Feedstock Grade Transition in a Continuous Pulp Digester using Model Based Management of Kappa Profile

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A thermal-hydraulic model for a continuous-pulp digester capable of simulating grade transitions between hardwood/softwood is used to study feedstock grade transition. Grade transition model is based on the industrial experience that the motion of wood chips in the digester closely approximates plug flow behavior. Simulation examples are presented that illustrate model features. Subsequently, the issues of Kappa profile management using two controller strategies namely, decentralized PI and linear Model Predictive Control are explored for a representative 5x5 problem. Grade transition via effective Kappa profile management is presented.

INTRODUCTION

Pulping mills convert wood chips to pulp suitable for paper production by displacing lignin from cellulose fibres. The conversion is achieved through a combination of strategies involving thermal, chemical and mechanical degradation of the wood chips. Continuous Kraft processes use large, vertical, tubular reactors called digesters where the chips react with an aqueous solution of sodium hydroxide and sodium sulphide, known as white liquor, at elevated temperature. A schematic of a single vessel digester is shown in Fig. 1 Large transport delays, complex dynamics, biological feedstock variability and process integration make control applications difficult. The capital-intensive nature of the pulp and paper industry mandates development of operating strategies that use enhanced control, soft-sensing and fault diagnosis methodologies, which are usually predicated on availability of a process model.

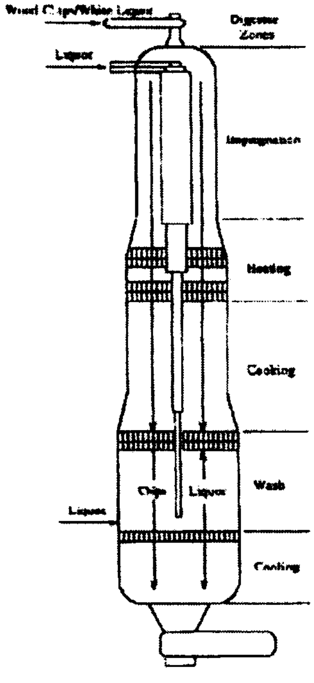

Fig. 1 : Schematic of a single vessel continuous digester.

A significant effort has been directed to development of first-principles models that describe the thermal-hydraulic degradation of wood chips in the continuous pulp digester. Most fundamental digester models in the literature can be classified into two broad categories depending on the attributes they emphasize, 1) pulping chemistry; and 2) hydraulic description of the chip and liquor streams.

The Purdue model [1] and its later extensions [2,3], of the pulping chemistry category, use detailed kinetics, mass and energy balances to describe the thermal degradation of wood chips. However, simplifying assumptions are made regarding axial compaction of chips and chip velocities. These assumptions are a necessary consequence of neglecting momentum transport. On the other hand, hydraulic description-based models [4,5] use equations of motions to describe chip and liquor flow dynamics, but assume simpler chemistry constraining the validity of the models to narrower ranges of Kappa number, an important operating variable. Bhartiya *et al.* [6] presented a direct integration of the works of Wisnewski et al. [3] and Michelsen [5] that some of the deficiencies described above. The detailed kinetics and mass/energy transport of the extended Purdue model are augmented with a momentum transport description, yielding a thermal-hydraulic model of the continuous digester. A direct benefit of incorporating momentum lies in the ability to simulate grade transition through a rigorous description of the velocity of the transition front.

For efficient and flexible operation, it is often desirable to swing the continuous digester between different feedstock grades without stopping the digester (say, from hardwood to softwood). Such grade changes inevitably have large transition times associated with them. In the current work, we make use of a fundamental thermal-hydraulic model of the digester to explore feedback control of feedstock grade transition. Contemporary practices for grade transition use feedforward control and manual control strategies. Doyle and Kayihan [7] have suggested control of the Kappa number profile along the length of the digester (instead of the endpoint alone) as an effective means of regulating the reaction path in the digester thereby achieving a tighter control of the endpoint properties. In the current work, the idea of profile control is extended to control of the digester during feedstock grade transition. The digester "plant" is simulated using the thermal-hydraulic Purdue model [6]. This idea is explored using two feedback control strategies, namely, decentralized PI and linear Model Predictive Control (MPC) for a representative five input by five output problem. It is demonstrated that transition from hardwood to softwood can potentially lead to digester plugging. Doyle *et at.* [8] have also presented grade transition control of the digester, albeit using a non-hydraulic model. For purposes of the current work, we assume availability of real-time Kappa measurements at four different locations along the digester, namely, upper and lower heaters, extraction screens, and blow line, as indicators of the Kappa profile. Although, real-time measurements are not generally feasible, schemes for inferring Kappa numbers using readily available measurements have been reported in literature [9,10] and can be employed to obtain estimates. Results obtained point to the feasibility of using a model-based strategy for grade transition.

Simulation of Grade Transition Using a Manual Strategy

Pulping mills often switch the feedstock grade from hardwood to softwood and vice versa to satisfy demands from the downstream paper machine section. Industrial experience indicates that minimizing blending of the feedstock grades at the feed results in effective transitions. The model assumes that a discrete transition front enters the top of the digester and proceeds downwards. All kinetic parameters upstream of z_0 are assigned the new grade properties while old grade parameters are retained downstream. Properties within the control volume with the transition front are volume averaged based on the location of the front. Fig. 2 shows Kappa profile snapshots at different times during a feed transition from softwood (higher lignin content) to hardwood (lower lignin content). The grade swing was obtained with an open-loop operating policy that involved decreasing the upper and lower heater temperatures from 429 K to 416 K and 443 K to 424 K, respectively, as the front reached the respective heater locations. Also the white liquor flowrate was decreased by 40% after the transition front crossed the extraction screens. The numbers in parenthesis indicate time in hours and the control volume number where the transition front lay when the snapshot was taken. It is noted that after two hours of grade change

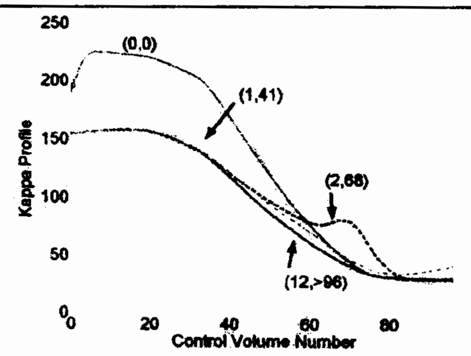

Fig. 2 : Kappa profile snapshots during feedstock grade swing from softwood to hardwood.

(The numbers in parenthesis time in hours and the control volume number where the transition front lay when the snapshot was taken respectvely.)

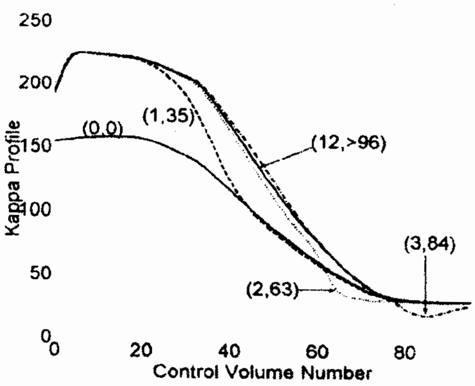

Fig. 3 : Kappa profile snapshots during feedstock grade swing from hardwood to softwood show overcooking.

(The numbers in parenthesis indicate time in hours and the control volume number where the transition front lay when the snapshot was taken, respectively.)

implementation, the grade transition front reaches control volume number 68 and the chips beyond the front location (softwood) are severely undercooked. This is expected since the softwood, which has not completely exited from the digester is subjected to the milder cooking appropriate for hardwood (less temperature, less chemicals).

The case of hardwood to softwood transition is shown in Fig. 3. In this instance, opposite operating condition changes were effected, namely, the temperatures and the white liquor flows were increased in a single step in anticipation of the new softwood grade (highter lignin content). After two hours of operation, the grade transition front reaches control volume number 63. It is noted that the hardwood in the digester downstream of the front location shows overcooking. This is particularly pronounced when the front reaches near the exit of the digester after 3 hours of grade change. Aggressive operating condition changes in anticipation of the grade change can potentially plug the digester. On the other hand, the softwood to hardwood transition allows better drainage of the pulp. This observation is consistent with the mill experience that a hardwood to softwood transition is more "problematic" than vice-versa. The attribute is a result of the complex interactions between the mass, energy and momentum conservation equations and is not discernible in previous models [1-5].

The above grade transition examples made use of an open-loop operating policy: step changes in heater temperatures when the transition front reached the respective heater locations, and changes in liquor flowrate after the front traversed the extraction screens. In practice, temperature and chemical changes are made in a series of steps over a period of time. A slower addition of temperatures and chemicals ensures proper drainage of pulp through the digester (this is particularly critical for the hardwood to softwood transition), but generally leads to longer excursions in the Kappa number. Use of feedback, to control only the endpoint Kappa number (pulp quality) is not effective due to the range time delay in the digester. We make use of ideas by Doyle and Kayihan [7] of kappa profile control as means of accomplishing grade transition. The remainder of the paper explores use of feedback strategies to accomplish grade transition via Kappa profile control.

Grade Transition as a Profile Control Problem

For purposes of the current work, we assume availability of real-time Kappa measurements at four different locations along the digester, namely, upper and lower heaters, extraction screens, and blow line, as indicators of the Kappa profile. Although, real-time measurements are not generally feasible, schemes for inferring Kappa numbers using readily available measurements have been reported in literature [9,10] and can be employed to obtain estimates. A summary of the control problem is provided below;

- Controlled Variables : Kappa # at upper heater, Kappa # at lower heater, Kappa # at extraction screens, Kappa # at blow line (end-point) and the residual effective alkali at the extraction screen.
- Manipulated Variables : Upper heater temperature, lower heater temperature, makeup white liquor to upper heater, makeup white liquor to lower heater and white liquor flow at top of digester.
- Measured Disturbance : Feedstock grade transition treated as a binary switch [8]. Two control strategies were explored for control of Kappa number profile, namely a decentralized PI scheme consisting of 5 SISO loops and a centralized linear constrained model predictive controller using step response models [11] with output feedback. Both schemes use a 10-minute sampling interval. Linear transfer function models (first order plus time delay(FOPTD), FOPTD with single zero, second order plus time delay (SOPTD), SOPTD with single zero) were identified from step tests data.

For the decentralized scheme, output/manipulated input pairings were determined using RGA, steady-state gain matrix, and process analysis (details omitted). The final pairings are as follows, Upper Heater Kappa - make up liquor to upper heater; lower heater Kappa- upper heater temperature; extraction screen Kappa - lower heater temperature; blow line Kappa - make up liquor to lower heater; residual effective alkali - white liquor to top of digester. "Improved" PI IMC tuning rules were employed [12].

RESULTS AND DISCUSSION

Kappa # profile control during a feedstock grade change from hardwood to softwood is presented. As suggested in [8], grade transition is considered as a feedforward disturbance triggered by a binary switch. Setpoint changes were implemented only after the transition front reached the appropriate locations. For example, the lower heater Kappa#setpoint was changed after the transition front reached the lower heater location. The linear MPC controller with a 10-hour prediction horizon anticipates the large magnitude disturbance (change in blow line Kappa#due to grade change ≈ 155) and begins to take aggressive corrective action by increasing the flow rates and temperatures. However, these changes in liquor flows are felt almost instantaneously

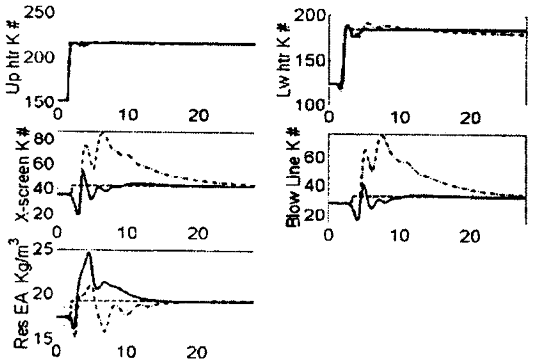

Fig. 4 : Grade transition control during a feedstock swing from hardwood to softwood using MPC (Solid) and PI (dash-dot) controllers.

(The PI controller had to be severely detuned to avoid digester plugging. The dashed line shows the setpoint.)

downstream by the old grade resulting in overcooking. A consistent experience within the pulp and paper industry is that hardwood to softwood transitions are considerably more difficult than vice-versa. A similar problem was observed with the decentralized PI control scheme. Thus, both controllers had to be sufficiently detuned. Simulation results with the detuned controllers are shown in Fig. 4. The MPC controller shows superior performance for control of blow line Kappa#. The PI controllers exhibit an extremely sluggish control of the blow line Kappa#, due to their inability to cope with the large deadtimes. With more aggressive PI control a ringing behavior is observed. Mills generally rely on feedforward strategies to accomplish grade transition. The current work demonstrates that opportunities exit for augmentation of these feedforward strategies with model based feedback control (MPC) action.

CONCLUSION

Ideas of Kappa profile management for grade transition have been presented. The ability of MPC to handle complex dynamics (for example, large dead-times) allowed superior control performance relative to PI for the same species. For feedstock grade transitions, feedback control can be achieved by implementing setpoint changes in the Kappa #s at various locations of the digester. In the current work, Kappa#s at four locations along the digester length were considered. A Kalman filter based inference of Kappa profile is currently in progress. This will allow a better approximation of the Kappa profile. A tighter control on the profile will enable better control of pulp properties that depend on the history of cooking (for example, fibre length).

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