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A comminution model parametrization for low consistency refining

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ABSTRACT

Fibre shortening is typically an unwanted morphological change during low consistency refining that degrades pulp. A comminution model parametrization was proposed to assess fibre shortening during the low consistency refining of mechanical pulps. Fibre length distribution data from before and after refining with a variety of pulp types, net-powers, feed flow rates, angular velocities and plate geometries was analyzed. The estimated parameters from the comminution model showed to have correlations with refiner gap: the cutting rate had an inversely proportional power-law relationship with the refiner gap; narrower gaps promoted fibre cutting at the middle of the fibre whereas wider gaps promoted a more uniform cutting. Plate geometry was also demonstrated to have a role in the fibre cutting location. The proposed parametrization was compared to other modeling works using the likelihood ratio test, showing that it is appropriate to describe the results reported.

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1. Introduction

Industrial refiners are rotatory devices equipped with a bar-groove patterned rotor and stator separated by a gap of 0.1–2.5 mm. Fibres in a pulp suspension are fed to the refiner, forcing them to pass between the rotor and stator. Fibres are subject to multiple strain events inside the refiner during bar-bar crossings as the rotor rotates (see Fig. 1). The strain events are responsible for structural changes to the fibres [1].

Low consistency (LC) refining is a heterogeneous process with a wide distribution of forces that lead to various fibre structural changes (e.g. deformation, fibrillation, delamination, fibre shortening). These structural changes make fibres more suitable for papermaking, but in general fibre shortening is undesired because it reduces sheet strength.

LC refining of mechanical pulps is of interest as it has been shown to decrease energy consumption for a given pulp quality target [2,3]. Although LC refining implementation has its benefits in terms of energy savings, fibre shortening limits the amount of energy that can be saved in mechanical pulping.

To date, the majority of studies on fibre shortening during LC refining have used only the average fibre length values and the specific energy consumption (SRE) to assess fibre shortening. This approach provides a limited explanation to a complex phenomenon since some studies have concluded that refiners cut fibres at different rates depending on their length [4] and the cutting location varies depending on the pulp type [5].

Thus, there is the need for a more fundamental understanding of fibre shortening in order to take full advantage of the energy saving potential of LC refining of mechanical pulps.

2. Comminution in low consistency refining

The size reduction of particles is a three-dimensional problem, however its rigorous mathematical analysis is complex. However, the problem can be simplified to an idealized one-dimensional case under certain assumptions; in the case of size reduction of wood pulp fibres due to LC refining, the problem is simplified to an idealized one-dimensional case since fibres have high aspect ratio (between 30 and 100) and size reduction practically occurs along fibres' length. Hence, size reduction of wood pulp fibres is often referred as fibre shortening.

The one-dimensional size reduction mechanism was first described by Epstein [6] who introduced the concepts of probability of breakage and distribution of smaller sizes. This balance population method known as the comminution model has been used in several fields to study the mechanisms of particle size reduction due

Abbreviations: LC, low consistency; TMP, thermomechanical pulp; SRE, specific refining energy; MEL, modified edge load; BIL, bar interaction length; MLE, maximum likelihood estimation; LRT, likelihood ratio test; SEL, specific edge load.

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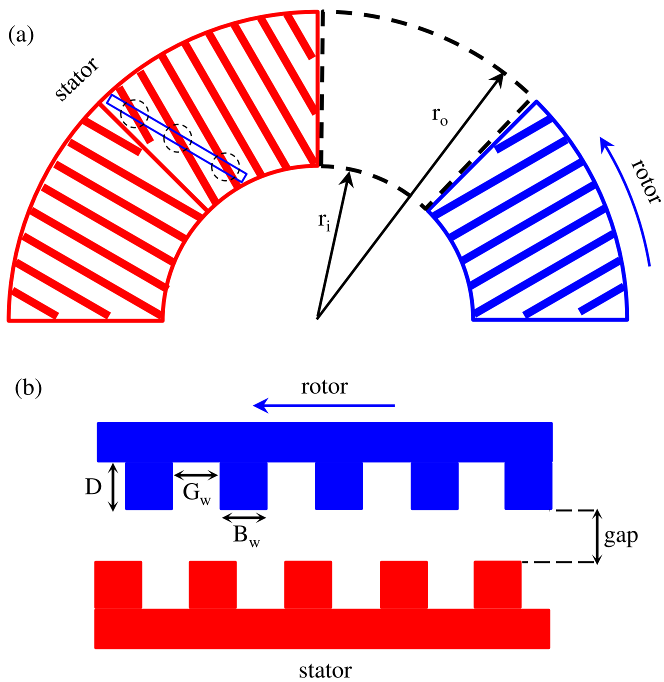

Fig. 1. Schematic of a refiner stator (red section) and rotor (blue section) elements. (a) Lateral-view. (b) Cross-view; B_w is bar width; G_w is groove width; D is groove depth; r_i is inner radius and r_o is outer radius. Dashed lines show bar-bar crossings. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

to crushing, grinding, vibration, and other processes including LC refining.

Corte and Agg [4] showed that a refiner cuts longer fibres faster than shorter fibres whereas a laboratory beater cuts long and short fibres at the same rate. In other words, it highlighted that the refining mechanism between these two devices was different. Roux and Mayade [7] described mean fibre length changes due to refining, however, the re-distribution of smaller sizes after cutting was not included in the study. Olson et al. [8] used a comminution model to explain fibre length behavior during refining. It was found that the cutting rate was strongly dependent on SRE and fibre length; it was independent of the feed consistency and was higher at high energy treatments, which suggested that cutting was not a fatigue process. Heymer [9] used a comminution model to assess the heterogeneity of a refining process analyzing the fibre length distribution changes. It was found that heterogeneity was greater at treatments with a small number of impacts at high intensity (or greater homogeneity with large number of impacts at low intensity) and larger residence times can decrease the heterogeneity.

2.1. Comminution model equation for LC refining

Roux and Mayade [7], Olson et al. [8] and Heymer [9] used the comminution model equation using SRE as an independent variable written as (see Appendix A for details of the mathematical derivation):

$$\frac{dy_i}{d(SRE)} = -\bar{S}_i y_i + \sum_{j=1}^{p} B_{ij}\bar{S}_j y_j \quad (1)$$

y_i is the proportion (or relative frequency) of fibres in the bin i, S_i is called the selection function describing the probability that a fibre in the ith bin gets shortened. B_{ij} is called the breakage function describing the conditional probability that given a fibre in the ith bin is shortened to a fibre in the jth bin. Eq. (1) is just an adaptation from the linear batch grinding equation and although it is valid to analyze fibre shortening during LC refining, it does not allow comparisons between trials performed at different conditions because important refining variables such as plate geometry, angular velocity and refiner size are not considered. Many refining studies have emphasized that plate geometry and angular velocity are key to understand changes in pulp properties. For example, Elahimeher et al. [10] demonstrated how the number and size of bar-bar crossings changed with plate geometry and angular velocity and later on, Elahimeher et al. [11] related the effect of plate geometry to pulp properties. Additionally, the use of SRE as the independent variable in Eq. (1) poses another limitation since two refining operations can have the same energy consumption, yet lead to different fibre modifications; for instance, a large number of impacts of low-energy-per-impact leads to fibrillation, whereas a small number of impacts of high-energy-per-impact leads to fibre shortening [12].

To address these issues, the comminution model equation is written in terms of the refiner radius as shown in Eq. (2) (see Appendix B for details):

$$\frac{Q}{\omega}\frac{1}{4\pi\alpha\beta}\frac{1}{r}\frac{dy_i}{dr} = -S_i y_i + \sum_{j=1}^{p} B_{ij} S_j y_j \quad (2)$$

where Q is the volumetric flow rate, ω is the angular velocity, $\alpha = B_w/(B_w + G_w)$ and $\beta = 2G_w D/(B_w + G_w)$. B_w is the bar width, G_w is the groove width and D is the groove depth (see Fig. 1 for details).

The dimensionless number α describes the ratio of bar area to total area of refiner and it has been widely used by several refining studies such as Elahimeher et al. [10,11,13] and Rajabi Nasab et al. [14] as well as included in some refining theories such as the MEL (Modified Edge Load) theory. On the other hand, β is describing the free area of flow and has been also used by Kerekes [12] and Heymer et al. [15] when they analyzed the volumetric flow through the refiner cross section area.

In Appendix B, it was assumed that the selection function S_i^* was proportional to the angular velocity ω and the ratio of bar area α. The reason for this assumption is based on the findings of Elahimeher et al. [13] who observed that fibre shortening was strongly correlated to product of angular velocity and the bar interaction length (BIL), the latter being a measurement of the leading edge of bar crossings. Since the bar-bar crossing shapes are parallelograms, BIL is equal to half the perimeter of the crossing. Additionally, Elahimeher et al. [11] demonstrated that: (1) the bar-bar crossing area (A_c) is a linear function of α^2 and (2) the square root of bar-bar crossing area is linearly correlated to the crossing perimeter. Therefore, the assumptions in Eq. (3) can be made:

$$\sqrt{A_c} \propto BIL \propto \alpha. \quad (3)$$

2.2. Model parametrization

For short periods of grinding, the products of breakage are too small in quantity to be significantly re-broken making possible the calculation of B_{ij} [16]. This situation applied to an industrial refiner would require to collect a sample at a radial position close to the inner radius r_i. Assuming that this sampling could be achieved, the sample would contain a mixture of other radial positions since pulp flows inwards in the stator grooves and outwards in the rotor grooves [17]. Industrial refiners thus impose a significant limitation on the experimental calculation of B_{ij} making it necessary to reduce the number of parameters in the model in order to assess fibre shortening using a comminution model.

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