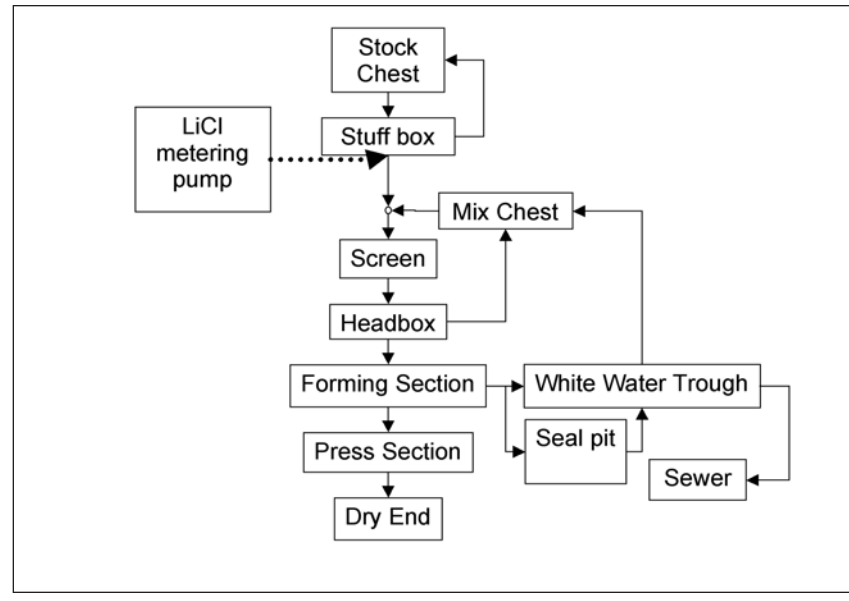
After sampling was completed for the pulse addition of lithium to the paper machine, an additional waiting period was observed to allow the process to reach steady state once again. The metering pump was then turned off, resulting in a step decrease in lithium concentration, and samples were again taken at the three sample sites until steady state was achieved.

Lithium testing

The samples that were collected during the trial were tested using ICP spectrometry to determine the lithium concentration. To prepare the samples for testing, each sample was filtered to remove large solid particles which would otherwise clog the small tubes in the ICP spectrometer. The first 10–20 mL of the sample passing through the filter was discarded, and the next 50–100 mL of the filtered sample was collected and analyzed in the ICP spectrometer. The

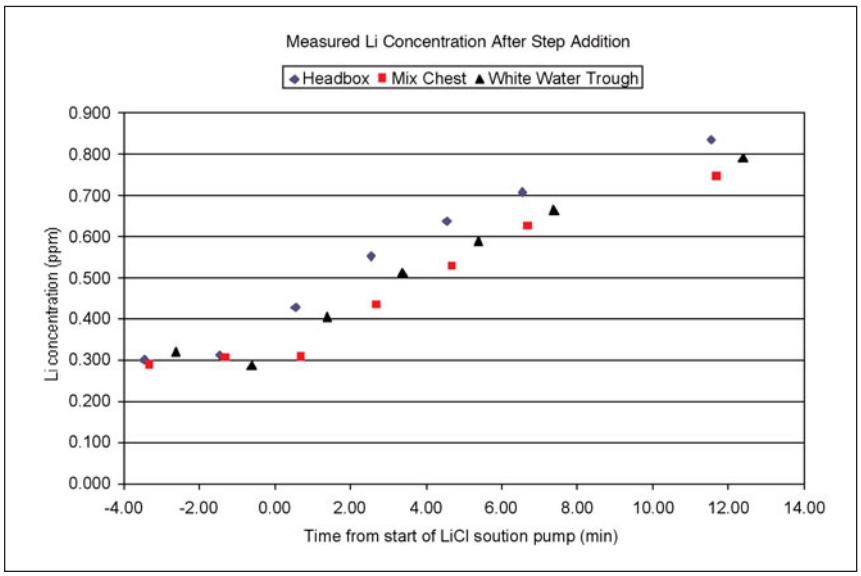
lithium concentration can be measured in the spectrometer using a number of different wavelengths. Due to the abundance of other elements and molecules in the samples, interference was encountered at some of the wavelengths which can be used to measure lithium. The 610.4 nm wavelength gave results with the lowest interference values.

Figure 2 shows the lithium concentrations at the three sampling points for the step addition of lithium chloride solution. The negative time values for the first three points indicate that these samples were taken before the step addition. The 0.3 ppm concentration of lithium before the step addition indicates that there is already lithium in the system, which will have to be taken into account when assessing the model. As expected, the lithium first shows up in the headbox after a time delay equal to the transport time from the outlet of the thick stock line from the stuff box to the headbox. After an initial high response, there is a gradual increase in lithium concentration due to buildup in the system and loop transport delays. The mass within the white water trough reduces the initial response, while the mass within the mixing chest eliminates the initial response almost completely.



1. Flow diagram of wet end of pilot-scale paper machine.

Figure 3 shows lithium concentrations after the pulse addition of 100 g of lithium solution to the stuff box. The one sample with a negative time value was taken before the LiCl pulse addition. The lithium concentration at this point reflects the original baseline value plus the effects of the step addition discussed before. The headbox exhibits an initial high response to the pulse addition, followed by a drop as the pulse passes through the headbox. There is a second lithium concentration increase in the headbox as the pulse makes its way back through the recycle loop, after which a gradual decrease is observed. The white water trough and mixing chest show a high initial response followed by a gradual decrease in concentration due to mass holdup.



2. Lithium concentrations in the headbox, mixing chest, and white water trough for step addition of lithium chloride solution.

Figure 4 shows lithium concentrations after the metering pump for the lithium chloride solution was shut off. The original level of lithium in the system is equal to a baseline value plus a contribution due to the earlier step addition of lithium. The decrease is first seen in the headbox as soon as the lithium addition to the thick stock is stopped. The mass holdup within the mixing chest results in a slow decrease of lithium concentration in the white water which is fed back into the system as dilution water.

Modeling of PM1 for lithium trial

To simulate the paper machine for the lithium trial, some modifications were made to the paper machine model previously developed for the pilot-scale paper machine [1]. A chemical signal was designated as lithium, and an additional output port was added to the mixing chest

which provided a signal representing the lithium concentration in the chest. The modeled value of the lithium concentration in the mixing chest was calculated as the mass of lithium in the chest divided by the mass of water in the chest.

An output was also added to the selective mixer block that was used to simulate the white water trough. The new output carries the same signal as the primary flow from the white water trough, except that the time delay is not applied to this signal. The samples for lithium chloride that were taken from the white water trough were taken from a point close to the outflow and should be well represented by the new output signal. The modeled concentration of lithium in the white water trough is calculated as the mass flow rate of lithium divided by the mass flow rate of water.

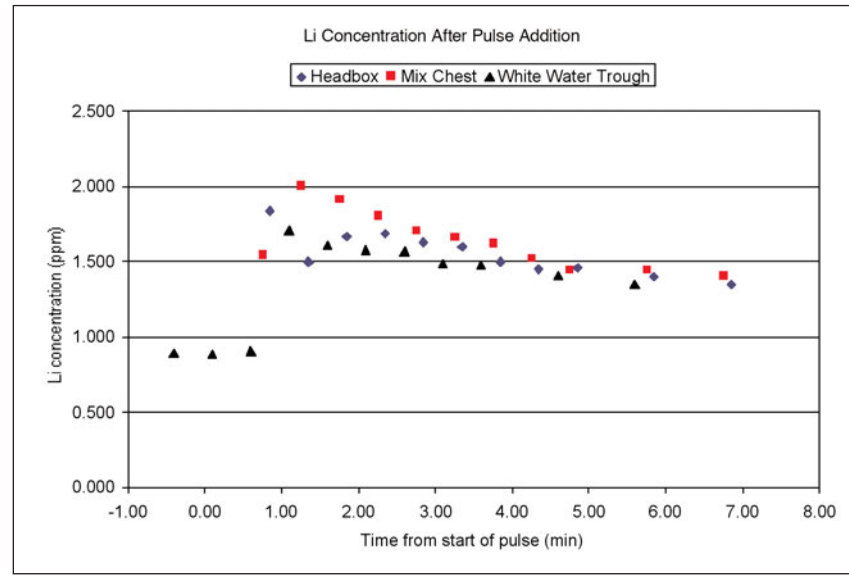
The samples for headbox lithium concentration were taken from the headbox recycle line at the mixing chest end. To determine a simulated value for the modeled lithium concentration at the headbox, the signal from the headbox recirculation port to the mixing chest was branched and the lithium flow rate was divided by the mass flow rate of water.

Two starter flow blocks were used to simulate step addition and pulse addition of lithium chloride solution to the model. Each of these starter flow blocks was time-driven and connected to a transport delay block. Each of the transport delay blocks was then connected to the stream from the stuff box to the mixing chest.

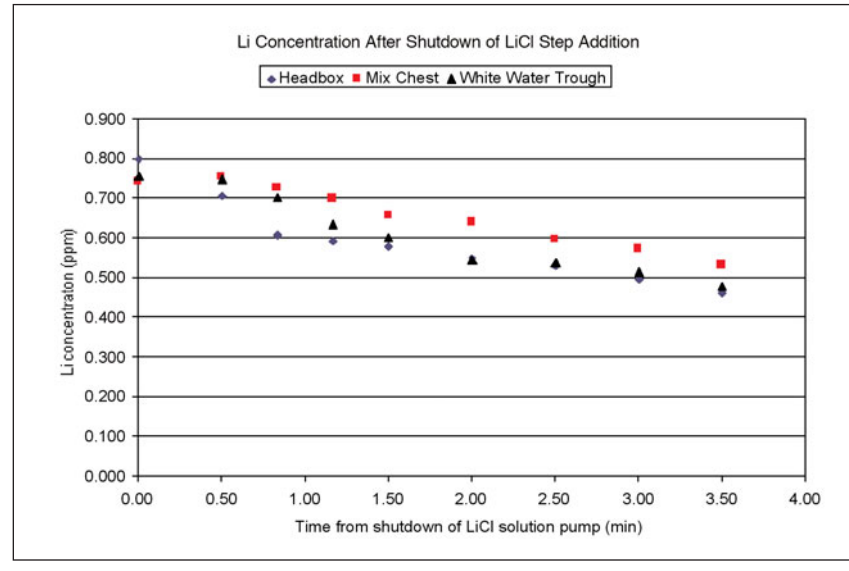
The operating parameters for the model were determined based on the data and information from the spring paper run described earlier and the properties of PM1 in Walters Hall. The PM1 model used for the lithium trial was run with the user-defined parameters for the PM1 lithium trial simulation.

The simulated concentrations of lithium in the headbox, mixing chest, and white water trough were recorded for the step increase, the pulse addition, and the step decrease of LiCl solution. For the simulated step increase, lithium concentration values were taken at 0.01 min. intervals for 15 min., starting 1 min. before the start of the simulated addition. For the simulated pulse addition, lithium concentration values were recorded every 0.01 min. for 8 min., starting 1 min. before the start of the simulated pulse addition. Lithium concentrations for the simulated step decrease were recorded every 0.01 min. for 5 min., starting 1 min. before the shutdown of the step addition.

From Fig. 2, we can see that before the step increase, which was the first addition of LiCl solution to the system, there was an initial concentration of Li which can be assumed to come from an outside source. The data that was acquired during the paper machine simulation of the lithium trial was adjusted to account for the Li concentrations from the outside source and then compared to the lithium values that were obtained through testing of the samples collected during the paper run. The adjustments to the simulated lithium concentrations re-



3. Lithium concentrations in the headbox, mixing chest, and white water trough for pulse addition of lithium chloride solution.



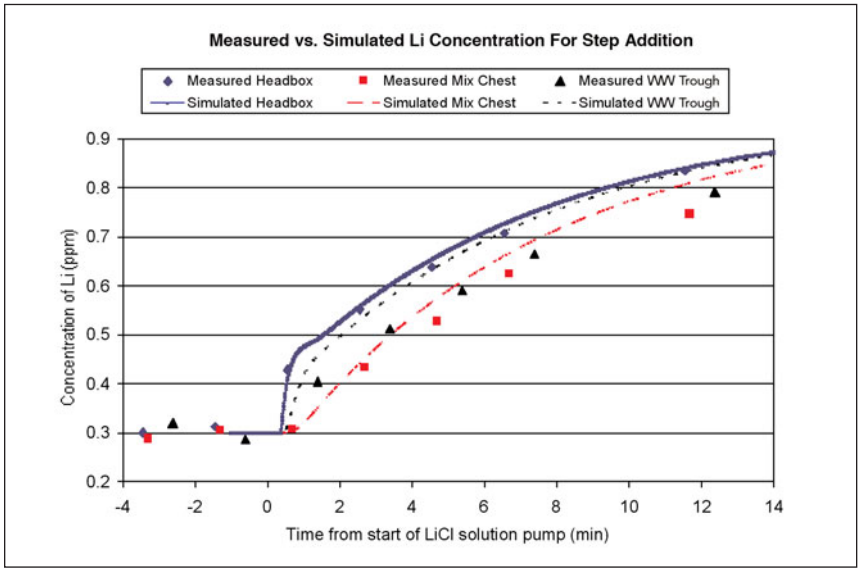
4. Lithium concentrations in the headbox, mixing chest, and white water trough for step reduction of lithium chloride solution.

quired the addition of a base amount of lithium to bring the initial concentrations from the simulation to near that of the measured initial concentrations.

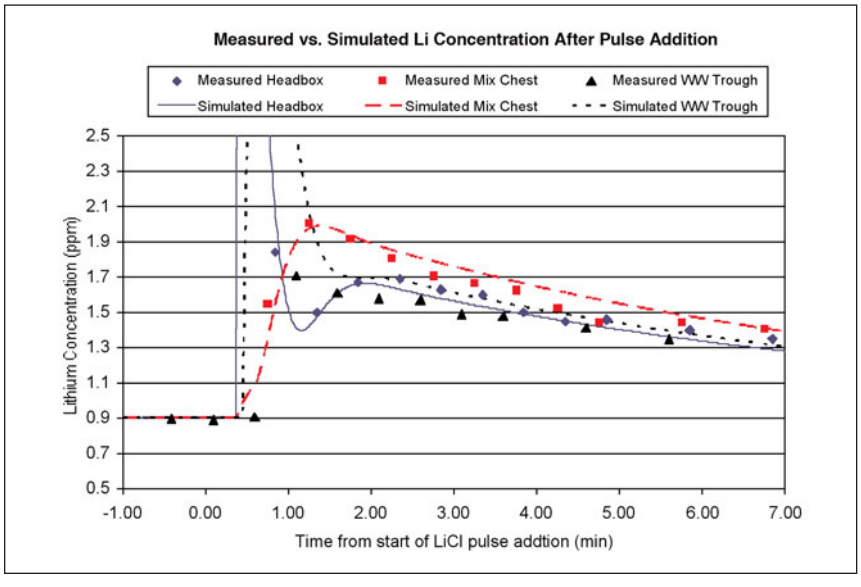
RESULTS

Figure 5 shows the measured and calculated values of Li concentrations for the step addition of LiCl solution. For each of the measured lithium concentrations, the simulated value at the same time was taken and the error in the simulated value was calculated as a percentage of the measured value. For the step increase, the values obtained from the headbox, the mixing chest, and the white water trough had average percent errors of 2.6%, 5.1%, and 9.3%, respectively, and maximum percent errors of 7.1%, 9.0%, and 13.0%, respectively. The low error values obtained for the step addition of LiCl solution show that the simulation can reasonably model the dynamic processes associated with the step increase of a system constituent.

Figure 6 shows measured and simulated lithium concentrations and for the pulse addition of lithium chloride solution. In this case, the average percent errors of the simulated values obtained for the headbox, mixing chest, and white water trough were 3.7%, 4.4%, and 38.6%, respectively, and the maximum percent errors were 13.8%, 11.6%, and 334.4%, respectively. The errors in the simulated values for the headbox and the mixing chest were low for the pulse addition, which shows that the simulation works well for these points. The errors for the simulated values of the white water trough were high during the initial pulse for the observations at 0.59 min. and 1.09 min. If these two points are excluded, the average error is only 4.5%, indicating that the model is accurate beyond the initial pulse.



5. Measured vs. simulated lithium concentrations for step addition.



6. Measured vs. simulated lithium concentrations for pulse addition.

The simulated values for the white water trough from time 1.84 min. onwards are higher than the simulated values for the headbox, while the measured values for the headbox are greater than those for the white water trough for this same period. The model does not appear to give an accurate representation of the Li concentration in the white water trough for the pulse addition case during the initial pulse, but does give a good estimate of headbox and mixing chest consistencies. Optimization of the model with refined parameters should help to improve the capabilities of the simulation. To refine this model further, it would be necessary to obtain sample measurements at a shorter time interval, which would enable a more accurate plot of the Li concentration peaks associated with the initial pulse.

Figure 7 shows the measured and simulated values of lithium concentration for the shutdown of the LiCl solution pump. The modeled values for the headbox and the white water trough showed the most immediate effect due to mass holdup, while the mixing chest showed a more gradual decrease. The error in the simulated Li concentrations was determined for each of the measured lithium concentrations. The average percent errors for the simulated val-

ues at the headbox, mixing chest, and white water trough were 2.2%, 4.6%, and 1.6%, respectively, while the maximum percent errors were 4.0%, 7.7%, and 4.9%, respectively. The low error values show that the model was able to simulate the lithium concentrations accurately at all three sampling points.

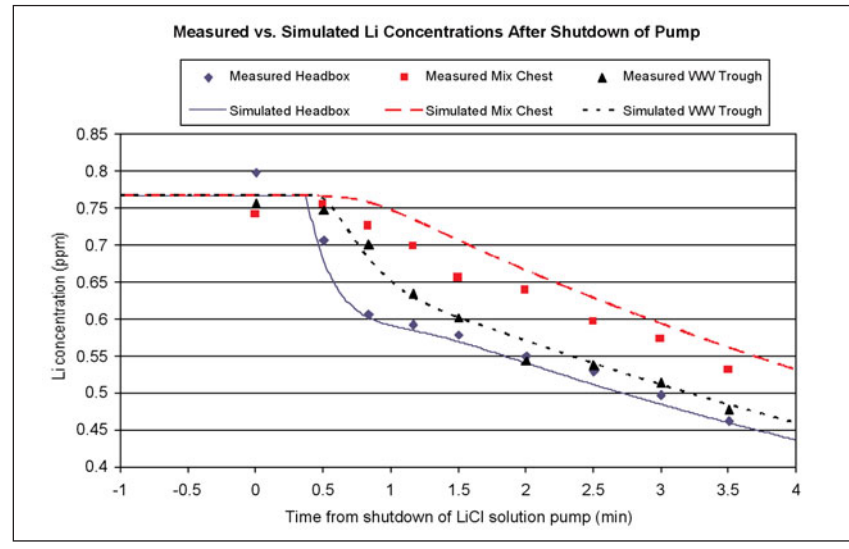
CONCLUSIONS

The paper machine simulation developed for the pilot machine was able to model the system during production and during the lithium trial with good accuracy. Some of the discrepancies in the results from the lithium trial may be reduced by optimizing the user-defined model parameters or by creating more sophisticated models of the paper machine components.

The capabilities of this model are highly dependent on the selection of values for the user-defined parameters, which requires the user to have a good understanding of the particular machine under study when trying to simulate a specific operation. The construction of this model in modular block form allows the user to reconfigure the machine in a variety of ways, allowing for greater versatility when modeling different systems. Changes can be made to the model configuration as well as to the user-defined parameters to see the results of various actions without the cost or time necessary for a trial paper run.

As a learning tool, this model allows the user to change parameters in real time and view the effects that these changes will have on the process.

Future work on this simulator package will include further development of the blocks in the simulator library to include energy balances. This enhancement would make it possible to evaluate the energy requirements of the system and would enable a better evaluation of system capabilities.



7. Measured vs. simulated lithium concentrations for step reduction of lithium chloride solution addition rate.

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LITERATURE CITED

1. Barber, V.A. and Scott, G.M., *TAPPI J.* 6(1): 11(2007).

AUTHOR INSIGHTS

The development of models that enhance the optimization and understanding of various paper machines is important to industry and to the research community. In the course of this work, a simple set of models has been developed that can be configured to represent a wide variety of systems.

This research follows up on previous work by the authors on the development of a modeling package by evaluating the dynamic capabilities of this model when simulating a pilot-scale paper machine.

The most difficult aspect of this research was designing experiments that would simply and reliably test the dynamics of the system. This challenge was addressed by the use of a tracer that could be easily quantified in samples collected throughout the machine after pulse and step additions. The results showed that the model of the wet end, though consisting only of simple blocks, was able to model the system dynamics better than expected.

The model evaluated in this work can be used to simulate paper machine mass balances, allowing for optimization of machine parameters while avoiding the cost of on-machine trial runs. The method of evaluating model performance through the use of a chemical tracer could also be used for other paper machine models.

Future work will involve expansion of the model library to include pulping and converting operations as well as energy balances.



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