Industrial Lo-Solids pulp digester simulation by the Purdue model

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ABSTRACT: The Purdue model was adapted to simulate an industrial Lo-Solids pulp digester using ad-hoc reaction kinetics for *Pinus radiata* cultivated in Chile. Simulation results for blow line kappa number, pulp yield, free liquor temperature profile, and pulp production rate all agreed well with pulp mill data from Celulosa Arauco y Constitucion's Arauco plant in Chile. Researchers then applied the mathematical model to simulate an increase in filtrate flow to the modified continuous cooking zone to save white liquor consumption, keeping blow kappa number at its target value. Simulation results show a 9.1% savings of white liquor and a significant decrease in dissolved solids content, thus improving the Lo-Solids pulping process.

Application: Pulp mills can use the mathematical model to simulate different conditions of operation in order to improve pulp digester performance.

Mathematical models of the kraft pulping process are powerful tools that can be used to represent plant operations and dynamic and steady state behaviors, and to simulate different operating conditions for process control and optimization.

Among available pulp digesters mathematical models [1], the Purdue model has been widely used and validated with pulp mills data. The Purdue model was originally developed by Smith and Williams [2] to represent the dynamic behavior of a conventional pulp digester. The model was further improved by Butler and Williams [3].

The Purdue model considers a continuous digester as a continuous plug flow reactor with three phases: the wood chips, the entrapped liquor (liquor that has diffused into the chips), and the free liquor (liquor that surrounds the chips). The wood is represented by five chemical components: high-reactivity lignin, low-reactivity lignin, cellulose, galactoglucomannan, and arabinoxylan. The entrapped liquor and free liquor are represented by three chemical components: effective alkali, hydrosulfide, and dissolved solids.

The model assumes that the wood chips and the entrapped liquor are at the same temperature and the free liquor is at a different temperature. In all, the mathematical model is composed of 13 state variables. These state variables depend on time and axial digester position, and to avoid dealing with a set of partial differential equations, a series of staged continuous stirred tank reactors (CSTR) is used to approximate the position of all state variables at any given time. With this simplification, the governing equations are a set of ordinary differential equations derived from mass and heat balances, chemical kinetics, heat and mass transfer coefficients, and packed chips compaction factors. These equations are integrated by a fourth order fixed step Runge-Kutta method.

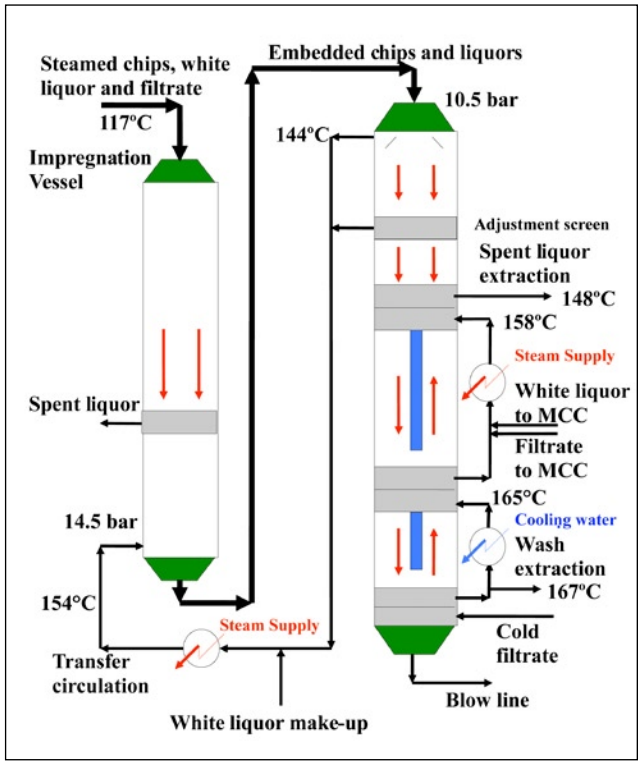
This study compared plant data from an industrial digester with model predictions. The Purdue model was modified first to include the chemical kinetics parameters for *Pinus radiata* grown in Chile [4]. Because the original Purdue model was designed to work with a conventional continuous cooking digester, a second modification was needed to incorporate the Lo-Solids cooking carried out by Celulosa Arauco y Constitucion's Arauco plant in Chile, and new compaction factors given by the digester manufacturers.

THE INDUSTRIAL DIGESTER

The continuous digester installed at the Arauco plant is a retrofitted two vessel Lo-Solids cooking process digester. The first vessel is the impregnation vessel (399 m^3 total capacity) in which steamed chips are embedded with white liquor and filtrate; its diameter ranges from 3.8 m to 4 m. Wood chips are cooked in the second vessel to obtain fiber pulp. The original digester was designed for conventional continuous cooking, was later adapted to carry out modified continuous cooking (MCC), and finally was retrofitted for a Lo-Solids cooking process. In the Lo-Solids process, the amount and concentration of dissolved solids from the chips are reduced by withdrawing spent liquors from several parts of the digester and by injecting white liquor and filtrate to keep the system concentrations (**Fig. 1**).

The capacity of the digester is 1250 air dried metric tons (admt)/day, its total volume is 2090 m^3, and its diameter ranges from 6.84 m to 7.8 m. Seven zones can be distinguished within this type of Lo-Solids digester: an impregnation zone located at the impregnation vessel, and the following zones located at the digester vessel: the heating zone, the adjustment screen, the extraction zone, the cooking zone, the washing zone, and the blow zone.

Chips, white liquor, and filtrate are fed to the impregnator and the liquor diffuses into the chips. The impregnated chips are carried to the top of the digester vessel by the liquor. The heating zone is at the top of the digester vessel, with liquor extractions followed with white liquor make-up, which are first heated and then reinjected to the bottom of the impregnation zone.



1. Schematic of Kamyr digester, Arauco plant (1250 a.d. metric tons/day).

The adjustment screen allows the withdrawal of liquor that is incorporated in the liquor withdrawal of the heating zone to give the process enough time to reach thermal equilibrium among chips, entrapped liquor, and free liquor. In the next extraction zone, the main spent liquor is withdrawn through a screen. Chips and free liquor flow concurrently up to this extraction screen and countercurrently in the next MCC and washing zones.

The MCC zone uses an internal central pipe to inject hot liquor formed by liquor withdrawal from the MCC screen, a white liquor make-up, and filtrate. The main chemical reactions are carried out in this zone. The wash zone also uses a central pipe to reinject hot liquor that is withdrawn from the wash zone screen. In this zone, the pulp is washed, but the temperature is high enough so that chemical reactions are not stopped, extending the cook zone so that a larger amount of wood can be processed. The blow zone uses several pipes to inject cold filtrate to cool down the pulp. **Table I** shows the lengths of each zone and number of CSTRs used in the simulation. The process zones total 80.9 m, but the physical height of the impregnator is 32.5 m, and 55.5 m for the digester vessel.

MODEL ADAPTATION

The Purdue model was adapted to the physical characteristics of the industrial digester, but those characteristics differ in size, stream configuration, operational conditions, wood species (*Pinus radiata* grown in Chile), and compaction factors. The two-vessel industrial Kamyr digester (Fig. 1) was rearranged to a one vessel reactor compatible with the Purdue model for simulation purposes. The impregnation vessel was placed over the second vessel, and the short transfer time (3-5 min.) of chips and liquor from the bottom of the impregnator to the top of the digester was negligible, compared with the long residence times of chips (6-8 h) and liquors (2-5 h) in the process. Extractions, injections, and recirculation of liquors (Fig. 1) were incorporated in the flow diagram of the Purdue model. **Table II** presents operational conditions of some variables used in the simulation of four steady-state cases (A, B, C, and D) captured from the laboratory facilities of the industrial plant (Arauco) [5]. The work of Füllgraff et al. [4]

Zone	Height (m)	Continuous stirred tank reactor stages
Impregnation	26.6	61
Heating	11.7	29
Adjustment screen	7.8	17
Extraction	0.4	1
MCC	10.7	30
Washing	20.4	49
Blow	3.3	13
Total	80.9	200

I. Industrial pulp digester dimensions.

Speed of chips feeder (rotary valve)	14 revolutions/min
Feeder flow factor for wet chips	0.855 m^3/rev
Density of wet chips (softwood)	375.61 kg/m^3
Chips moisture (wet basis)	0.5741 kg/kg
Lignin chips content (20% high-reactivity, 80% low-reactivity)	0.25 kg/kg o.d. wood
Cellulose chips content	0.45 kg/kg o.d. wood
Galactoglucomannan chips content	0.20 kg/kg o.d. wood
Arabinoxylan chips content	0.10 kg/kg o.d. wood
Ambient temperature	10°C
Alkali concentration in white liquor (NaOH equivalent)	93.67 kg/m^3
Hydrosulfide concentration in white liquor (NaOH equivalent)	37.82 kg/m^3
Alkali concentration in filtrate liquor (NaOH equivalent)	4.81 kg/m^3
Hydrosulfide concentration in filtrate liquor (NaOH equivalent)	~ 0 kg/m^3
Dissolved solids in filtrate liquor	90.27 kg/m^3

II. Input variables to digester simulations.

Temperatures (°C):	
of white liquor to impregnation vessel	116.7
of filtrate liquor to impregnation vessel	116.7
of chips to impregnation vessel	116.7
of recirculated liquor from the upper heater	154.4
of recirculated liquor from the lower heater	157.3
of recirculated liquor from wash cooler	164.8
of filtrate liquor	70.0
of pulp from blow line	81.0

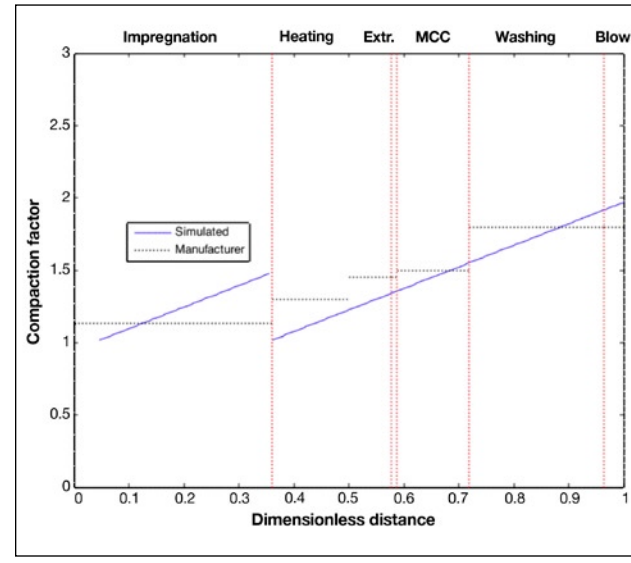
Flow-rates (L/min):	
of white liquor to impregnation vessel	2124.3
of white liquor make-up to upper heater	463.2
of white liquor to lower heater (MCC)	1031.1
of filtrate liquor to impregnation vessel	1183.5
of filtrate liquor to lower heater (MCC)	1245.7
of filtrate liquor to blow line	12124.7
of recirculated liquor from digester to impregnator	6997.7
of extracted liquor from digester to impregnator	1306.8
of spent extracted black liquor	8230.5
of spent liquor from MCC zone	6985.9
of spent liquor from wash zone	1808.8
of wash recirculation	1302.8

III. Operational conditions for steady-state case A.

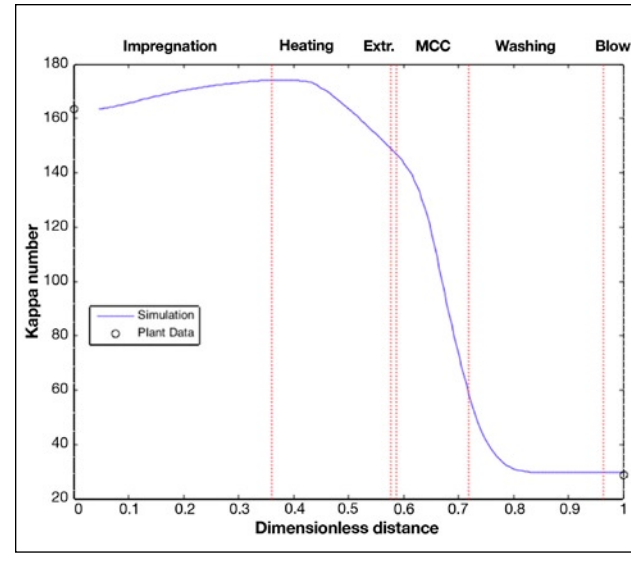
explains the methods of analysis. **Table III** presents additional information for steady-state case A from process on-line measurements. Corresponding data are available for steady-state cases B, C, and D. Simulations, also reported by Araneda [6], follow the reaction kinetics proposed by Christensen et al. [7], with specific pre-exponential coefficients determined by Füllgraff et al. [4], for soda and kraft reactions of *Pinus radiata* grown in Chile. **Figure 2** shows the compaction factor of the industrial digester. The horizontal lines are average design values reported by the manufacturer for five zones of the digester. For simulations, these values were fitted by two straight lines. The compaction factor after the bottom of the impregnation zone was restarted at its initial value at the top of the digester, because the embedded chips are loosened again in the transfer pipe.

RESULTS AND DISCUSSION

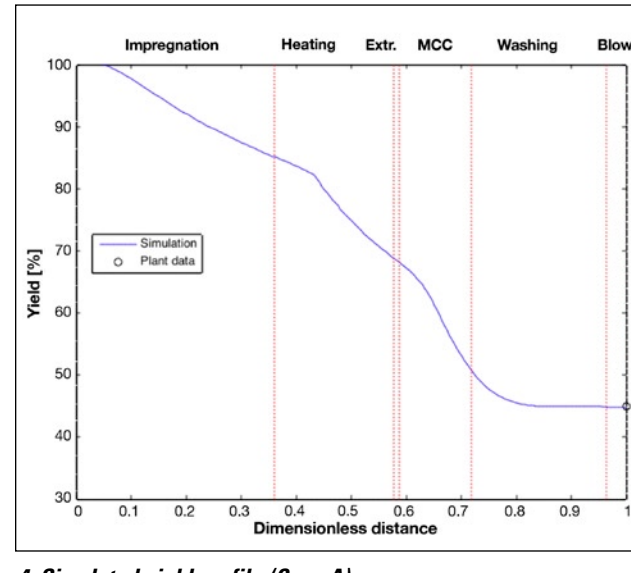
The most important responses in kraft pulping are blow kappa number and yield. **Figure 3** and **Fig. 4** show the steady-state profiles of both variables along the digester (case A). **Figure 5** shows embedded chips and free liquor temperature profiles (case A). **Figures 2-10** have been drawn from the first CSTR stage calculation (instead of starting at z=0) for a better visualization of profile trends. Values at z=0 are given in the text and in Tables II and III.



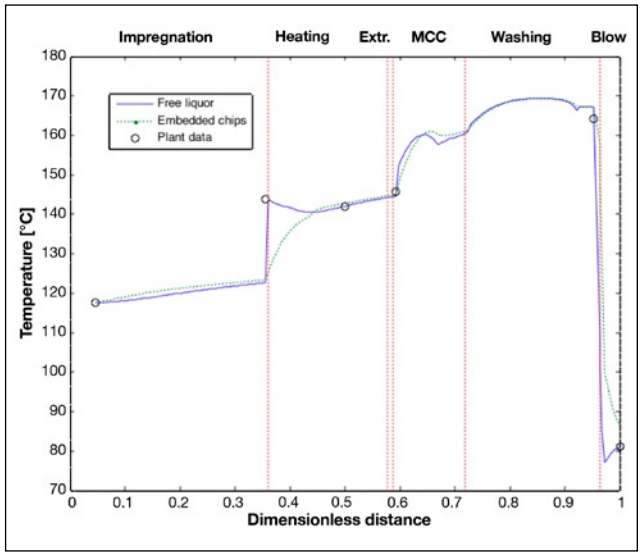
2. Compaction factor of digester.



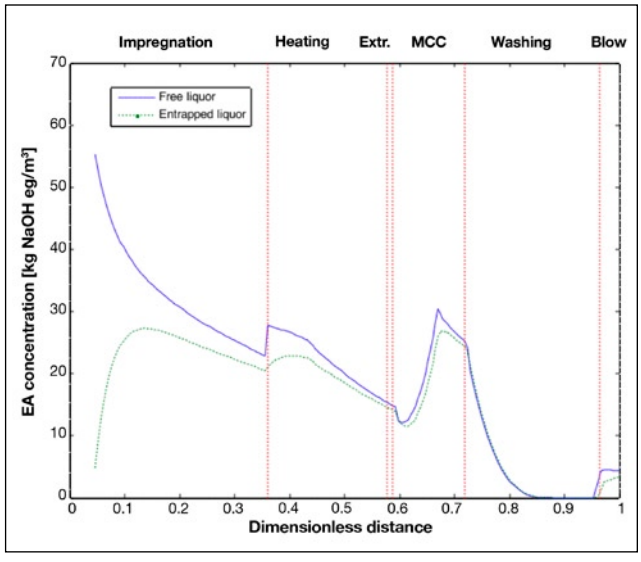
3. Simulated kappa number profile (Case A).



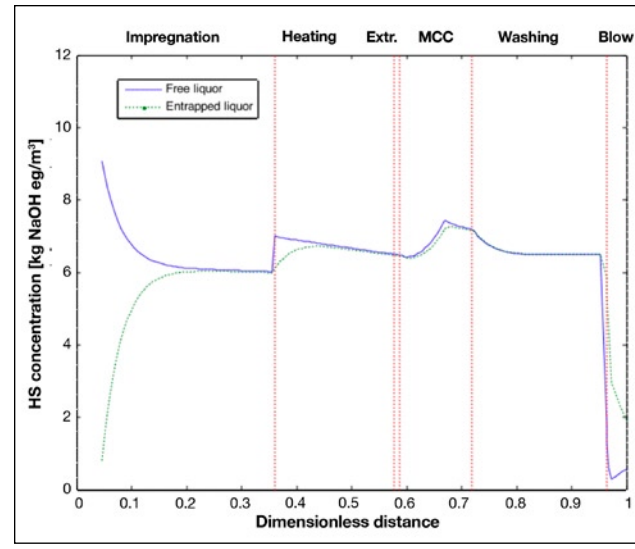
4. Simulated yield profile (Case A).



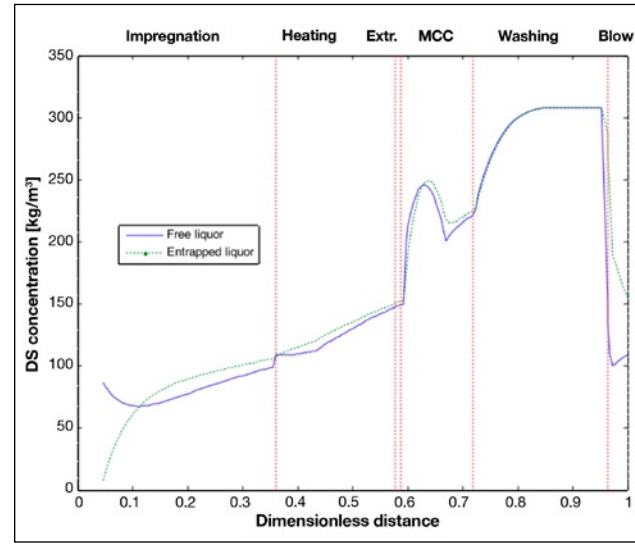
5. Simulated temperature profiles (Case A).



6. Simulated effective alkali profiles (Case A).



7. Simulated hydrosulfide profiles (Case A).

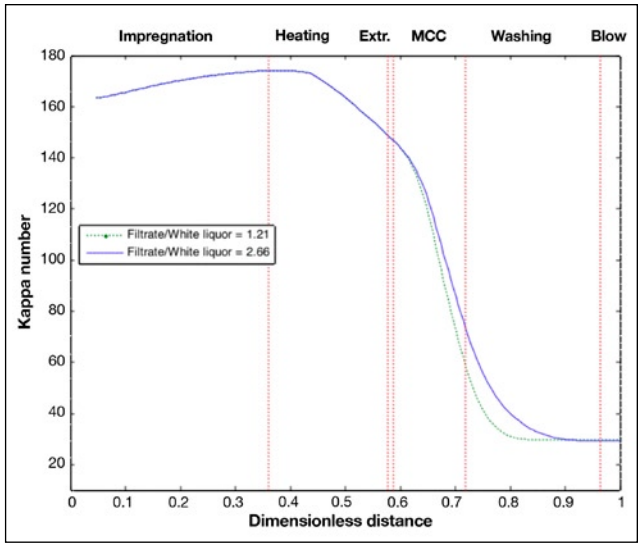


8. Simulated dissolved solids profiles (Case A).

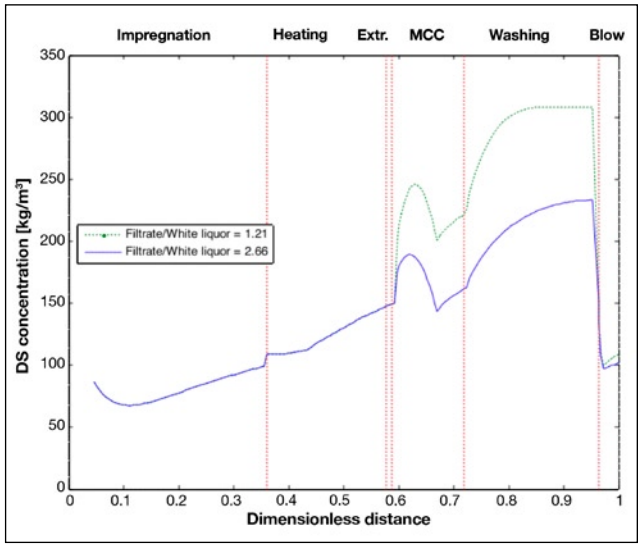
The kappa number profile is typical of many Kamyr digesters [8,9]. Initial kappa number is 163.5 from laboratory analysis. Kappa number increases slightly in the impregnation zone through degradation of some carbohydrates (arabinoxylans), while lignin remains almost unchanged. In the heating zone, carbohydrates continue their degradation, but the injection of hot liquors from the upper heater start lignin and cellulose reactions (Figs. 2 and 3). The wood degrades significantly in the MCC zone through injection of white liquor, reinjection of hot liquors, and reaction heat. Cooking continues into the washing zone (a characteristic of MCC pulping) up to a normalized distance of 0.8. From then on, blow kappa number reaches a constant value of 29.6 (measured plant kappa number is 28.8).

Yield profile (Fig. 4) reflects kappa number behavior; it decreases continuously along the digester. The position of some sudden changes in slope corresponds with slope changes of kappa number, at different rates of degradation of wood. These changes are more pronounced in the MCC zone, less pronounced in the washing zone, and finally quenched at the blow line. Predicted yield by the model is 44.9%, versus plant estimates of 45% to 46%.

Figure 5 shows free liquor temperature measurements at several points. A peak in temperature is observed at the injection of hot liquors from the upper heater. Heat transfer between free liquor and embedded chips becomes evident in the first part of the heating zone, after which desirable thermal equilibrium is reached. Heat transfer is again observed at the blow zone. In the MCC zone, temperature is increased once more by recycling of hot liquors from the lower heater. Heats of reaction increase temperature above 160°C in the washing zone; however, reactions are slowed due to the consumption of effective alkali. Model predictions generally agree well with reported plant operation, and hence *Pinus radiata* corrected kinetics, and modified compaction factors represent the pulping process well in this particular case.



9. Comparison of kappa number profiles for two filtrate to white liquor flow rate ratios in MCC recirculation.



10. Comparison of free liquor dissolved solids profiles for two filtrate-to-white liquor flow rate ratios in modified continuous cooking recirculation.

Profiles of liquor components also were simulated, although no plant measurements are available for comparison of results. However, Figs. 6-8, show that mass transfer between phases is relatively important in the impregnation zone. Two peaks in effective alkali content are clearly seen at the points of injection of white liquor (heating and MCC zones). Effective alkali is completely consumed at a dimensionless distance of 0.84, and pulping reactions are stopped (Figs. 3 and 4). Hydrosulfide profiles exhibit a plateau from half of the impregnation zone up to almost all the washing zone (dimensionless distance 0.96). The injection of cold filtrate in the blowing area causes a drastic dilution of liquors and a fall in hydrosulfide concentrations. Hydrosulfide has been considered to act as a catalyst in wood pulping, which might explain the flat profile; but the kraft reaction for low-reactivity lignin (dominant in content over high-reactivity lignin) also is much slower than the corresponding soda reaction. Dissolved solids (Fig. 8) increase moderately up to the extraction screen, rise strongly at the MCC and washing zones, and are washed away by the bottom filtrate stream.

Free liquor component profiles of Figs. 6, 7, 8, and 10 are similar to those reported by Miyamishi and Shimada [1] in their simulation of a Lo-Solids kraft digester, as corresponding profiles follow similar trends.

The design production rate of pulp in the digester and fiber line (wash filters, bleachers, and paper machine) is 1250 admt/day (air dry, 10% moisture). From the chip data in Table II and the predicted digester yield, 1244 ton/day of pulp (dry basis) are calculated at the digester blow line. The estimated efficiency of the fiber line after the digester is 93.5%. Hence, digester and fiber line pulp throughput becomes 1292 admt/day, a figure in accord with the expected value.

Table IV shows predicted results from the digester model for four steady-state cases simulated in this work. A fair agreement with industry reported data is observed.

Once the digester model is proven reliable, simulations at different conditions of operation can be undertaken. As an application example, the filtrate flow rate was doubled (1245.7 to 2491.4 L/min) in the MCC recirculation stream. This disturbance introduces more effective alkali into the washing zone, in which this reactant is scarce (Fig. 6), but hydrosulfide is still abundant (Fig. 7). Therefore, pulping reactions are restarted and cooking penetrates even deeper in the washing zone, decreasing the blow kappa number, as the simulations predict. To counterbalance this effect and to reestablish the blow kappa number at its original value, white liquor is decreased (1031.1 to 937.4 L/min) in the recirculation to the MCC zone. As a result, cooking reactions extend from previous distance 0.8 to actual 0.88, shortening washing to a narrower region (Fig. 9).

The dilution of liquor components also decreases dissolved solids (Fig. 10), a clear advantage in Lo-Solids pulping, which results in improved mechanical properties of pulp [10]. Unfortunately, unlike other models, the Purdue model does not predict pulp viscosity [1]. Yield barely increases, from 44.9% to 45.1%. The remarkable feature of this trial is the saving of 9.1% of white liquor expenses in the MCC zone. However, during the transition, the kappa number decreases to its lower specification limit for 3 h (allowed kappa number deviations are ±2 from the target value), because free liquor and filtrate

Case	Blow kappa number		% yield	
	Model	Plant	Model	Plant estimates
A	29.6	28.8	44.9	45-46
B	26.1	28.6	44.2	45-46
C	31.9	28.4	45.1	45-46
D	31.5	30.7	45.1	45-46

IV. Comparison of model results with plant data.

flow rate changes were performed simultaneously, and in a single steep step. Kappa number can be maintained within its operational limits if flow inputs are carried out in a series of successive small steps, and at different time trajectories, to account not only for static compensation of kappa number, but for dynamic compensations on digester responses. It is clear that an optimization problem arises in this example: the benefit of reducing white liquor consumption must be compared with larger heat requirements in the lower heater and in the multiple stage evaporators that must process augmented amounts of more diluted spent black liquor.

CONCLUSIONS

The Purdue model is a powerful tool to simulate the pulping process. We adapted the model to the physical characteristics of a two-vessel industrial Kamyr digester, and to the particular reaction kinetics of *Pinus radiata* cultivated in Chile. The model gives useful and improved information of dynamic and steady digester behavior. Model predictions agree well with observed data from actual mill operations, such as blow kappa number, yield, free liquor temperature profile, and pulp production rate. Simulated profiles of free liquor components (effective alkali and hydrosulfide) might provide valuable insights into the pulping process, and can explain observed results of the industrial digester responses. The simulation of the Lo-Solids Kamyr digester of the Arauco plant was successful, and the model can be used to support optimization strategies and in testing control algorithms. **TJ**

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INSIGHTS FROM THE AUTHORS

Chile has expanded its pulp production from 2 million to 5 million tons per year in the last 5 years, hence digester simulation is of economical importance in plant operations. A reliable model is a powerful tool for process simulation at different conditions, and also for optimization and control.

This work was supported by previous research on pulp kinetics of *Pinus radiata* grown in Chile [4].The most difficult aspect of this research was adapting the Purdue model from standard cooking to an industrial two-vessel Lo-Solids digester. The most relevant changes were: different size, different streams configuration and operational conditions, different wood species (*Pinus radiata* grown in Chile), and different compaction factor.

The lab scale batch pulping kinetics found through previous research [4] were successful in reproducing industrial digester behavior. The most interesting simulation result was a savings of 9% of white liquor if the filtrate flow rate is increased in the recirculation zone.

The next step is simulation of industrial batch digesters processing *Pinus radiata*; experimental laboraty scale batch kinetics for *Eucalyptus globulus*.

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