Literature survey
Measurement techniques suitable for the refining zone of disc and conical LC refiners

Oddbjørn Eriksen, Lars-Åke Hammar

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Literature survey

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1 Summary

The objective has been to make some general conclusion regarding techniques for studying the operation of low-consistency (LC) refining. Even if there are some opinions that it is not possible to compare the refining processed of high- (HC) and low-consistency refining due to their different (steam and water) atmosphere, it seems to be some common behaviour of the fibres in the refining regardless of the different techniques. Visual observations in the refining zone give an idea of the flow pattern of the fibre material in the refining zone, but not in quantitative aspects. Sensors measuring variables as temperature, pressure and shear force in the refining zone give a complement to the knowledge of the fibre treatment. However, the challenges to measure in the wet and harsh environment should not be underestimated. The measurement technology applied in the refining process has to be considered as immature at the moment. Some general observations and measures should undoubtedly be mentioned:

1. A back-flow of fibres is observed in the refining zone both from studies in low- and high-consistency disc refining. Completely different material such as chips and fibres to be more treated fibres are observed to behave equal. This seems to be a fundamental behaviour of the fibre flow through the refining zone even if it is in water or steam phase.

2. Fibres stapled on the bars are observed in several studies. The stapled fibres seem to be more concentrated to the leading edge of the bars. This seems also to be a fundamental behaviour of the fibres in the refining zone, and it is observed both in high- and low-consistency refinings. The fibres are momentarily stapled on the bars. The amount of fibres covering the bars is also observed to be small. Thus, most of the fibres are located in the grooves. This behaviour can to a certain degree be prevented or controlled by the plate design. The trade off will be the production capacity.

3. The residence time in a HC-refiner is observed to increase if the consistency is increased due to smaller centrifugal forces acting on the drier mass suspension. At similar conditions i.e. rotational speed of the refiner, the residence time in a LC-refiner should be shorter. However, the rotational speed of the LC refiner is generally lower compared to the speed of the high-consistency refiner.

4. In general, the temperature increases in the refining zone by increased radial position in a pressurized refiner. The temperature increase is much higher in the HC refiner compared to the temperature rise across the refining zone of a LC refiner. The temperature of the LC pulp increases by 3-4 °C per passage through the refiner, which accounted for the 90-95 % of the input energy. Thus, most of the energy input goes to heat. The temperature of the pulp flowing in the grooves has been observed to be slightly lower than the temperature of the bars. The friction forces are essential in the heat generation.

5. It is also claimed that the pulp properties affect the temperature profile. The temperature difference was smaller for pulp of softwood than that of hardwood pulp. The short fibres of hardwood generated the highest temperature in the first
part of the refiner, while the long fibre softwood pulp had a temperature profile that increased more regularly along the length of the refining zone.

6. The measurements of pressure have showed that the pressure rise can be coupled to the passage of the bars of the rotor disc, and probably to the leading edge of the bars. The size of the pressure peaks differs from different studies.

7. The plate clearance has been measured in some studies. Indirect measurements on the shaft seem not to be reliable when it comes to measurements of variations down to micrometer scale. In the HC refining, measuring of the gap directly in the refining zone has been possible for some decades. In LC refining the plate clearance is even smaller than in HC refining and true gap clearance measurements are not established in mill-scale operation. Recently, pilot-scale studies have focused on the importance of gap clearance measures compared to the theoretical refining intensity in order to comparing refining results.
2 Introduction

In the mechanical pulping process low-consistency refining is primarily applied as post-refining which concerns refining late in the process line. Recently, more attention is put on the LC refining in an earlier stage in the mechanical pulping line due to benefits in the specific energy consumption. However, the operation of the LC refiner is more demanding due to a narrower operating window with a plate gap down to a few fibre widths. The plate clearance in a high-consistency refiner is several times larger. The need to control the process operation is essential in order to create a pulp of desired quality. Thus, it is necessary to collect more information from the process. The topical information of interest is associated to the flow phenomena and the fibre coverage of the bars in the refining zone as well as the stresses applied to the fibres in contact with the bars. Such information can be obtained using sensors and measurement technology. The most relevant variables to be analyzed in this context are probably force, pressure, temperature, residence time, vibrations and the quantity of pulp. In addition, visualization of the pulp flow behaviour using photographic methods will support the interpretation and increase the overall comprehension. In general, there is limited information about the pulp flow performance in the refining zone, and thus, the knowledge of the fundamental refining mechanisms are lacking.

Most of the research in the mechanical pulping process has been focused on HC refining. Studies of different measurement techniques applied in the refining zone of LC refiners are not often examined. Most of the knowledge comes from studies made on the beating process of chemical pulps. This literature review focuses on important mechanisms observed by different measurements connected to the activity in the refining zone. In this review, theories and models concerning the refining process are mainly omitted. Primarily observations made by different measurement techniques are reviewed and discussed.
3 Background

All existing models concerning mechanism in low-consistency refining has been developed through the refining of chemical pulp. Among the researchers that have discussed the beating of chemical pulps widely is Page (1989). He strongly claimed that it is the solid fibre phase that transmits the forces across the beating gap while the hydrodynamic forces control the presentation and arrangement of the fibres in the beating zone. This is obviously supported by the fact that work of beating is far greater than the work of circulating the beater roll without stock at the same gap. Page also emphasized that the factors that affect the mechanical rather than the hydro-dynamical forces such as friction of the bar or the shape of the bar edge, are known to have substantial effect on the beating action.

Figure 1.
The beating effects can be described by the stresses that fibres experience during the time the fibres are trapped between the passing stator and rotor bars (Page (1989)).

Hypotheses about the behaviour of the pulp and fibre suspension in beating and refining are mainly built on the work of the Dane Sigurd Smith who defended his doctoral thesis on theoretical considerations about the performance of a Hollander already in 1919. His theory anticipated that the beating of cellulose fibres primarily took place at the leading edges of the blades of the beater. Smith assumed that the fibres were stapled to the edges because the edges were less affected by wear compared to higher up on the blades (Stephansen 1967). Banks (1967) mainly supported this theory. However, he proposed that the fibres appear as flocs of fibres on the frontal edges of the bars, and that the edges are not fully covered by fibres. He assumed that only 50-70 % of the edges were covered by flocs of fibres as opposed to Smith’s fibrage theory which supposed a complete covering of the tackle elements.
Figure 2. Smith’s theory from 1919 assumed that the fibres were stapled to the edges because the edges were less affected by wear compared to higher up on the blades (Stephansen 1967).

Espenmiller (1969) had similar opinion about the refining action as Smith. His five steps hypothesis (Figure 3) was nevertheless a step further because the behaviour of the refiner was quantized in terms of energy consumption, consistency and mechanical pressure at different point of action between the fibres and the bar pattern. Espenmiller assumed that 90% of the refining energy was consumed at the leading edge where a mechanical pressure on the fibres could reach 30-70 bars (1000-5000 psi) resulting in a compacted and compressed mat (wad) of fibres. According to the theory, the consistency at this point could be as high as 50-60% due to the interpretation that a high rate of water is expelled from the fibrous structure. Espenmiller believed that the sliding action or shearing movement of the bar when two bars are opposite of each other consumes the remaining refining energy (10%). The split or bruised fibres from the initial impact between the leading edges may be further treated at this point of action by rolling or flattening actions. When the pressure on the fibre mat is released the high-consistency wads rapidly reabsorb water and redispersed to their original consistency by the intensive hydraulic and mixing action.
Figure 3. Espenmiller’s (1969) five steps hypothesis about the refining action is shown.

Page (1989) stated that the action of the beater has been described in terms of two parameters, one to indicate the number of impacts received by the fibre and the other to indicate their intensity. There are several theories and models concerning the low-consistency refining process that is based on these parameters. The theories are based on combinations of mathematical models, model experiments and direct observations from refining trials. The main theories are the C-factor theory (Kerekes 1990, Kerekes and Senger 2006) and the specific edge load theory (SEL) (Wultsch and Flucher 1958, Brecht and Siewert 1966) and its extensions in form of the intensity and frequency model (Danforth 1969, Leider and Rihs 1977, Leider and Nissan 1977), the specific surface load theory (SSL) (Lumiainen 1990a, 1990b, 1995), the modified specific surface load theory (MSSL) (Musselman et al. 1997) and the modified edge load theory (MEL) (Melzer and Septke 1995). In addition, a hydrodynamic model has been proposed by French researchers (Roux et al. 1999, Radoslavova et al. 1997, Roux and Joris 2005). Some of the different approaches are described and evaluated by several researchers, among them are Hammar (2003), Olson et al. (2003), Welch (1999) and Baker (1995).
To apply the models in practice by mill operators or in control strategies in the production line are not simple because several of the parameters such as friction coefficients, power distribution and the conditions of the refiner plates are difficult to determine on-line. In addition, Page stressed that the theories based on the number and intensity of impacts have not been proven to have real physical significance. He claimed that it has yet to be demonstrated that any impacts actually take place. Mohlin (2006a, b) stated that the term refining intensity is mainly valid because of its close relationship to the gap clearance. Her results indicate that gap clearance is the basic refining variable when comparing refining results.

Page concluded that a mechanistic theory of the beating action is missing. His opinion was that a theory should be made in terms of the stresses that fibres experience in the beating zone, and their response to those stresses. Thus, direct measurements in the refining zone have been strongly appreciated in order to measure the actually stresses. In this survey some of the different measurement approaches are described in order to evaluate the methods and the outcome. The measurement techniques applied in the HC refining have also been considered.
4 Physical measurement in the refining zone

Due to the extreme environment inside of the refiner, few real measurements are performed. Difficulties with electrical connections in environments surrounded by water and steam have given researchers challenges when applying sensors in the refining zone. A few attempts have been conducted in the past. New technology based on fibre-optic both as sensors and as carrier of signals has opened for extended applications and possibilities to investigate physical mechanisms in the harsh environment. A review of past investigations and experience are essential to consider the matters and challenges previous scientists were confronted with. Such information is important in order to establish new attempts to reveal fundamental mechanisms and built new knowledge.

Table 1 gives an overview of selected physical measurements in the refining zone made by different authors.

Table 1. Physical measurements in refining

<table>
<thead>
<tr>
<th>Variable / technology</th>
<th>Low-consistency Author(s) Year</th>
<th>High-consistency Author(s) Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Banks</td>
<td>1967 Atack et al.</td>
<td>1984</td>
</tr>
<tr>
<td>Fox</td>
<td>1980 Stationwala et al.</td>
<td>1992 Alahautala et al.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1997/1999 Alahautala et al.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2004 Alahautala et al.</td>
</tr>
<tr>
<td>Photographic</td>
<td>Khlebnikov et. al. 1969 Atack and Stationwala 1975</td>
<td>Eriksen 2003</td>
</tr>
<tr>
<td></td>
<td>Fox 1980 Senger et al. 2004/2005</td>
<td></td>
</tr>
<tr>
<td>Pressure/ Normal force</td>
<td>Khlebnikov et. al. 1969 Gradin et al. 1999</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Senger et al. 2004/2005</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Johansson et al. 2001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Eriksen et al. 2003/2006</td>
</tr>
<tr>
<td>Temperature</td>
<td>Nordman et. al. 1981</td>
<td>May et al. 1973</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Härkönen and Tienvieri 1995</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Johansson et al. 2001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Eriksen et al. 2003/2006</td>
</tr>
<tr>
<td>Plate clearance</td>
<td>Nordman et. al. 1981</td>
<td>Stationwala et al. 1979</td>
</tr>
<tr>
<td></td>
<td>Mohlin 2006 Dahlqvist and Ferrari 1981</td>
<td></td>
</tr>
<tr>
<td>Residence time</td>
<td>Arjas et. al. 1970</td>
<td>Ouellet et al. 1995</td>
</tr>
<tr>
<td></td>
<td>Fox 1980 Murton et al. 2002/2005</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Strand and Mokvist 1987</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Eriksen et al. 2003/2006</td>
</tr>
</tbody>
</table>
4.1 Visual observations in the refining zone

According to Page (1989) he and his co-workers were the first to image fibres in the beating zone. This attempt was conducted already in 1962 in an Aylesford beater using bleached sulphite pulp. The micrographs showed single fibres in the refining zone as well as fields of view that showed no fibres at all. In addition, they observed micrographs that contained appreciable numbers of fibres distributed throughout the beating zone. Thus, they concluded that the beating action aimed at breaking down flocs of fibres trapped when two bars approach one another.

To be able to visual study the fibre flow in a refiner gap, Fox et al. (1979) constructed an experimental refiner of clear plastic. The photography was performed by focusing a high-speed camera on the desired portion of the refiner. Standard photographic techniques were employed using high-speed film. The used pulp fibres were bleached kraft made from southern pine. The data demonstrated that the stock flow was three-dimensional and includes at least primary, secondary and tertiary flows. It was observed that the pulp fibres were stapled to the leading edge of the tackle by fluid dynamics forces and subjected to the maximum refining action. A tremendously acceleration clearly existed in the flow loop out of the rotor and in the stator. Another interesting observation of their experiment was that they observed an outward radial flow in the rotor and an inward flow in the stator existing in the circulation region. In addition, they measured also the pressure and the residence time in a 300 mm Sprout Waldron laboratory refiner as reported in another section. The pressure measurement indicated that the motion of the rotor caused pressure gradients in the refiner and that the pressure distribution was not uniform. In addition, Fox (1980) claimed that there existed a pressure gradient between the stator and rotor disc which gave a flow from the stator groove into the plate gap. According to the author, this wiping flow helps holding the fibres against the leading edge of the rotor bars so that refining work can be done.

![Diagram](image)

**Figure 4.** The different flows in the refining zone as interpreted by Fox et al. (1982).
Researchers at Paprican in Canada and Tampere University of Technology in Finland have studied fibre flows in high-consistency refiners using photographic techniques and image analysis. The former group has reported work within this field since the early 1970s (Atack and May 1970, Atack et al. 1984, Atack et al. 1989, Atack and Stationwala 1990, Stationwala et al. 1992). Stationwala and co-workers studied the pulp distribution and pulp motion in the refining zone of a commercial chip refiner. They recorded the pulp motion in a single disc refiner in the second stage by high-speed photography. They observed that the pulp appears in the form of flocs and that only 50 to 85 % of the bar surface was covered with pulp. The tangential motion of fibre flocs, change of floc shape and floc disruption were observed during a bar passage.

The Finnish studies are conducted lately (Alahautala et al. 1997, 1999, 2004). They have studied the pulp flow as well as pulp quantities between the discs in a mill-scale refiner. The former studies used an endoscope and scientific grade CCD camera supplied with other optical techniques in order to improve the visualising in a first-stage refiner at four different radial locations. The measurement was done through plate patterned sapphire windows. Installations probes were screwed into each of the four holes located in different radial positions in the refiner front cover. The measurements focused on pulp velocity, pulp orientation, pulp coverage and the presence of fibre flocs. The latter article by Alahautala and his co-workers contains a description of an experiment using a pulsed laser light source and a CCD camera. Both of the experiments were conducted in the same refiner. One of the greatest challenges was to transmit the light from the stator to the rotor disc. The uncertainty of the measures was relatively large due to contamination of pulp in the gap between the refiner casing and the rotor disc. However, the results strongly indicated that the leading edge of the bars collects and carries along a considerable quantity of pulp like Smith proposed already in 1919 (Stephansen 1967, Page 1989). This result is in line with similar conclusion drawn from studies in low-consistency refiners (Fox et al. 1979, 1982, Fox 1980, Goncharov 1971, Banks 1967).

4.2 Force and pressure measurements

4.2.1 Low-consistency refining

A few attempts have been performed to measure forces or pressures in low-consistency refiners. Russian researchers at the pulp and paper research institute in Leningrad were pioneers when they reported force measurements in low-consistency refiners 30-35 years ago (Khlebnikov et al. 1969, Goncharov et al. 1970 and Goncharov 1971). Khlebnikov and Goncharov used different measurement techniques in different type of refiners. The first group used wire tensiometers (strain gauges) encapsulated in plexiglass beams fixed to each side of a bar in a conical refiner. The second group used a special developed two-component sensor of the tensiometer type in a disc refiner. A sensor element (spring steel) was fixed to the working surface, and the tensiometers were connected to this element. Goncharov stated that his results obtained in disc refiners basically confirmed earlier findings collected in a conical refiner.
Goncharov (1971) studied the forces over single bars in a specially designed refiner with 300 mm diameter discs. The experimental data is associated with the distribution of the pressure along the width of the bars in the refining zone. It was possible to measure the normal and tangential forces acting on the fibre layer in the plate gap by means of specially developed two-component sensors arranged in three places along the radius of the discs. The axial force and the torque acting on the disc of the rotor were also measured. In addition, the author claimed that he was able to measure the distribution of hydraulic pressure along the radius both on the front and on the rear surfaces of the rotating disc.

It was shown that the results of the beating process were determined by the pressure exerted on the frontal part of the working surfaces of the bars covered by a layer of fibres. The pressure reached up to 35 bars (3.5 MPa) in the first part of the bar when the refining was conducted at recommended optimum conditions as stated to be a specific edge load of 1.5 Ws/m on this particular pulp i.e. unbleached sulphite pulp. Results from the pilot trial were confirmed in an industrial scale refiner as well. Table data indicate that the pressure reached even higher in an industrial refiner. The pressure decreased rapidly after 2-3 mm of the bar width and levelled out at only 10-15 % of the maximum pressure. The maximum pressure was 13 times higher than the calculated average pressure assuming that the total bar surface was utilized in refining.

Visual observation as well as high-speed records through a transparent stator disc showed that a fibre layer was formed on the leading edge of the bars and the width of this layer was...
2.3 mm along the width of the working surface of the bars equal to that on the maximum pressure zone. When the edges of the bars with the overhanging fibre layer approached each other, double fibre quantities came into the gap and resulted in a very high degree of fibre compression. This stage corresponded to the maximum pressure zone. The relative agreement between the measured and calculated values of the axial forces required for beating indicated that the axial force acted on the fibres at the edge of the bars in the maximum pressure zone. Goncharov concluded that the determining factor is the pressure acting on the frontal section of the working surface of the bars rather than the actual pressure calculated over the geometrical surface of their contact. A similar statement was made by Espenmiller (1969) who estimated that 90% of the effective refining power was consumed at the leading edge of the bars.

Goncharov also found that:
- The maximum pressure increased with increasing width of the bars due to more fibres collected on the leading edge
- The width of the zone of rising pressure was independent of the width of the bars
- The maximum pressure decreased as a function of the radial distance from the centre due to reduced thickness of the fibre layer at the frontal edge along the radius
- The shortening of the fibres, which is deteriorating of the mechanical properties of the pulp, increased with increasing pressure

Khlebnikov and his co-workers found that the actual width decreased with increasing plate clearance. They found also that the rotational speed of the refiner as well as the pulp consistency affected the maximum pressure on the fibres. Increasing rotational speed and increasing consistency increased the pressure.

Goncharov concluded that the most economical way in order to obtain the highest strength properties of the pulp was to use smaller bar widths because the pressure was lowest and less deteriorating for the fibre quality. Atack (1977) reviewed the work of Goncharov. He stated that the operative width of the bars was approximately equivalent to the average fibre length of the pulp to be treated, and by operating at this level of bar width the maximum number of fibres is treated per unit available area of the beating zone.

Researchers at the University of British Columbia and Paprican in Vancouver have reported a lot of interesting work related to studies of normal and shear forces imposed on fibres during refining. A single bar laboratory refiner has been used to increase the knowledge about the influence of the forces. Among several articles the following references are particularly relevant: Martinez and Kerekes (1994), Martinez et al. (1997), Batchelor et al. (1997), Senger and Ouellet (2001) and (2002). Mainly, their research supports the findings of Goncharov and Khlebnikov that aim at a pressure peak appears at the leading edge of the bar when two bars approaches each other.
The normal and shear forces acting on the fibres and flocs of fibres play an important role of the final pulp quality. According to Senger and Ouellet (2002), the normal force has been shown to contribute to internal fibrillation of the fibre wall through transverse compression and bending of fibres, while the shear force has been shown to cause external fibrillation of the fibres. Thiruvengadaswamy and Ouellet (1997) claimed that shear stress induced by compression is more effective for structural breakdown of wood than compression forces alone.

Martinez et al. (1997) describe the relationship between the strain imposed on a floc and individual fibre properties such as coarseness and diameter, floc consistency, compressibility. It was found that the effect of gap size on the peak force is strongly dependent on the size of the floc, the mass of fibres caught between the gap and the compressive modulus of the floc. As a result a theoretical and experimental force distribution as the bars passed over one another is shown. In an earlier report, Martinez and Kerekes (1994), describe the behaviour of flocs during bar crossing. Flocs were found to remain intact at larger gap sizes, but ruptured into two parts at very small gap sizes. The authors claimed that the shape of this distribution is similar to the normal force distribution curve reported by Goncharov (1971). Batchelor et al. (1997) indicated also that the shear force increased to a peak over the first part of the bar surface and then decreased to an even level over the remaining width of the bar. The shear force was strongly dependent on the magnitude of the normal force acting on the floc. The peak of the shear force was related to a corner force or as termed by Page (1989) a ploughing force.

Nordman et al. (1981), Caucael et al. (1991, 1992a, 1992b) and Hietanen (1991) are others that have reported pressure measurements in low-consistency refiners. Nordman and co-workers studied the conditions in a small conical LC refiner and with some additional tests in a mill-scale disc refiner. Temperature and pressure transducers (piezoresistive sensors) were installed in pipes and outer shell of the refiner. A sensor for the bar clearance measurement was installed in the outer shell. They measured average pressure amplitudes between 0.1 and 0.5 bar (10-50 kPa). Weaknesses of their experiments were that the results were based on average values as well as the sensors were mounted 2 mm below the actual surfaces of the tackle. These average values were calculated based on measurements captured from several revolutions of the rotor disc. Thus, no high peak values were found. Results from a frequency analysis showed that the angular velocity of the rotor disc and its harmonic signals was observed as well as some higher frequencies. The latter were related to the bar crossing frequencies. The amplitudes were higher in the high frequency region than in the lower region indicating that the pressure variation originated from the bar passage. Probably, the pressure was substantially higher in parts of the refining zone compared to the recorded average pressures. According to Nordman and his co-workers, several of the transducers were damaged by shives or knots. The reason was implicitly related to the low pressure range (6.6 bar), which enhances the conclusion that the pressure could have been much higher. The authors concluded that they could not observe any
hydraulic pressure pulses, which could exert a beating effect. Thus, it was assumed that the beating action was mechanical and exerted by direct contact with the bars.

The measurements of Caucalet al. (1992b) indicated average mechanical pressures of approximately 8 bar (800 kPa). The measurements made by Cauca and co-workers were based on axial thrust measurements and the pressure values were accordingly calculated. In two earlier reports Caucalet al. (1991) and (1992a) another measurement is described. In this work remotely mounted piezoelectric transducers were used. The pressure was assumed to be transferred through water in a pipe binding the transducer to the medium in the refining zone. A hole of 1.5 mm in diameter in a bar was made and the hole was tied to the tube at the back of the plate. Different tube lengths between 120 and 460 mm were tested and the authors found that the signals were damped when the tube length was increased. Reported pressure pulses were in the range of 0.5 to 1 bar (50-100 kPa). It was indicated that only the flow of suspension was responsible of the internal pressure variations (Caucalet al. 1992a).

Hietanen (1991) reported results that showed pressures higher than 26 bar (2.6 MPa) when the plate gap was extremely small (15 µm). She stated that the effective pressure on the fibre mat increased with increasing axial thrust, which is equal with a decreasing plate gap clearance.

Fox (1980) discussed the static pressure conditions in the refining zone of a 300 mm laboratory LC refiner. He displayed results from a study where the pressure field was measured by a water monometer in the grooves of the plate tackle. The pressure was measured in twelve radial positions. He showed basically small pressure fluctuations in the range between ± 100 kPa (± 800 mm Hg). Fox stated that the motion of the rotor caused pressure gradients in the refiner, and that the pressure distribution was not uniform. He concluded that the flow was not likely to be evenly distributed under such circumstances. As a result of a general observation, he stated that the pressure gradient forced the fluid back in the stator grooves towards the centre. Beyond trials incorporating dams in the plate pattern, the pressure was mainly negative in the refining zone. According to Fox, this influences the stability of the operation of the refiner. In addition, Fox claimed that there exists a pressure gradient between the stator and rotor disc which give a flow from the stator groove and into the plate gap. He used the term wiping flow to explain that the flow helps holding the fibres against the leading edge of the rotor bars so that refining work can be done.

4.2.2 High-consistency refining

Despite several experimental studies have focused on the behaviour of the high-consistency refiner, few investigations are reported about the pressure in the refining zone. Attack and Stationwala (1975) was probably the first who measured both temperature and pressure in a 1066 mm (42 inches) open discharge refiner. The pressure measurements using piezoresistive sensors showed a somewhat irregular, but periodic, pattern of variation of up to ± 0.28 bar (28 kPa) around the value of the saturated steam pressure. They observed also intermittent pressure spikes up to 6.2 bar (620 kPa) gauge pressure. These
spikes were ascribed to localized mechanical pressure resulting from the movement of large fragments of wood passing the pressure sensor. According to the authors, steam pressure generated in the refining zone accounted for between 50-70% of the reaction force, which balanced the axial load of the refiner disc. The rest of the reactive force was mechanical and originated from the wood fragments trapped between the refiner plates.

Work performed at PFI showed results from high-frequency pressure and temperature measurements in a 510 mm (20 inches) atmospheric single disc pilot refiner using a combined piezoresistive pressure and temperature transducer (Eriksen 2003, Eriksen et al. 2005a). Pressure changes were observed during chip feeding and during step changes in refiner operating conditions. Decreasing plate clearance gave significantly increased pressure readings. At a small plate clearance, pressure peaks up to 60 bar (6 MPa) were observed. These occurred periodically with a periodicity corresponding to the bar passage of the rotor disc. Else, stochastic pressure spikes in excess of 10 bar (1 MPa) were measured. It was also observed that the bar-to-bar passage was less visible in time series where the refiner was operating at stable conditions i.e. when the plate gap was relatively large. The average pressure readings lay between 2 and 4.5 bar (200-450 kPa) close to the periphery of the refining zone. According to the author, the relatively high and stable average pressure readings indicated that steam pressure was built-up and in turn contributed to counteract the axial thrust in the atmospheric refiner. It was discussed that stagnant pulp in the grooves may have contributed to the resistance against an open steam flow.

The main focus in the doctoral study by Eriksen (2003) was to investigate how to make high-frequency pressure measurements in the refining zone of a high-consistency chip refiner. Results from high-frequency measurements of pressure and temperature in the refining zone of high-consistency refiners were presented. Measurement with fibre optic pressure sensors using extrinsic Fabry-Perot interferometer technology was concluded to give the most promising results in mill-scale refiners. Piezoresistive temperature and pressure transducers were claimed to be reliable in a pilot-scale refiner trial. However, the results from a trial in a mill-scale refiner were characterized as uncertain due to negative influence of the measurements by the wet environment as well as the power hum generated by the large mill-scale refiners.

Eriksen and co-workers (2005b) report high-speed measurements of pressure using eight fibre-optic sensors of approximately 1 mm in diameter assembled at different radial positions in the refining zone. The results showed that the average pressure in the intermediate zone was higher than 25 bar (2.5 MPa). Rapid pressure variations of at least ± 5 bar (500 kPa) were measured. The authors indicated that the pressure fluctuations were probably even higher in the fine bar zone, while the average pressure was at the same level as in the intermediate zone. The pressure was lower in the coarse zone, and fewer peaks of high pressure were found in the first part of the refining zone. The measurements indicated that neither the amount of fibres covering the bars of the plates nor the mechanical pressure was evenly distributed along the radial direction of the refining zone. Theoretical
assessments supported the results when some underlying obligations are fulfilled, which involve only a partial coverage of fibres on the bar intersection area (50-60 %) and a fairly low tangential friction coefficient as well as an average steam pressure in the range of 5-6 bar (500-600 kPa) (Eriksen et al. (2006a)). However, Berg and Karlström (2005) applied similar sensor technology in a similar mill-scale refiner, and they found that the average (static) pressure was close related to the temperature. Based on this observation they stated that the steam was saturated.

Another promising result reported by Eriksen and co-workers, showed that several of the eight fibre-optic sensors measured common periodic pressure pulses associated with especially one identified bar crossing frequency. This bar crossing frequency was associated to the fine bar zone and it was shown as a distinct peak at 25.2 kHz in the frequency analyses. This common periodicity was clearly observed when the plates were new. Measurements with worn plates gave additional frequencies indicating that the flow pattern had changed during the elapsed time. The presence of the distinct peak frequency indicated that the main pressure pulses were generated in the definite radial location in the refining zone. The latter result was supported by additional measurements performed by external accelerometers assembled on the refiner housing because the vibrations showed the same frequencies as were revealed by the pressure sensors (Eriksen 2003, Eriksen et al. 2006b).

Senger et al. (2004) used a piezoelectric sensor measuring the dynamic forces in a small 300 mm (12 inches) laboratory refiner. They observed large peaks in both the normal and shear forces occurring over the initial part of an impact occurring from the passage of a rotor bar. The pressure peaks were estimated to be higher than 40 bar (4 MPa). Senger et al (2005) measured using a novel piezoelectric force sensor the normal and shear forces acting on pulp flocs and wood chips measured over a 5 mm section of an individual bar in the stationary plate of a pilot single-disc refiner. The results indicated that the forces on pulp flocs at 20% consistency were qualitatively similar to those at low-consistency, measured in a previous study. There was a large peak in both the normal and shear forces occurring over the initial part of an impact that decreases greatly over the final portion of the impact. For wood chips, it was observed that impacts would last for several bar crossings and occur periodically with each rotation of the refiner. The authors claimed that this was in accordance with earlier high-speed photographic observations of the flow of chips in mechanical pulp refiners.

Backlund (2004) studied the tangential forces along the refiner gap in commercial HC-refiners, both ordinary flat and conical single-disc refiners. Two different force sensors were developed for the tangential force measurement in commercial TMP refiners, one based on the use of piezoelectric sensors and the other on strain gauges. The latter was also conducted by Gradin and co-workers (1999) in a 500 mm (20 inches) pressurized pilot refiner. The most interesting results, from the study reported by Backlund, showed:
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- The tangential force in the gap of a SD refiner and in the flat zone of a CD refiner increased along the radius
- The tangential forces in the gap showed greater variance at the centre compared to the periphery
- The temperature profile and the tangential force profile had maximum at different positions
- Energy input could be deduced from the tangential forces in a first stage SD refiner
- In general the flat zone had a large influence on the fibre disintegration in the CD refiner

4.3 Temperature measurements

The temperature measurements performed by Nordman et al. (1981) in a small conical LC refiner made use of sensors of the semiconductor type. The sensor surfaces were in contact with the pulp suspension when the sensors were located in the grooves, while the sensors assembled in the bars measured the temperature at the bar surface from a beneath position. Thus, the heat transport through the metallic surface of the bar should be assessed when the results are interpreted. The observations they made was that the temperature of the pulp increased for each passage through the refiner by 1-2 °C. This accounted for 90-95 % of the input energy. The temperature of the pulp flowing in the grooves was always slightly lower (0-3 °C) than the temperature in the bar at the corresponding place. At lower peripheral speed of the refiner the temperature difference between the grooves and the plate gap increased.

Refining of different pulp furnish showed that the temperature was dependent of the type of pulp to be refined. The temperature difference between the grooves and the bars was smaller for pine pulp compared to birch pulp. However, when pine pulp was refined the temperature in the refiner increased more regularly along the length of the refiner. For birch pulp the temperature increased rapidly in the first part of the refiner and levelled out or even decline slightly towards the exit section. The authors remarked that the plate clearance was smaller when birch pulp was refined compared to refining of the softwood species.

In high-consistency refiners, temperature measurements are widely used. Such measurements have been reported since 1973 (May et al. 1973). Among the many reports the following can be mentioned Johansson et al. (2001), Mosbye et al. (2001), Engstrand et al. (1995), Härkönen and Tienvieri (1995), Stationwala et al. (1979) and (1991), Lunan et al. (1983) and Atack and Stationwala (1975). The following paragraphs describe shortly some reflections associated to such measurements:

Engstrand et al. (1995) added alkaline sulphite to the dilution water of a Sprout-Waldron Twin-60 high-consistency refiner under hydraulic pressure control. It was shown that the
plate gap increased due to swelling properties of the fibre wall resulting in a reduction in the specific energy while the temperature in the fibre pad increased probable due to increased friction between the pad and the refiner plates.

Mosbye et al (2001) wanted to determine whether temperature measurements in the refining zone could be used to control the production rate. The temperature profiles in the two refining zones of a Twin-60 refiner were strongly affected by the production rate, dilution water and hydraulic pressure. It was found that temperature measurements could be used to keep the production level constant by changing the speed of the plug screw feeder. The highest temperature peak was measured at a distance approximately \(\frac{3}{4}\) of the total radius of the disc. The mill-scale Twin-60 refiner was operated at a casing pressure of 4 bar (400 kPa).

A combined pressure and temperature transducer was used by Eriksen and co-workers when they investigated the conditions in a 500 mm atmospheric high-consistency pilot refiner (Eriksen 2003, Eriksen et al. 2005a). Mainly, temperatures at or below 100 °C were measured. Figure 6 shows temperature readings associated to one bar-groove passage of the rotating discs (between the broken vertical lines).

![Figure 6](image-url)

**Figure 6.** A combined temperature and pressure transducer was used to measure the change in pressure (top) and temperature (bottom) during one bar crossing (Eriksen et al. 2005a)

The authors interpreted that the temperature and pressure increased due to pulp squeezed between the sensor surface and a rotor bar, and the flat parts of both sides of the deflection indicated smaller amount of pulp present at the location of the sensor. Analysis of the
interrelation between the variables showed that the temperature lagged behind the pressure by 50 µseconds. The high temperature increase of approximately 25 ºC during the short time period was explained by the fact that the simultaneous pressure increase was almost 1.5 bar (150 kPa). The latter could be associated to a shift in saturated water vapour pressure from 1.5 to 3 bar (150-300 kPa), which would give a temperature shift of approximately 16 ºC. Another consideration that was discussed was the effect of plate touching since the initial gap was small (0.25 mm) whereas the heating of the refiner might have created an offset in the plate clearance. May et al. (1973) observed also that the temperature close to the periphery in an atmospheric refiner was in the order of 130 ºC. They ascribed it to be caused by plate touching too.

4.4 Plate gap clearance

Nordman and co-workers (1981) were also conducting plate clearance measurements in LC refiners using an eddy current sensor. In order to ensure a sufficient accuracy, a small part of the plates on the rotor disc, in opposite position of the sensor, had to be modified. A smooth surface larger than single bar widths was required. The initial accuracy was stated to be 1 µm, however, the reliability of the absolute value was observed to be 20 times larger. It was also challenging to establish a real zero-point. They did this as a post-operation after each refining trial by forcing the rotor disc towards the stator until metallic contact was obtained.

Their experiments were conducted such that the bar clearance span varied between 10 and 400 µm. A main conclusion was that the plate gap clearance was especially sensitive to changes in the rotational speed of the refiner. Increasing the angular velocity at a constant beating load caused the bar clearance to increase, and as expected, increasing the beating load resulted in decreasing plate clearance. However, Nordman and his co-workers could not establish a relationship between the bar clearance and the pulp quality. They stated nevertheless that the gap mainly was too high to assume that single fibres could be trapped between the bars on the opposite discs. Thus, they concluded that if fibres receive some kind of compressive mechanical treatment in refining then the fibres appear in bundles or flocs of fibres. On the other hand, they found that the fibre dimension (hardwood vs. softwood) and the physical conditions of the fibres determine the gap clearance.

Disc clearance sensors are more or less established technology in high-consistency refining. Today, relative gap changes can be measured. However, still there are a lot of uncertainties associated to gradually wear and off-set values. The foremost studies connected to gap measurements in mill-scale refiners were done 25 years ago. Stationwala et al. (1979) reported from a mill-study where the plate gap clearance was measured by eddy-current, non-contact displacement type proximity transducers. The reproducibility of the measured values under ordinary operating conditions was reported to be in the order of ± 40 µm. Thereafter, Dahlqvist et al. (1981) and Jackson et al. (1986) introduced mill-scale studies using Sunds Defibrator’s true disc clearance (TDC) sensor for supervision of the refiner.
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plate gap and control of the motor load. Mohlin (2006a, b) reported results from pilot-scale studies with mill size LC refiners where modified TDC sensors were tested. The results were very promising, and thus, she stressed that the plate clearance is a favourable variable to compare refining results compared to the theoretical term refining intensity.

4.5 Residence time

The residence time of pulp fibres in the refiner gives information of the radial velocity of the fibres through the refining zone. The corresponding distribution will also give an image of the treatment of the pulp suspension. If the distribution has a sharp peak, it signifies that the major amount of fibres is treated in a similar manner. The treatment is homogeneity. The broadening of the residence time distribution gives information of the recirculation of pulp, which in turn signifies that the treatment of the fibres are more heterogeneous.

Measurements of residence time in low-consistency refiners have been reported by Arjas and co-workers already in 1970s (Arjas et al. 1970, Arjas 1971, 1980a and 1980b). Arjas summarized his work by stating that the form of the residence time distribution is dependent on the construction of the conical refiner and its operating parameters (Arjas 1980a). The Finnish group used radioactive tracers (Manganese-56 with a half-life time of 2.6 hours) to measure the residence time. Fox (1980) selected another way round because he assumed that the half-life of the manganese was too short. He mixed fibreglass with Na-24 as the isotope (15 hours half-life) into the pulp suspension. The main conclusion from this study was that the flow rate had the most pronounced effect on the mean residence time as well as the corresponding distribution. The rotational speed of the refiner had a large influence on the distribution. The lowest speeds had the broadest distributions indicating that the fibres stay much longer in the refining zone. Fox also measured the residence time with only water present (with another isotope: Ag-110). He concluded that the water runs through the refiner faster than the fibres.

The last years have more focus on residence time measurements being connected to the conditions in high consistency refiners. This subject has been investigated by the following groups of researchers: Ouellet et al. (1995), Senger et al. (1998), Härkönen and Tienvieri (1995), Härkönen et al. (1999), Murton et al. (2002) and Murton and Duffy (2005). They have measured the residence time both by using light through fibre-optic probes and radioactive tracers. A new approach was discussed by Senger and co-workers (2006). They studied the residence time by analysing the signals from force sensors distributed radially outwards in the refining zone.

Härkönen and his co-workers measured the residence times in various parts of the refiner plate gap in order to study the flow conditions in the refining zone. They used radioactive tracers to measure the residence time. The experimental setup consisted of five radially positioned holes in the refining zone where the radioactive detectors were placed. The trials were run with irradiated chips, impregnated with potassium bromide or lanthanum nitrate. The two impregnating fluids consisted of the radioisotope 82Br and 140La with half-life
times of 36 and 40 hours respectively. In the first trials the irradiated chips were fed into the feed of the refiner. Later the irradiated chips were fed directly into the refining zone through the same holes in which the detectors were placed as well as together with the feed as before.

The first trials showed that there was an intensive turbulence in chip and fibre flow before it entered the narrow plate gap. Because of the mixing, the measured residence time was not a sharp pulse but one with a slowly descending tail. The authors studied the response function more closely and used it to characterize the fibre transport and fibre mixing phenomena. They have derived the residence time in different characteristic parameters. Further use of the measured parameters ended up in an estimation of amount of fibre back-flow.

Another result showed that increasing consistency, from 32 % up to 64 %, increased the residence time of the fibres in the primary refiner. This is as expected since the centrifugal force decreases because the amount of wet mass decreases. At the lowest consistency it was observed that the highest amount of back-flow of pulp and water appeared along the stator side of the refining zone.

An impressive experimental layout for residence time measurement is reported by Ouellet and his co-workers (1995). The same setup was also used by the group of Senger et al. (1998). The technique contained a series of fibre-optic probes positioned at the inner and outer radii of the refiner stator disc. Light was brought to each probe through a series of small fiber optic strands positioned around a larger central strand that picked up light reflected by pulp in the refining zone. When the refiner was fed with alternatively black dyed and bleached pulp, a variation in the reflected light appeared when the different pulp units passed the fibre-optic probes. By computing the cross-correlation between the two signals, the time delay and in turn the residence time was found.

The fibre-optic probes were made from 15 thin, coated acrylic fibres with a diameter of 0.75 mm. These optic-fibres surrounded a larger fibre with a diameter of 2 mm. The diameter of the whole probe was 3.75 mm. Nine probes were located at the outer radius of the refining zone and six probes were installed at the inner radius of the refining zone. The small fibres, all simultaneously, carried the light from the source. The source was a 300 W halogen lamp. The larger fibres were also gathered together. These carried the reflected light back to a photodetector. Only one photodetector was used in this experimental layout. A preliminary layout with only two probes, one at each radial location, failed because of too much noise in the measured signals. The measurements were conducted in a pilot refiner fed with kraft pulp. The measured residence time was larger than the values predicted by the Miles and May theory.

### 4.6 Vibrations of the refiner housing

Both Wultsch and Flucher (1958) and Pettersen and Gunström (1980) have used phonometric measurements on the refiner housing in order to interrelate the noise and
vibration measurements to the motor load of the refiner. The latter work was managed by PFI, and it is reported later in English by Pettersen (1986). The PFI group reported work on conical beaters and disc refiners. Among the results, it was shown that the pressure pulses generated from bar crossings created vibrations both in the stator and the rotor discs, which in turn generated acoustic oscillations. The analyses revealed that the corresponding peak frequencies were shifted towards lower frequencies when the motor load increased. However, the shift was only a few Hertz. This phenomenon was assumed to be due to lag in the motor related to its synchronized rotational speed.

Some of the additional results from this study were as follows:

- New plates generated more noise and vibrations than worn plates
- Higher axial thrust gave increased vibration amplitudes whereas the peak frequencies associated to the inlet region (lower frequencies) were more dominating compared to the predominant higher frequencies (when the axial thrust was lower) associated to the outer part of the refining zone
- Vibration analysis related to the radial position showed a parabolic curve indicating a parabolic distribution of the applied energy
- Wave propagation in the surface structure of the refiner housing were detected when the housing was exerted in vibrations
- One experiment indicated that the clearance between the stator and rotor housing varied up to 20 µm during operation

Strand and Hartler (1985) and Strand and Mokvist (1987) studied the vibrations of a high-consistency refiner. They claimed that the origin of vibrations is directly related to the intensity of the pressure pulses resulting from the passing of rotor and stator bars. Thus, Strand and Mokvist (1987) assumed that the intensity of the vibrations, which in turn correspond to the refiner bar frequencies, could be used to characterize the dynamic forces applied to the fibres. In this article they showed one frequency spectrum based on vibration analysis made on one refiner and another spectrum showed the frequencies obtained from the corresponding bar intersecting area (bar pass area). The similarities between these spectra were striking. The former study was performed using a special designed accelerometer mounted on the back of a stator plate. The frequencies related to the accelerometer signal could be divided into four definite regions, as shown in Figure 7, associated to the breaker bar, coarse bar and fine bar sections in addition to vibrational overtones as equivalent termed harmonics (Strand and Hartler 1985).
Figure 7. The frequency spectrum made on measurements of vibrations obtained by Strand and Hartler (1985) shows four distinct regions corresponding to the different sections of the refiner plates.

Eriksen and co-workers (2006b) revealed the proposed interrelation between the pressure pulses created by the overlapping bars and the vibrations of the housing of high-consistency refiners. The frequency analysis of the pressure measures in the refining zone gave almost a mirror image of the vibration spectra appearing from readings of an accelerometer attached on the refiner housing. This was in agreement with the indications made by Strand and Mokvist (1987), who claimed that the pressure pulses appearing from the squeezing of pulp between the stator and rotor bars propagate as vibrations in the mechanical structure of the refiner.

In addition, interpretation of the latter measurements gave origin to a hypothesis that assumes that the pulp flow propagates radially outwards in waves caused by low-frequency disturbances as feeding variations and interruptions by the ribbon feeder or coarse bars. This interpretation is illustrated in Figure 8, which also illustrates the vibration frequency caused by the beating of pulp fibres in one definite area in the refining zone.
Figure 8. The interpretation of measurements of pressure pulses in the refining zone and vibrations of the refiner housing conducted by Eriksen and co-workers (2006b) is illustrated in the sketch of the refiner discs with their tapers.
5 Measurement on fibre properties in the refining zone

This section describes shortly some studies that focused on the pulp quality development through the refining zone of high-consistency refiners. Especially the study conducted by Härkönen and his co-workers (2003) is unique due to their particular pulp sampling technique. Similar sampling techniques are, as far as the present authors know, not reported from low-consistency refining trials. So, even if this study is performed in the HC refining, the idea and the experimental setup are really fascinating. Härkönen et al. (2003) made several interesting observations in the refining zone by taking samples directly from the refining zone at different radial positions in order to study the fibre development. The front plates of the refiners were equipped with radially stepwise positioned holes from which pulp could be collected. The withdrawal of pulp was conducted through the moveable sampling equipment.

In the primary refiner they observed that when pulp reaches the narrow disc gap freeness and fibre length was reduced, while the tensile and tear strength properties were improved. The fibre distribution was then transformed to finer fractions. From earlier studies in high-consistency refiners, it is known that the fingerprint of the pulp properties is set already in the primary refiner. The remaining refining stages are mainly developing the pulp properties further.

Atack and co-workers (1983) replaced a part of a refiner plate with a special transparent plate that made it possible to take photos through. Also samples of pulp material were obtained from the HC-refining zone at different radial locations during normal operation of the refiner. They saw that the reject content decreased as the material progressed through the refiner as well as a large proportion of the pulp strength development occurred in the fine bar section of the refining zone. However, most of the work in the fine bar section was done without any substantial reduction of the fibre length. Another interesting observation was that chips were shredded into coarse pulp ahead of the breaker bars. The material in the breaker bar section consisted of coarse fibres and few shives. They also observed recirculation of coarse pulp in the inner part of refining zone. Backflow occurred along the grooves of the stationary plates and forward flow along the grooves of the rotating plates. Fibres were stapled on the bars attached to both discs in the coarse bar section of the refining zone. The pulp was flowing radially outwards along the grooves and in the plate gap.

Figure 9 shows the development of freeness from the previous discussed experiments by Härkönen et al. (2003) and Atack et al. (1983). The agreement on freeness development is surprisingly equal even if the samples were collected from different process stages. Also the refiners’ size were different as well as the origin wood raw material.
Figure 9. Freeness (CSF) development versus the radial distance from the periphery is plotted according to results presented by Härkönen et al. (2003) and Atack et al. (1983).
6 Concluding remarks

What can be learned by this review and the reported experience from past scientists? It should be notified that it is the same mechanisms researcher’s today want to elucidate as previous scientists has search for in decades. Thus, the subject should be treated with respect. It is no reason to underestimate the challenges that lay ahead of the present and future investigations. However, two reasons point towards an advantage of the researchers of today. Firstly, the present researchers have the past experience to profit on, and secondly, the technology development has escalated such that it should be possible to find or develop the right technology for this purpose as well.

Based on the present survey, it looks like the quantitative aspect of the measured variables should be focused on. A mechanistic model can only be initiated by knowledge of the quantitative value of the desired variables and their interrelation. As Page (1989) pointed out, the stresses applied on the fibres are of major interest because the fibre development that happens in refining appears primarily from contact between the fibres and the tackle material. High-frequency force and pressure measurements over the entire bar width are of extreme importance in order to explain the prevailing theories and hypothesis. Smith’s hypothesis from 1919 enhanced and developed by Banks (1967), Espenmiller (1969) and Fox (1980) are fascinating. Espenmiller claimed that 90 % of the refining power is exchanged at the edges of the bars, and that the dry content in the intersection area is estimated to be 50-60 %. According to that, the low-consistency refiner treats the pulp suspension at high consistency!

The disadvantage with temperature measurements is the heat exchange that prevents fast measurements. It should also be questioned what more information temperature measurements can give compared to force or pressure measures. Successfully force and pressure measurements give probably more information than temperature alone. However, it could be valuably to measure extremely rapid temperature changes in order to see any effects of cavitations i.e. bubble collapse or friction effects.

Force or pressure measurements may also give information of the gap clearance, the floc size and the floc density. These variables are probably interrelated. Such measurements will also give valuable information of the fibre coverage ratio of the bar edges as well as the bar intersection area. A measure of the distribution of fibres in the entire refining zone would be helpful too. The latter is only possible if sensors are widely distributed both radially as well as tangentially around the refining zone. Floc density and floc distribution should also be possible to measure with laser-optic equipment as shown by Alahautala and his co-workers (2004). The question is whether it is possible to apply it in a low-consistency refiner.
Photographic methods are valuable as tools to enhance the comprehension of what happens in the refining zone. Image analysis may contribute to give more quantitative measures of the amount of fibres in the refining zone as well as the flow rate and the direction of pulp flows. Plate gap clearance, vibrations and residence time measurements are probably more effective as tools in control strategies than in exploitation in the research phase. However, together with other measurements these variables may be used to enhance the explanation of hypotheses.
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