On the complexity of LC refining: changing consistency and flow rate in the Beloit DD Refiner
Scientific and technical advances in refining and mechanical pulping, Pira Int., Leatherhead, UK.
On the complexity of LC-refining – changing consistency and flow-rate in the Beloit DD-refiner

Ulla-Britt Mohlin, STFI AB, Stockholm, Sweden

Summary

Industrial refining in a Beloit double disc refiner was studied for a TCF-bleached softwood kraft pulp. Refining consistency and production in the refiner were varied. The fiber treatment was evaluated by observing changes in WRV, SR-number, fiber length and fiber curl. The refining was characterized by refining energy, power input, refining gap and flow-rate.

It was found that the concept of specific edge load and specific energy did not satisfactorily describe the refining result. Within the interval of specific energy studied, WRV increased linearly with specific energy, but the slope of the line varied with the flow-rate through the refiner. Refining consistency did not influence the slope in the interval 3.0 – 4.5 %. The refining gap was mainly an effect of power input and was not influenced by the flow-rate. The effect of flow-rate on refining efficiency was not observed when the pulp was refined in a second stage.

The intercept of the straight line “WRV vs. specific energy” differed from the measured WRV-unrefined pulps in a systematic manner. At higher consistencies the intercept was higher than the measured value; at lower consistencies it was lower. This was interpreted as that the plate gap at which refining actually started increased with increasing consistency.

The results show that the specific edge load theory and other similar theories describing refining intensity are not sufficient. Attention has to be paid to the flow conditions in the refiner and the networking ability of the pulp suspension. The generality of these results was not investigated. Other plate patterns and other pulps might behave differently.

Introduction

Refining is the most important operation to tailor the fibers to obtain the paper properties wanted. Still, however, the understanding of the refining process is very limited. The most common way to determine the refining response of a certain pulp is to run it through a refiner of similar design and similar conditions as it is going to be used.

The refining process is usually described by two factors, refining intensity and refining amount. The most used parameters are specific edge load and specific energy (Baker 1995). Modifications of the specific edge load have been suggested, modified SEL-theory (Melzer 1995), specific surface load (Lumiainen 1995), the C-factor (Kerekes 1990) and other even more complex expressions (Joris 1995) (Radoslava, Roux et al. 1997)]. None of them has however been widely accepted. Of the simpler models, only the C-factor theory takes into account the properties of the fiber suspension.

Pilot and industrial-like laboratory refining studies are usually performed at constant specific edge load and with varying specific energy. Since constant specific edge load requires that the power is kept constant, other methods to changing specific refining energy are used. Constant specific edge load and varying specific energy can be obtained by multi-stage refining or by varying the production through the refiner at the same time as the power input is kept constant. The production through the refiner can be changed either by changing the flow-rate or changing the refining consistency. The drawback with the multi-stage refining is that the
fiber properties change with refining and this may affect the refining results. In a mill situation, however, an increase in specific energy is usually obtained by increasing the power, i.e. at the same time as the specific energy is increased the specific edge load is increased.

At STFI, the refining pilot plant is equipped in a way that allows for refining studies in a more mill-like manner by keeping the production level constant and varying the power input. This makes it possible to separate the effects of power input, flow-rate and refining consistency. To be able to refine at different conditions/intensities, commonly two levels of production (flow-rate) are used.

Refining is usually followed by measuring the SR-number and the handsheet properties. The drawback of using handsheet properties is that the interpretation in terms of changes to the fibers is complicated. This makes any straightforward understanding of refining impossible. In earlier studies (Mohlin and Alfredsson 1990; Mohlin 1991; Mohlin and Miller 1995) it was shown that on the fiber level the three important changes introduced by refining are fiber fibrillation (including internal and external fibrillation and fines formation), fiber shortening and changes in fiber curl. In the latter case the fiber can be both straightened or further deformed by refining. Measurements on the fiber suspensions, WRV as a measure of bonding, image analysis for fiber length and fiber curl can replace handsheet testing (Mohlin 1991, Mohlin 2001).

The main purpose of refining is to improve the bonding properties of the fibers. When using WRV as the measure of changes to the fiber bonding ability it is found that for bleached softwood kraft pulps the WRV increases linearly with refining energy, and that the refining result can be described with a slope and an intercept for the line WRV vs. refining energy. (The intercept does not always coincide with the WRV of unrefined pulps.)

One such example is shown in figure 1, a comparison of the Beloit 24” DD-refiner and the Metso JC01 conical refiner (Mohlin, Miller 1995). The pulp used was an ECF-bleached softwood market kraft pulp. The refining was done at 3.5 % consistency at two levels of production, i.e. flow rates. In spite of the great difference in intensities the WRV developed in a similar manner at both levels of production. The slope was somewhat different for the two refiners, 0.290 WRV units (g/g) increase per 100 kWh/t for the DD-refiner and 0.230 WRV-units for the conical JC01-refiner.

![Figure 1](image-url)  
**Figure 1.** WRV increased linearly with energy input. The refining efficiency was independent of refining intensity and production level but was somewhat different between the two refiners.
For never-dried unbleached softwood kraft pulps a deviation from linearity for the WRV-energy relationship has been observed (Mohlin, 2002). In contrast to the results for the bleached pulps, separate WRV-energy relationships were obtained when pH and production level in the refining were changed. However, a unique relationship between WRV-increase and refining gap was obtained. The refining gap was decreased both by increasing power and by increasing pH.

In the study reported here, it was decided to look in more detail on the effect of refining consistency and flow-rate in the refiner on refining result. The refiner used was a 24” Beloit double disc refiner equipped with Beloit refiner segments. The results lead to the surprising conclusion that the flow-rate in the refiners was the factor most important for the refining efficiency.

![Figure 2. For unbleached softwood kraft pulp the relationship WRV-energy deviated from linearity and was influenced both by level of production and pH. Refining activity, calculated as (WRV-increase) x (production), was directly related to plate gap, independent of pH and production level in the refiner.](image)

**Experimental**

**Pulp**

A market softwood bleached kraft pulp of the TCF-type from a Scandinavian pulp producer was used in the study. Two batches of the pulp were used. They differed somewhat in fiber length distribution and fiber curl. It was also observed that WRV of the unrefined pulps varied with residence time in the pulp storage tank, figure 3. A, B and C represent the three days the trial took place, B and C came from the same batch. The numbering represents the internal order of the samples each day.

![Figure 3. WRV of unrefined pulp was affected by pulp preparation. The legend indicates the order the experiments were run. There was a systematic trend to have an increase in WRV unrefined pulp when the second refining curve was taken at each consistency.](image)
Refining conditions

Refining was performed in the Beloit 24” double disc refiner at different target concentrations in the interval 2.0 % to 4.5%. The refining was performed as single-stage refining at two levels of production, 1.5 t/h and 0.84 t/h. The flow-rate at the different refining consistencies was adjusted to fit the two levels of production. Every refining curve contained five specific energy levels in the interval 40 – 120 kWh/ton. This corresponds to refining intensities according to the SEL-theory of 0.4 – 1.2 Ws/m for the low production and 0.7 – 2.1 Ws/m for the high production level. Besides power input and no-load power, the refining gap was recorded. The refining segments used were Beloit 24EJ 103 with edge length of 84.5 km/s identified with the code 4.0; 4.0; 7.1; 10°. The refining temperature was 20 °C.

Refining conditions are given in table 1. The target consistencies were not reached for the higher consistencies. The specific energy levels were recalculated according to the measured consistencies. To characterize the refining intensity, the slope of the line for SEL vs. specific energy is used in table 1.

Table 1. Process conditions for the refining curves

<table>
<thead>
<tr>
<th>Refining curve</th>
<th>Flow-rate l/min</th>
<th>Measured cons. %</th>
<th>SEL/spec energy (Ws/m)/(100 kWh/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0 % high</td>
<td>1250</td>
<td>2.08</td>
<td>1.92</td>
</tr>
<tr>
<td>2.0 % low</td>
<td>700</td>
<td>2.12</td>
<td>1.04</td>
</tr>
<tr>
<td>3.0 % high</td>
<td>860</td>
<td>3.15</td>
<td>1.92</td>
</tr>
<tr>
<td>3.0 % low</td>
<td>460</td>
<td>3.00</td>
<td>0.99</td>
</tr>
<tr>
<td>3.5 % high</td>
<td>680</td>
<td>3.30</td>
<td>1.60</td>
</tr>
<tr>
<td>3.5 % low</td>
<td>400</td>
<td>3.30</td>
<td>0.95</td>
</tr>
<tr>
<td>4.0 % high</td>
<td>620</td>
<td>3.87</td>
<td>1.71</td>
</tr>
<tr>
<td>4.0 % low</td>
<td>350</td>
<td>3.70</td>
<td>0.92</td>
</tr>
<tr>
<td>4.5 % high</td>
<td>580</td>
<td>3.85</td>
<td>1.59</td>
</tr>
<tr>
<td>4.5 % low</td>
<td>310</td>
<td>3.82</td>
<td>0.85</td>
</tr>
</tbody>
</table>

In addition to the single-stage refining, refining was performed as a second-stage refining of a pulp already refined with 80 kWh/t (at 3.5 % consistency). The purpose was to see if an already refined pulp behaved differently in the refiner. This refining was done at 3.5 % consistency.

Testing

Refined and unrefined pulps were analyzed with respect to WRV-whole pulp, WRV-fiber fraction (fines removed) and SR-number using SCAN-standards when applicable. Fiber dimensions and fiber curl were measured using the STFI FiberMaster (Karlsson 1999).

Results

For an efficient refining, three factors are important when it comes to fiber property changes. Fiber bonding should be improved using as little energy as possible and the degree of fiber curl and fiber damage should be minimized. The following discussion will mainly focus on the improvement in fiber bonding ability.
Refining efficiency for WRV-development

The most important effect of refining is the improvement in fiber bonding ability. This is mainly related to the changes in fiber fibrillation, i.e. internal fibrillation, external fibrillation and fines formation. All these changes are reflected in the WRV and the SR-number. The SR-number is believed to be more affected by fines than WRV. WRV whole pulp in relation to WRV fiber fraction is affected by the amount and the quality of the fines. The relationship between these variables is different depending on the type of refining equipment used, mainly as a result of different levels of fines production. In laboratory refining less fines and external fibrillation are produced in comparison with industrial refining (Mohlin 1991).

Figure 4. The relationship between SR-number and WRV was not influenced by the refining conditions, neither was the relationship between WRV-whole pulp and WRV-fiber fraction.

In this study the WRV-whole pulp, WRV-fiber fraction and SR-number followed each other. Figure 4 shows the relationships between SR-number and WRV and WRV-whole pulp and WRV-fiber fraction. No effect of refining conditions on those relationships was observed. This indicates that the type of fiber treatment was the same independent of the refining consistency and the production.

In the following discussion, WRV-whole pulp will be used as the measure of the refining effect. As shown in figure 1, the WRV usually increases linearly with specific energy. This makes it preferable to use WRV and not the SR-number as the slope of WRV vs. specific energy can be used to characterize refining efficiency.

Also in this study, WRV was found to increase linearly with refining energy when refining the bleached softwood kraft pulp. However, contrary to what was observed in the refining studies shown in figure 1, the slope changed depending on the refining conditions. Refining efficiency was larger at the higher production rate than at the lower, but there were also differences between the different consistencies. There was a 50% difference in refining efficiency between the lowest and the highest observed values. For most of the lines the regression coefficient was high and the differences in slopes observed were significant. For the single-stage refining it was only for one of the refining conditions (4% low prod.) that the
straight-line regression coefficient was below 0.98. It is plausible to attribute this to experimental difficulties.

Table 2. Characteristics for the refining curves

<table>
<thead>
<tr>
<th>Refining curve</th>
<th>Slope</th>
<th>Intercept</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WRV/energy</td>
<td>“WRV unrefined” [g/g]</td>
<td></td>
</tr>
<tr>
<td>2.0 % high prod</td>
<td>0.254</td>
<td>1.19</td>
<td>0.988</td>
</tr>
<tr>
<td>2.0 % low prod</td>
<td>0.252</td>
<td>1.19</td>
<td>0.988</td>
</tr>
<tr>
<td>3.0 % high prod</td>
<td>0.322</td>
<td>1.11</td>
<td>0.994</td>
</tr>
<tr>
<td>3.0 % low prod</td>
<td>0.229</td>
<td>1.17</td>
<td>0.987</td>
</tr>
<tr>
<td>3.5 % high prod</td>
<td>0.301</td>
<td>1.23</td>
<td>0.983</td>
</tr>
<tr>
<td>3.5 % low prod</td>
<td>0.220</td>
<td>1.31</td>
<td>0.995</td>
</tr>
<tr>
<td>4.0 % high prod</td>
<td>0.260</td>
<td>1.20</td>
<td>0.988</td>
</tr>
<tr>
<td>4.0 % low prod</td>
<td>0.220</td>
<td>1.26</td>
<td>0.915</td>
</tr>
<tr>
<td>4.5 % high prod</td>
<td>0.270</td>
<td>1.15</td>
<td>0.979</td>
</tr>
<tr>
<td>4.5 % low prod</td>
<td>0.240</td>
<td>1.18</td>
<td>0.987</td>
</tr>
<tr>
<td>3.5 % high 2nd stage</td>
<td>0.235</td>
<td>1.47</td>
<td>0.967</td>
</tr>
<tr>
<td>3.5 % low 2nd stage</td>
<td>0.251</td>
<td>1.47</td>
<td>0.950</td>
</tr>
</tbody>
</table>

To explain the different slopes the most evident explanation to look for is the difference in refining intensity between the two levels of production. Plotting refining efficiency (slope WRV/energy) against the refining intensity slope (SEL/ specific energy) clearly indicates that the effect of refining consistency on refining efficiency cannot be explained by differences in refining intensities, top diagram in Figure 5. The data are grouped according to the two levels of production, but within each group the refining intensity cannot explain the variation.

When looking for an explanation to the observed differences in slopes, an unexpected result was obtained. The refining efficiency for the first-stage refining, measured as the slope of WRV vs. energy, could to a large extent be explained by the differences in flow-rate, right bottom diagram in figure 5. The only exception was refining at two percent consistency at the high flow-rate. Flow-rate was thus more important for the refining efficiency than the production through the refiner or the refining intensity.

These results are not in agreement with earlier reported studies from where figure 1 originates. In comparison with the earlier studies another set of fillings (Beloit instead of Pilao) was used in the refiner and this could be the cause for the different response to flow-rate changes. Another possible explanation might be, of course, differences in the pulps used.

The effect of flow rate on refining efficiency was not observed for the second-stage refining, table 2. Instead the trend was the same as for the first-stage refining at 2.0%; the refining efficiency was similar at both flow rates. A common factor for the 2.0% first-stage refining and the second-stage refining was that for these refining curves a smaller refining gap was obtained at a certain power input, compared with what was observed for the other refining curves, see next section.
Figure 5. Refining efficiency, measured as the slope for the line WRV vs. refining energy, was mainly explained by the flow-rate differences through the refiner. The exception was 2% consistency at the high flow-rate. The refining intensity evaluated as the slope of the line SEL/spec energy or the refining consistency did not relate to the differences in refining efficiency.

Refining gap and power input

The results above indicate that refining at two percent consistency does not follow the same trend as the higher consistency levels. The reason is found when looking at data for the refining gap, figure 6. A significantly different relationship was obtained between the refining gap and the power input at 2% consistency. At the consistency levels above 3% no difference in the relationship between refining gap and power input was observed due to consistency. A small tendency to a larger plate gap at the higher production level at the same power input could be detected. This similarity in refining gap means that if refining comparisons are made at the same specific energy and different production rates, the plate gap will be significantly smaller at the higher production rate as a higher power is needed to reach the same specific energy. At the 2% refining consistency the production level had a larger influence on the refining gap.
The refining gap was very little affected by the production rate and the refining consistency. A common view is that low flow rates should be avoided, as it should increase the risk for plate clashing (Rihs et al 1997). No such trends are evident from the results presented here. On the contrary, according to the results of this study a lower production will need a lower power input to reach a certain specific energy and thus the plate gap will be larger.

The decrease in refining gap with refining, when going from first-stage to second-stage refining, is well known from earlier multi-stage refining studies, Figure 7. This is usually attributed to decreased fiber flocculation/floc strength. Decreased floc strength is also the probable explanation to the smaller refining gap at 2% consistency.

Combining the observations of the effect of flow-rate and refining consistency on refining efficiency and on refining gap, the complex nature of the refining process becomes evident. Two different process models can be formulated. For the single-stage refining above 3% consistency, the refining efficiency (WRV/energy) was influenced by the flow-rate. The relationship between power and refining gap was not influenced by the flow-rate or the refining consistency. For the single-stage refining at 2% consistency, and for the second-stage refining (3.5%), the refining efficiency was not influenced by the flow-rate but the refining gap was reduced compared with the other trials. In the latter cases the floc tendency or floc strength were probably lower than at the other ones.

The flow conditions in refiners are very complex. In the stator, a large recirculation flow has been shown to occur (Fox et al 1982) and the main transport of fibers out from the refiner takes place in the rotating disc or cone. Studies of the retention time in the refiner have also shown that the time in the refiner differs between the fibers and the water phase (Groome 1980). No systematic studies are available that show how these flow conditions are changed when flow-rate, refining consistency or pulp flocculation are changed. A possible interpretation of the results presented here is that at some floc strength levels there is a change from a one-phase system, a uniform fiber suspension, to a two-phase system, a fiber phase and a water phase.
The no-load power

The linear relationship between WRV and specific energy did not always point at the WRV for unrefined pulp. To some extent this could be attributed to that the WRV unrefined pulp changed with storage conditions. Taking the varying levels of WRV for unrefined pulp into account, some systematic trends were, however, detected.

The intercept of the lines WRV vs. specific energy corresponds to an artificial “WRV-unrefined pulp”. When this number was compared with the actual measured number an interesting observation was made. The higher the refining consistency, the smaller was this difference, figure 8. A plausible interpretation is that the refining starts at a plate gap that differs from the plate gap that corresponds to the no-load power. At the higher consistency, the fiber mat will start to take up load at a larger plate gap than at the lower consistency, figure 9. At the lower consistency, the critical plate gap becomes smaller when the fiber treatment starts.

Figure 7. The refiner gap was smaller for the once refined pulp in the second-stage refining.

Figure 8. The difference in WRV-measured for the unrefined pulp and the intercept of the straight-line relationship between WRV and energy input decreased with increasing refining consistency.
Figure 9. The origin to the different levels for extrapolated WRV to zero refining in relation to the measured value can be due to the fact that the refining does not start at the no-load.

The no-load power is defined as the power level, which is needed to run the refiner with pulp suspension at a large plate gap so that no refining could be expected. A mechanistic way of looking at the refining is that as the plates are brought into closer contact the fiber mat will at a certain plate gap start to take up the load and the refining will start. This does not necessarily have to coincide with the no-load power. The plate gap might, when the refining starts, be influenced by the fiber flocculation, i.e. fiber geometry and stock consistency. The 2%-refining consistency does not fit this picture as it has a completely different relationship between power input and refining gap.

Refining conditions and fiber length and fiber curl

Fiber length was reduced with refining. The analysis of the data showed that the fiber length reduction was mainly related to the power input, i.e. refining intensity and not to the degree of fiber treatment, figure 10. At the lower production, the fiber length reduction was more severe than at the higher production rate compared at the same power input. This means that the somewhat higher refining gap that was observed at the higher production rate protected the fibers from fiber cutting at comparable power. The correlation with power was stronger (for each level of production) than the correlation with the degree of fiber treatment (WRV-whole pulp, right diagram in figure 10), or specific energy. Only relative changes in fiber length are presented in figure 10 as the fiber length varied somewhat between the two lots of pulp used in the trial.
Figure 10. The relative change in length weighted average fiber length was mainly related to power. The relationship between fiber treatment, WRV, and fiber length changes was less consistent.

The second-stage refining resulted in a smaller plate gap than the single-stage refining. The fiber length reduction was in this case not related to the power input but to the refining gap, figure 11. The overall effect of the two-stage refining is however a better retention of fiber length for a certain specific energy.

Figure 11. Fiber length after single-stage and after second-stage refining vs. power input in the refiner and refining gap respectively.

The third fiber property that is changed with refining is fiber curl, figure 12. The fiber curl level of the unrefined pulp varied between the different refining series, which made the interpretation more difficult. At lower levels of refining, a reduction in fiber curl was observed. The shape factor increased. For higher degrees of fiber treatment, the improvement in shape factor did not occur. The improvement in fiber curl seems mainly to be related to the degree of fiber treatment, i.e. WRV and an increase in shape factor is observed to WRV about 1.4 g/g. At higher degrees of fiber treatment no correlation between the shape factor and
WRV could be observed. Instead the refining gap seemed to be the limiting factor for how much the shape factor could be improved, right diagram in figure 12.

Figure 12. Shape factor for fibers in length interval 1.5 – 3.0 mm vs. WRV and refining gap.

Discussion

The many years of refining studies without being able to explain why a certain pulp takes refining so different from another pulp might be a sign that we have not used the right set of tools when studying refining. In this report some observations are presented that suggest a way to reach a better understanding of refining.

The key to a better understanding of refining is to study the changes in fiber geometry, i.e. fiber length and fiber curl. Tools are available today, the STFI FiberMaster or other similar instruments. The use of WRV as a measure of fiber treatment instead of SR-number also simplifies the interpretation of the data as straight-line relationships were obtained for WRV vs. energy. The method is still not applicable for on-line testing. Evaluating refining results using only handsheet strength should be avoided, as the interpretation is complex. Fiber treatment, fiber curl and fiber shortening will all influence the sheet strength.

The results from this study tell that

- the flow conditions in the refiner can be more important than refining intensity.
- the refining consistency does not influence refining efficiency but might influence the refining gap/power level when refining actually starts.

The results suggest that the plate gap and the power input have a large effect on the refining result and that they should be looked at as the primary variables in refining instead of measures of refining intensity. This is in agreement with results from a study of refining of unbleached kraft pulp at different pH (Mohlin 2002).

That a high flow-rate is positive agrees with statements made by the refiner manufacturer (Rihls and Josephsson 1997). Their interpretation for the positive effect of increasing flow-rate was however not the one found here. Their interpretation was that a decreased flow-rate
decreased the plate gap to the level of metal contact and resulted in deterioration in fiber and paper properties.

The results from this study should not be generalized to be valid for other types of refiners or other refiner segment patterns. More studies are needed to develop a solid understanding of the refining process. The tools presented here are however believed to make it possible to revive refining research and refiner development.

Pilot-scale single-stage refining makes it possible to vary refining conditions without having to take into account a related change in fiber quality when interpreting the results. Conventional refining studies performed at constant refining intensity do not produce this type of systematic results. Multi-stage refining at constant SEL will be affected by the change in fiber properties due to refining. The other way of comparing at the same refining intensity and obtain different levels of specific energy would be to vary the production (flow-rate). As shown here that would influence the refining efficiency.

References
*Critical review of refiner theory.*
3rd International Refining Conference, Atlanta, Georgia, USA, PIRA.

*Inside a disc refiner*
Tappi J 65, 7 pp 80-83

Groome E J (1980)
*Fiber retention time in a disc refiner*
International symposium on Fundamental Concepts of refining, Appleton Wisconsin, pp 21-29

*Optimizing fillings for LC-refiners.*
3rd International Refining Conference, Atlanta, Georgia, USA, PIRA.

Karlsson H; Fransson P-I; Mohlin U-B (1999)
*STFI Fibermaster*

*"Characterization of pulp refiners by a C-factor."

*Specific surface load theory.*
3rd International Refining Conference, Atlanta, Georgia, USA, PIRA.

*New ways to forecast the technological results of refining.*
3rd International Refining Conference, Atlanta, Georgia, USA, PIRA.

*Low consistency beating - laboratory evaluation contra industrial experience.*
Current and future technologies of refining., PIRA International, UK.


Mohlin U-B (2001) Predicting the refining response of bleached market kraft pulps by laboratory refining KCL-rapport 2524; STFI-rapport CHEM 17


Rihs, J. and W. E. Josephsson (1997). Refining systems with flow recirculation. 4th International Refining Conference, Fiuggi, Italy, PIRA.