Mechanical pulping

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TMP properties and refining conditions in a CD82 chip refiner. Part I: Step changes of process variables, description of the tests

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Abstract: The study explores how changes in process variables, residence time and pulp consistency in refining influence the pulp properties. The equipment utilized in this study was a conical disc chip refiner (RGP82CD) producing thermomechanical pulp (TMP). The focus was on the ratio between tensile index and specific energy consumption. Pulp properties were measured for composite pulp samples taken from the refiner blow line. Residence times and pulp consistencies were estimated by use of the extended entropy model. This showed that the CD-refiner, with the flat and conical refining zone, has a process performance similar to that of a two-stage refiner set-up, and that the consistency in both refining zones is of high importance. Comparing different periods revealed that even if the values of measured blow line consistency are similar, significant differences in the estimated consistency in the flat zone can prevail. Therefore, only monitoring blow line consistency is not enough. Specifically, it was found that the pulp consistency after the flat zone could be very high, considerably higher than in the blow line, and this could have negative effects on tensile index and fibre length.

Keywords: conical disc refiner; energy; entropy model; fibre properties; pulp consistency; pulp properties; residence time; temperature profile; TMP.

Introduction

CD refiners were introduced in the late seventies. Tistad et al. reported operational experiences in 1981. Following this, few studies have been reported and those conducted mainly concern segment development, see for example Deer et al. (2007), Fostokjian et al. (2005), Bussiere et al. (2007), Johansson et al. (2001), Johansson and Richardson (2005). In the latter paper, measurements from temperature sensor arrays were included in the analysis. Temperature sensor arrays were also used by Backlund (2004) when analysing the effect of process variations on some pulp properties. Related to CD refiners, the work by Backlund is of particular interest as it includes the unusual element of pulp samples collected after the flat zone.

In 1993, Strand et al. performed a test on a CD 76 refiner including changes in rotational speed. Firstly, they showed that during operation at a given production rate, similar values of both specific energy and pulp properties could be reached although different rotational speeds were considered, namely 1500 and 1800 rpm. Secondly, they found that at higher rotational speed an increase in production rate, was enabled and thereby lower values in specific energy to a given pulp quality. As the values of freeness and tensile index were maintained at the same levels, an increase in energy efficiency with respect to these properties was demonstrated. Later, Härkönen and Tienvieri (1995) showed that the increase in production rate in a SD 65 refiner could decrease the specific energy at a given level of freeness. When operating at these refiner conditions, they obtained a slight decrease in both tensile index and tear index. Their study also included temperature measurements along the refining zone radius.

Characterization of the refiner conditions is not straightforward. Several studies have shown that different combinations of dilution water flow and plate gap can result in the same level of refiner motor load at a given production rate, see for example Johansson et al. (1980), Hill (1993) and Hill et al. (1993). This indicates that more variables than specific energy must be considered when describing the process conditions. It was also shown that different refiner conditions lead to different pulp properties despite equal load and production rate.

May et al. (1988) presented fibre residence time in the refiner as one way of improving the description of high

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consistency refining. Some years later, Härkönen et al. (1999) measured fibre residence time in a SD 65 by using a radioactive tracer with a short half-time. In their study, fibre residence time of primary, secondary and reject refiners were included as well as different segment patterns. They conclude that the residence time in the inner part of the segments varies between 2.5–7 as, while it is about 0.5 s in the outer part of the segments. The residence time is affected by segment design and refiner position. In this work, no attempt is made to link the fibre residence time to pulp quality. A similar approach was applied by Vikman et al. (2005), when studying residence time in a two-stage RGP82CD line producing hardwood CTMP. They compare their results to those by Härkönen et al. (1999), and conclude that the fibre residence time is strongly influenced by segment geometry. Furthermore, they conclude that the produced pulp quality was impacted by the fibre residence time and other variables. Based on these studies, it can be concluded that determining values of residence time from direct measurements is a complex task. If fibre residence time is demanded at a frequency of ordinary process variables, model-based estimations should be considered.

There are other studies, see e. g. Eriksen (2003), Senger et al. (2004) and Fredrikson et al. (2012), and references therein aimed at determination of the forces acting on the fibres inside the refining gap. Their focus has not been to link the forces extensively to the pulp property development, but rather to clarify force magnitudes.

Furthermore, Miles and May (1989) claimed that pulp consistency is an important variable. They argue that it determines the pulp properties that could be achieved at a specific energy consumption. Härkönen and Tienvieri (2001) conclude that today the TMP-refiner is controlled simply by measuring input and output variables. If we are to improve the TMP process and process control, we must become better acquainted with unambiguous basic physical factors and use these to describe the conditions in the plate gap and to define the refining result. Karlström and Eriksson (2014) addressed this by modelling the conditions in the refining zone and formulated the extended entropy model. The model is used to compute physical conditions in the refining zone e. g. consistency and fibre residence time as a function of radius. Based on these results the dynamical properties of the produced pulp has been estimated and modelled – see further Karlström et al. (2015, 2016a and 2016b).

This study explores energy efficient operation of CD refiners through measurements of pulp properties and of refining zone temperature profiles. The main hypothesis is that it is possible to find refiner conditions where specific energy is decreased and pulp properties are maintained. Specifically, this study considers the ratio between tensile index measured on handsheets made from composite pulp samples from the refiner blow line and the specific energy consumed in the refiner. A high value of this ratio is desired and associated with high energy efficiency in the refining (although this is not a rigorous definition of energy efficiency). Furthermore, we investigate if residence time and pulp consistency have the potential of relating changes in the process conditions to changes in the properties of the produced pulp. In other words, can these variables be used to explicitly characterize the state of process operation and the properties of the produced pulps?

Materials and methods

This study considers process data from a full-scale production line with a CD 82 refiner as chip refiner followed by a LC refiner (CF 82) in the main line. The produced pulp was screened and reject refined for final use for newsprint. The raw material was Norway spruce (*Picea abies*). The CD 82 refiner was running at 1800 rpm and is equipped with a 25 MW motor. The CD 82 refiner has two serially linked refining zones called the flat zone (FZ) and the conical zone (CZ). In both zones, temperature sensor arrays were mounted for measurement of temperature profiles. For further details, see Engstrand and Engberg (2014). Consistency and residence time were estimated by the extended entropy model described by Karlström and Eriksson (2014). The temperature measurements were used as inputs together with plate gap measurements, information about the specific refiner (e. g. plate pattern and taper) and additional process variables (e. g. dilution water flow rate, production and motor load). When it comes to the CD refiner, residence time and consistency estimates can be derived for both the FZ and the CZ, and these are considered in the analysis that follows.

With this set-up, a total of five tests were conducted during a period of three months covering a large operating window. The pulp samples were collected in the blow line of the CD 82 refiner during all tests. A careful sampling procedure is vital, and Ferritsius et al. (2017) showed that this involves composite pulp samples collected as approximately 30 grab samples during a three-minute period. The composite pulp samples were carefully homogenized, and 3–5 pulp consistencies were measured. Next, the pulp samples were packed in 55 g-packages and stored in freezer before further testing.

In this paper, "operating point" refers to a given setting of external process variables (gaps, dilution water

Table 1: Mean values of plate gaps, dilution water feed rates and production rate during the tests.

	TEST1	TEST2	TEST3	TEST4	TEST5
Prod, admt/h	13.4	15.9	15.0	**12.5–15.9**	14.2
Dil. w. FZ, l/s	3.26	**3.17–3.42**	3.79	3.40	**3.28–3.51**
Dil. w. CZ, l/s	4.76	5.23	**5.06–5.12**	3.88	**4.44–4.70**
Gap FZ, mm	1.53	**1.05–1.36**	1.24	1.48	0.86
Gap CZ, mm	0.86	0.78	**0.57–0.64**	1.14	0.65

flow rates and production rate), although the temperature profile in the refining zones may vary.

Five tests were conducted:

TEST1 involved continuous operation at a single operating point. This test involved a total of 20 composite pulp samples allowing studying procedures for pulp sampling and subsequent testing presented by Ferritsius et al. (2017a).

TEST2 investigated the refining conditions in the FZ by applying step-changes in the associated dilution water flow rate and plate gap. Seven operating points and nine composite pulp samples were covered.

TEST3 aimed at investigating the refining conditions in the CZ by step-changes in the associated dilution water flow and plate gap. However, operational problems occurred during this test; a reduced number of just four composite pulp samples were obtained and the potential to analyse this test was limited.

TEST4 targeted influence of production rate changes by testing three levels in the range 12.5 to 15.9 admt/h. In total, this test series comprises three operating points and 15 composite pulp samples.

TEST5 further investigated changed in the amount of dilution water by applying changes in the flow rates to both the FZ and the CZ. In total, this series comprises three operating points and 15 composite pulp samples.

For numerical values of selected process variables, see Table 1.

Process data and pulp properties for TEST1-5 are listed in the appendix, Tables 3–7. Production rate was determined based on measuring flow rate and consistency (laboratory) out from the latency chest. The level in the latency chest was kept constant. During all tests, process variables were measured at a frequency of 4 Hz.

The pulp samples were hot disintegrated according to ISO 5263-3:2004 before further testing. Freeness was measured according to ISO 5267-2:2001. Fibre length was measured according to ISO 16065-2:2007 using FiberLab. Average length-length weighted fibre length (ww) has been used in this study because it has been shown to be a better measure of the amount of long fibers compared to the length weighted average (Ferritsius et al. 2018a). Measurements in FiberLab were made three times and averages of these are reported in this paper. Somerville shives was measured according to Tappi 275 sp-98. Handsheets without recirculation of white water were made according to ISO 5269-1:2005. The density of the handsheets were measured according to ISO 534:2011. Tensile index were measured on the handsheets according to ISO 1924-3:2005.

For tensile index values, the number of handsheets was increased compared to the ISO standard, and 20 strips were used instead of 8. Duplicate testing was applied resulting in each tensile index value was based on 40 strips. Light scattering was measured according to ISO 9416:2009.

We have used the classification introduced by Karlström and Isaksson (2009) where variables are called *internal*, indicating that they refer to the conditions inside the refining zone, whereas e. g. refiner motor load and specific energy are called *external variables*. The extended entropy model requires temperature profile measurements, which are internal variables in themselves. Pulp consistencies, residence time and forces were calculated along the radius using the temperature profile measurement together with measured process variables and the extended entropy model.

The study presented in this paper focuses on TEST2, TEST4 and TEST5. The results obtained from the pulp property measurements where analysed together with both the estimated and measured refiner variables. In this paper, results derived from each test are presented. In a forthcoming paper Ferritsius et al. (2018b), the results from different tests are compared.

Results

Step changes to the flat zone (FZ), TEST2

The first operating point was at the prevailing refiner conditions (i. e. set-points chosen by the operators) at the start of the test. From these set-points, changes in plate gap and

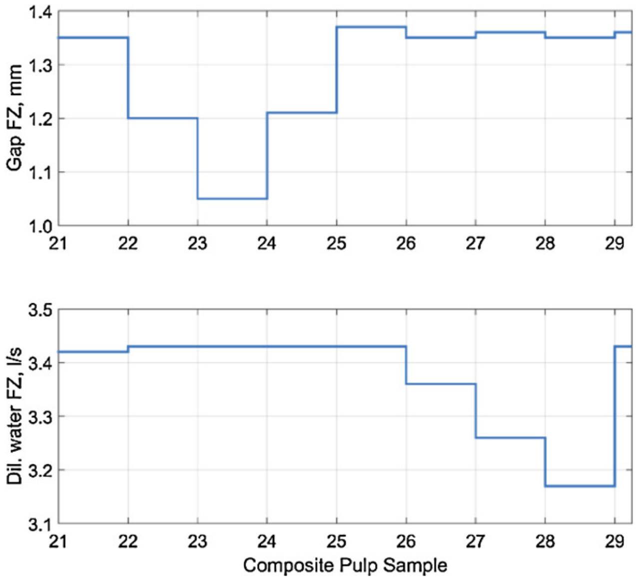

Figure 1: Changes in plate gap and dilution water flow rate to the FZ (flat zone) in TEST2.

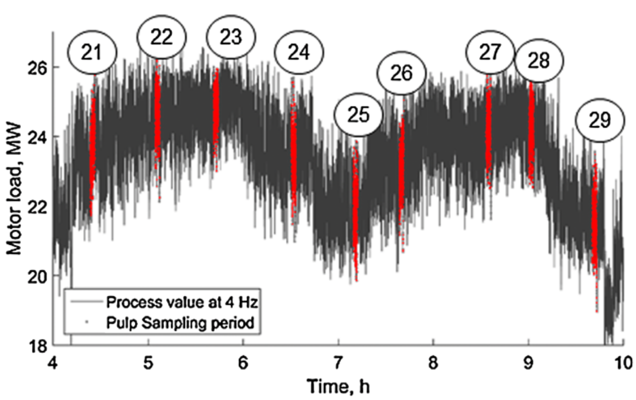

Figure 2: Motor load of the CD 82 refiner during TEST2. Red marks periods when composite pulp samples were collected.

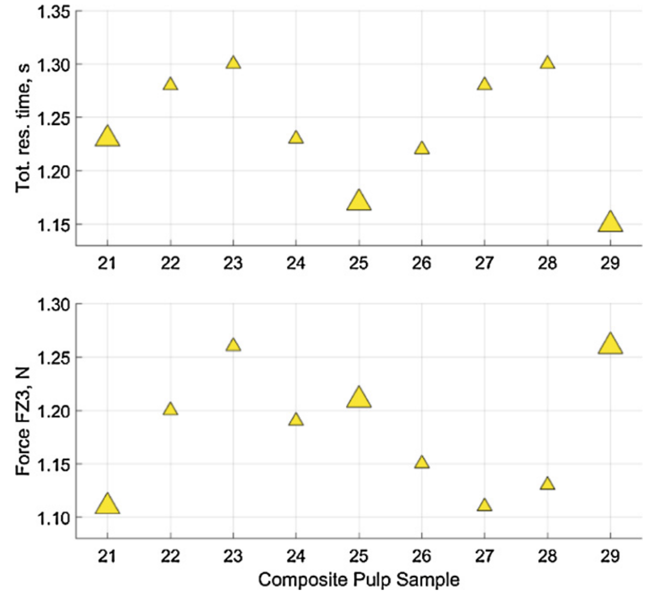

Figure 3: Total residence time and force at the third temperature sensor in the FZ during the time of composite pulp samples in TEST2. The larger symbols have the same set-points for the external variables.

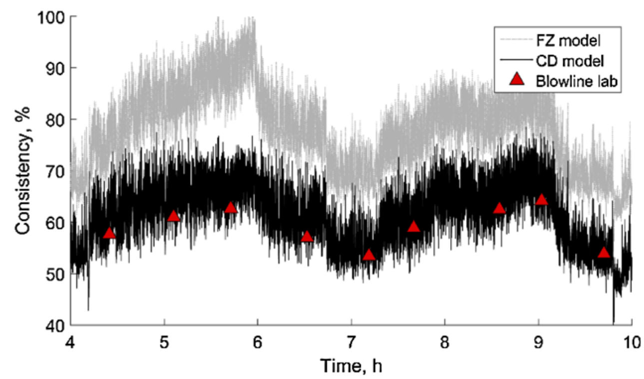

Figure 4: Calculated pulp consistency after FZ (FZ model) and CZ (CD model) during TEST2 (Karlström et al. 2015).

dilution water flow rate were applied according to Figure 1. A subsequent numbering was used, resulting in the composite pulp samples of all tests being referred to as number 21 to 29. These set-point changes influenced the refiner load as shown in Figure 2. The set-points for the external variables were the same for samples #21, #25, and #29, but the level of motor load differed by about 2.5 MW.

Using the extended entropy model, the internal variables residence time, pulp consistency and force along the radius was calculated. The third temperature sensor was placed at the contraction point of the FZ of the segment. It is believed that most of the fibre separation occurred close to this position. In Figure 3, estimates of force in this location is shown together with the total residence time (i. e. both in FZ and CZ) at the time of each composite pulp sample.

Figure 1 and 3 show that the total residence time increased both at decreased plate gap and decreased dilution water flow rate. The force, however, increased when the plate gap decreased, but decreased when the dilution water flow rate was decreased. Comparing the three periods with the same set-points, marked with larger symbols in Figure 3, larger values of the estimated force was obtained at the periods of composite pulp samples #25 and #29. During these periods, motor load and residence time were both set at lower values. These results could indicate that the estimated force at this location may deliver additional information useful for prediction of pulp properties.

The response in consistency was estimated after the FZ and CZ, respectively, see Figure 4, and both of these fol-

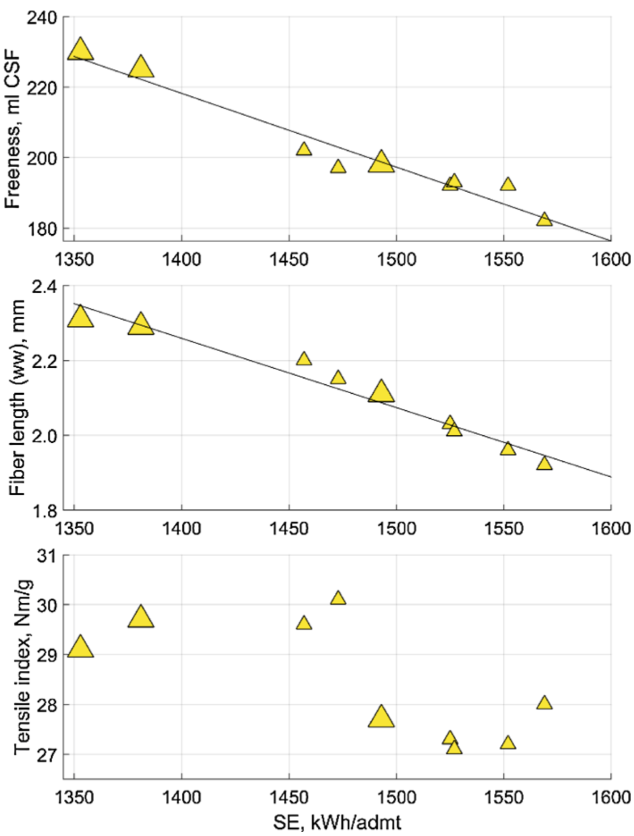

Figure 5: During TEST2, freeness and fibre length decreased with increased specific energy. However, tensile index did not increase despite higher specific energy. The larger symbols have the same set-points for the external variables.

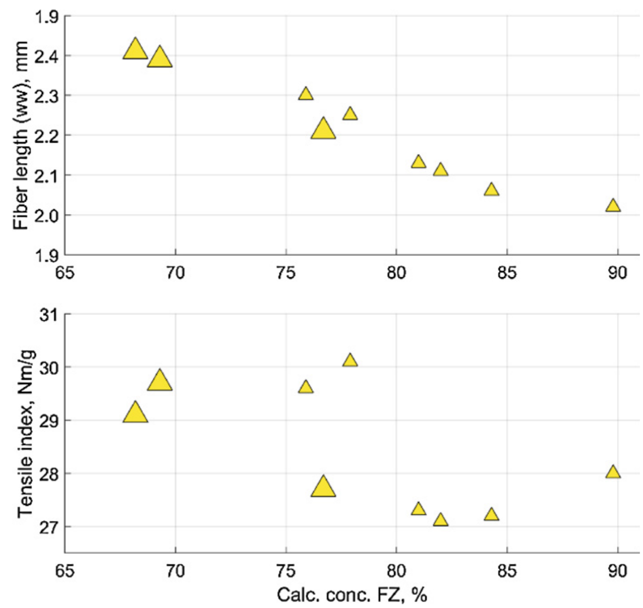

Figure 6: Values of pulp consistency above 70 % after the FZ gave lower values in both fibre length and tensile index. For the larger symbols, the external variables have the same set-points.

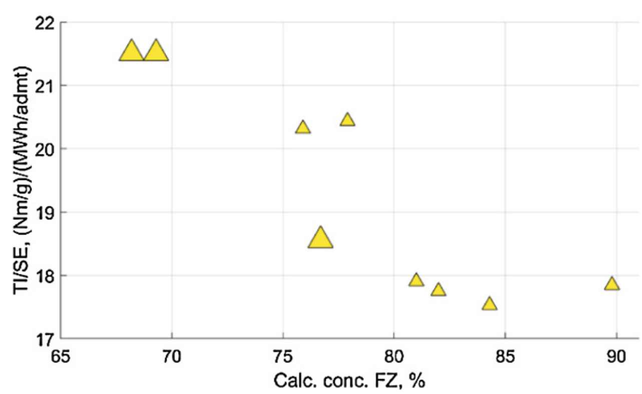

Figure 7: TI/SE was lower for the samples collected during periods when the pulp consistency after the FZ was very high. For the larger symbols, the external variables have the same set-points.

lowed the response in motor load. The absolute values after the flat zone were much higher than after the CZ during this test. The values of calculated pulp consistency after the CZ agreed very well with the measured pulp consistency in the blow line, $R^2 = 0.966$.

Moreover, a co-variation between residence time and specific energy was obtained, $R^2 = 0.953$, and the ratio of residence time in FZ and CZ decreased with increasing total residence time, $R^2 = 0.982$. The same pattern was observed in TEST1 (Ferritsius et al. 2017). Also, calculated pulp consistency after the CZ and total residence time had a very high co-variation in this test, $R^2 = 0.999$.

Freeness and fibre length displayed a linear correlation to specific energy, while tensile index did not correlate to specific energy, see Figure 5.

The set-point for the external variables was the same for pulp sample #21, #25 and #29. Sample #25 and #29 obtained higher values for both fibre length and tensile index than sample #21. This could be related to a phenomenon called “dry cutting” for pulp sample #21, which is likely to occur when the pulp consistency exceeds values of about 70 %, see Figure 6.

“Dry cutting” has also been reported by Strand and Grace (2014) and Liukkonen et al. (2014). At the start of TEST2, the refiner was running with a pulp consistency that was higher than 70 % after the FZ. When the same settings were repeated, the value was slightly below 70 %.

Lastly, for TEST2, changes in both tensile index (TI) and in specific energy (SE) can be illustrated by using the ratio TI/SE, see Figure 7.

The high pulp consistency after the FZ had a large impact on the result. Similar patterns were found for TI/SE versus pulp consistency after the CZ, both estimated and

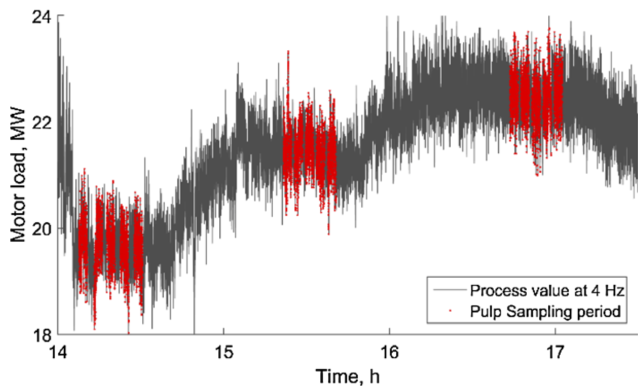

Figure 8: The refiner motor load increased when the production rate was increased during TEST4. The composite pulp sampling periods are marked in red.

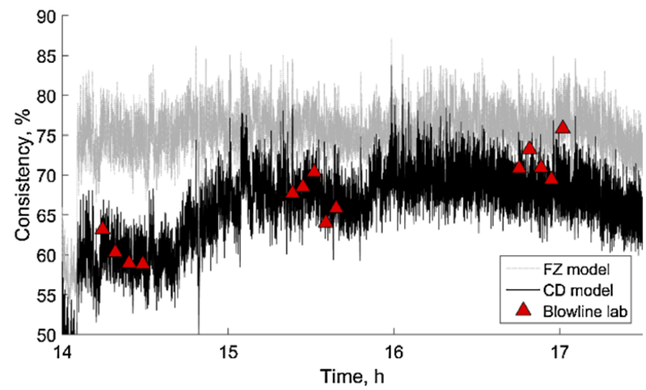

Figure 10: Calculated pulp consistency after the FZ (FZ model) and CZ (CD model) during TEST4 (Karlström et al. 2015).

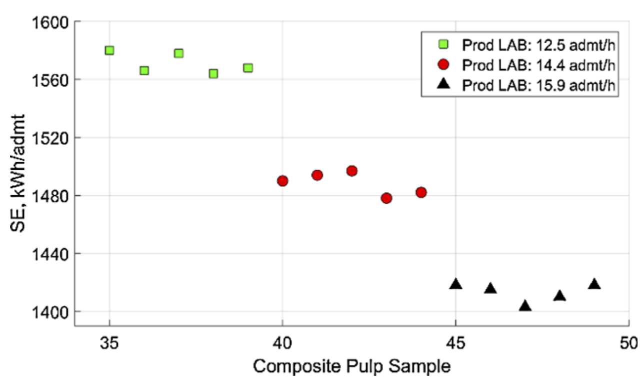

Figure 9: The specific energy decreased when the production rate increased during TEST4.

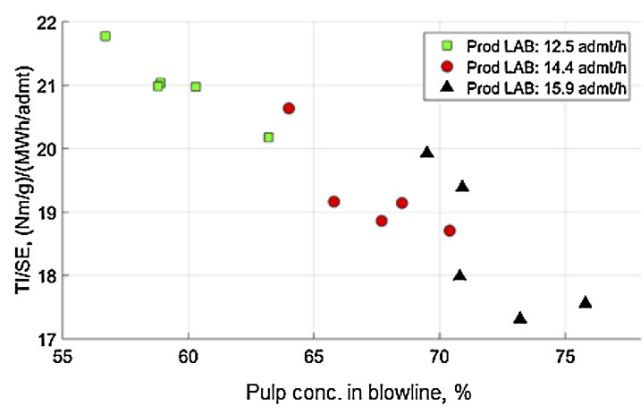

Figure 11: TI/SE ratio decreased in TEST4 with increasing pulp consistency, measured for blow line samples.

measured. This is expected since no changes were made in the CZ dilution water. The consistency after CZ was considerably lower than after FZ, and it is probably the high consistency after FZ that explains the lower tensile index and fibre length although the specific energy was higher than for some of the other samples.

Step changes in production rate, TEST4

In the same way as in TEST2, the first operating point of TEST4 was at the prevailing refiner conditions. From this level, the production rate was increased twice starting at 12.5 admt/h and increased to 14.4 admt/h and then to 15.9 admt/h. At each level of production rate, five composite pulp samples were collected. The refiner motor load increased when the production rate was increased, see Figure 8. However, the specific energy decreased, see Figure 9. The variations in average load and specific energy between the five samples taken at each level of production rate can be regarded as small.

The pulp consistency after the CZ increased when the production rate was increased since the set-point for dilution water flow rate was unchanged, see Figure 10. Some differences in consistency between the composite pulp samples can be observed at each production level. The changes in production rate had higher impact on the pulp consistency after the CZ than estimated after the FZ (Figure 10).

Considering pulp properties, some variations were observed at each production level. It seemed that a higher pulp consistency measured after CZ resulted in lower tensile index values, causing the ratio TI/SE to decrease during TEST4, Figure 11. The ratio TI/SE showed a similar behaviour versus the estimated pulp consistency after the FZ was considered, see Figure 12.

It is obvious that the differences in estimated pulp consistency after the FZ for the operation points are very

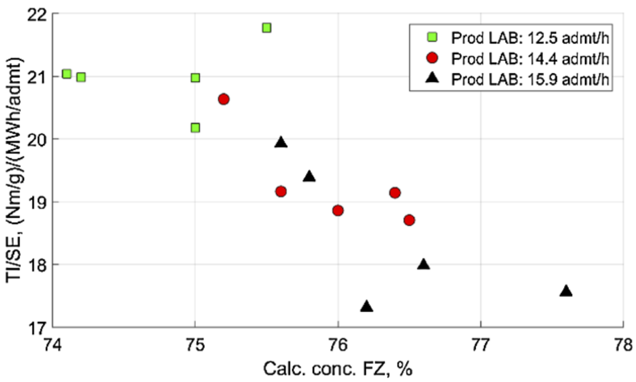

Figure 12: TI/SE ratio decreased in TEST4 with increasing pulp consistency calculated after FZ.

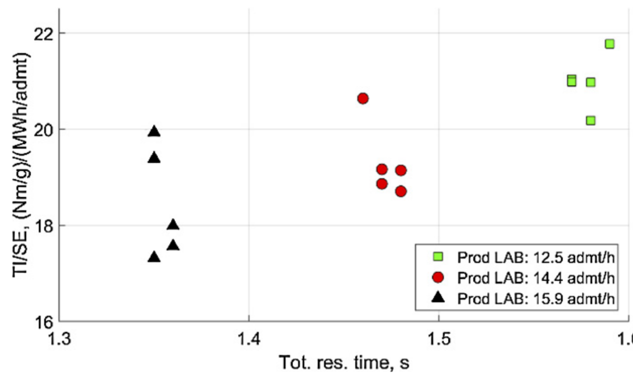

Figure 13: TI/SE ratio seemed to increase with increased residence time, but it is probably an effect of different pulp consistencies at the different production levels.

small compared to measured pulp consistencies after the CZ. These small differences in consistency after FZ were amplified in the CZ. The consistency after the FZ in this test was very high (above 70 %) for all samples, which was similar to TEST2. The differences in production between the three operation points influenced the pulp consistency along the whole radius. The operation point at the highest production resulted in almost the same high consistency after CZ as after the FZ. The high consistency in the CZ might also contribute to a low TI/SE ratio.

At each level of production rate, the variations in estimated pulp consistency after the CZ were smaller compared with the measured consistencies (see Appendix). Furthermore, the differences in estimated pulp consistency after the CZ for the two highest levels of production rate were smaller than for the corresponding measured consistency. The co-variation between mean values of the estimated pulp consistency and the measured consistency after the CZ was lower ($R^2 = 0.842$) than in TEST2. The deviations between measured and estimated values were highest at the highest pulp consistencies. This might be a consequence of unstable steam flows at high production rates, which is not fully handled by the model.

Fibre residence time and specific energy showed a high degree of positive co-variation also during this test, $R^2 = 0.993$.

Other studies have shown that the ratio TI/SE is favoured by high production rates and low residence times (Strand et al. 1993, Härkönen and Tienvieri 1995). However, the results obtained in this test did not show the same trend, see Figure 13.

As shown, the consistency was high during the entire test and this could have a significant impact on the obtained TI/SE values and explain the opposite results to the literature regarding production and residence time.

Obviously, a large variation in TI/SE could be obtained between composite pulp samples subsequently collected at the same setting of process variables. In TEST4, the variation in measured pulp consistency could be identified as a possible explanation of these variations.

Also, the estimated pulp consistency after FZ can explain the variation in TI/SE ratio. The pulp consistency along the entire radius is important especially if the pulp consistency in some part of the refining zone is above 70 % as shown in TEST2.

Step changes in dilution water flow rates, TEST5

During a period of about 3.5 hours, three operating points were evaluated in TEST5. The first operating point was at the prevailing refiner conditions (i. e. set-points chosen by the operators) at the start of the test, thus corresponding to TEST2 and TEST4. The second operating point was reached by a step-change in the dilution water flow rate to the FZ from 3.28 to 3.51 l/s. Subsequently, the third operating point was reached by a 0.26 l/s reduction in the dilution water flow rate to the CZ. The magnitude of this reduction for the third operation point was about the same as the preceding increase in flow rate to the FZ that was applied to reach the second operating point. At each operating point, five composite pulp samples were collected from the blow line. The motor load was fairly stable during the pulp sampling periods of operating point 1 and 2, but a decreasing trend in motor load was observed at operating point 3, see Figure 14.

The decreasing trend in motor load at operating point 3 could not be explained by any changes in plate gap or dilution water flow rate during this period and were proba-

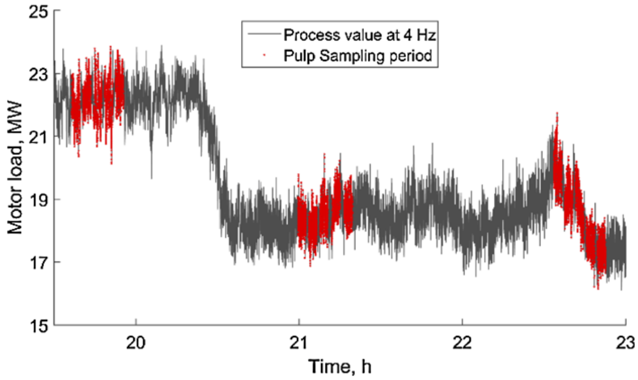

Figure 14: The refiner motor load during TEST5. The composite pulp sampling periods are marked in red.

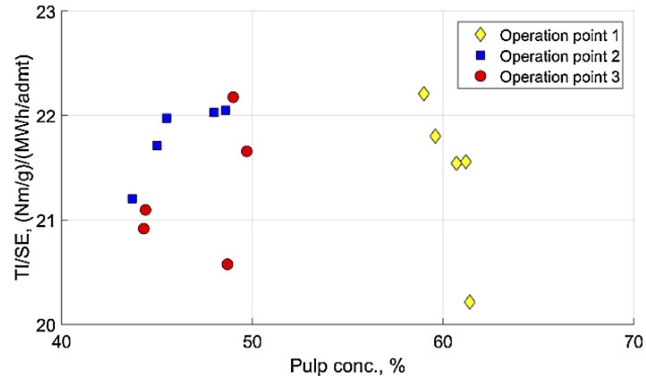

Figure 16: The ratio TI/SE versus measured pulp consistency in the blow line for composite pulp samples of TEST5.

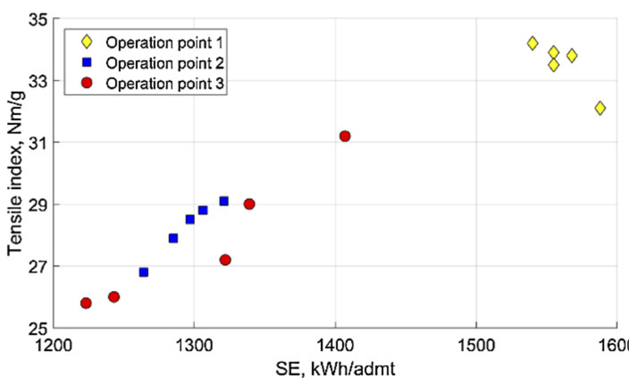

Figure 15: Tensile index for the composite pulp samples of TEST5. With respect to specific energy, the tensile index increased at operation point 2 and 3, but not at operation point 1.

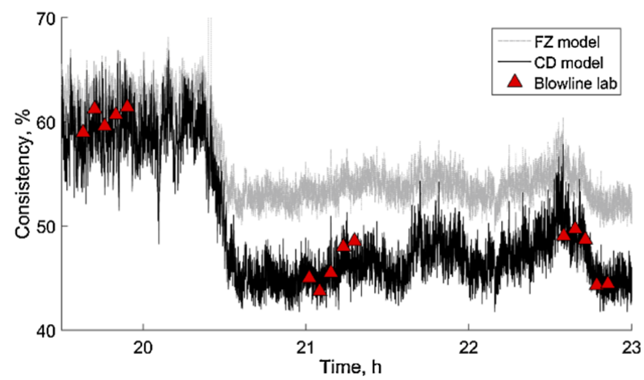

Figure 17: Calculated pulp consistency after the flat and CD zone for TEST 5 (Karlström et al. 2015).

bly caused by some feeding disturbances. Clearly, changes in the amount of dilution water flow rate to the FZ had a large impact on the motor load, while the effect from the change in dilution water flow rate to the CZ was minor.

The decreasing trends observed in motor load at operating point 3 resulted in a decreasing trend also for tensile index during the same period. Tensile index values for all composite pulp samples of TEST5 versus specific energy are shown in Figure 15.

Further, it was found that the ratio TI/SE could vary about 1.5 units at each operating point. This can be seen in Figure 16, where the measured consistency in the blow line for each composite pulp sample is also shown.

These results indicate that there are other variables in addition to pulp consistency influencing the TI/SE ratio. Considering absolute values, the estimated pulp consistencies after the FZ was considerably lower in TEST5, see Figure 17 than in TEST2 and TEST4, (c.f. Figure 4 and 10). Also the differences in estimated pulp consistency after the FZ and the consistency after the CZ were lower in this test compared with the other tests. In this test, the TI/SE ratio was above 20 for all samples in contrast to TEST2 and 4, which had some samples with considerable lower ratio, as low as 17.4.

The estimated pulp consistency after the CZ agreed very well with the measured pulp consistency in the blow line for this test, $R^2 = 0.972$. Also in this test, fibre residence time increased with specific energy ($R^2 = 0.998$). The degree of co-variation between specific energy and consistency is also high, both for measured ($R^2 = 0.968$) and estimated consistency (FZ $R^2 = 0.993$, CZ $R^2 = 0.989$). Numerical values related to these results are given in the appendix, see Table 7.

All samples taken during TEST5 had values of the TI/SE ratio exceeding 20, which is higher than the values obtained from TEST2 and TEST4. All three operating points in TEST5 were running at values below 65 % of the estimated pulp consistency after the FZ, which is considerably lower than during TEST2 and TEST4.

Table 2: Values of selected measured and estimated variables during TEST2, 4 and 5.

Variable		TEST2	TEST4	TEST5
SE, kWh/admt	Max	1580	1580	1590
	Min	1170	1400	1220
Est. ConsFZ, %	Max	90.0	77.5	62.0
	Min	62.0	74.0	52.0
Est. ConsCD, %	Max	66.0	66.0	60.0
	Min	47.0	57.5	44.0
TI, Nm/g	Max	30.0	34.5	34.0
	Min	25.5	24.5	26.0
TI/SE, (Nm/g)/(MWh/admt)	Max	21.4	21.8	22.2
	Min	17.4	17.5	20.2
∂TI/∂SE		↓	↑	↑
∂TI/∂ConsFZ		↓	↓	↑
∂TI/∂ConsCD		↓	↓	↑

Discussion

Tensile index is only one of many pulp properties that are commonly used for pulp characterization. In many investigations, freeness has been used to evaluate energy efficiency. In this study, tensile index was chosen since we believe that it has important information about the paper making potential of the pulp. The TI/SE ratio has earlier been referred to as energy efficiency (Ferritsius et al. 2014), which has been avoided in this paper. The usage of this ratio has its limitations, for example, when it comes to comparisons between primary and second stage-refiners. In this study, all composite pulp samples collected were from the same refiner that was operated within a moderate range of applied specific energy. This is assumed to allow comparisons between obtained values of the TI/SE ratio with changes in important process variables, such as pulp consistency.

In Table 2, internal and external variables for TEST2, 4 and 5 are summarized. Taken together, the results presented show that the pulp consistency, along the whole radius in the refiner probably affects the TI/SE ratio. Regarding the importance of the pulp consistency for development of pulp properties, see for example Backlund (2004), Hill et al. (1993) and Miles and May (1989).

Additional comments can be made and discussed related to the above presented results including the following remarks:

The estimation of forces at each temperature sensor using the extended entropy model has shown that the highest values were obtained at the third sensor in the FZ (Karlström et al. 2015). This sensor was placed at the contraction point for the plates and it is likely that a large part of the fibre separation occurred close to this position. From TEST2, where step changes in the FZ conditions were targeted, it was shown that a decrease in plate gap caused an increase in refiner motor load and in estimated fibre residence time as well as in estimated force at the third sensor. A decrease in dilution water flow rate to this zone gave an increase in both motor load and in residence time, but at the same time, the force at the third sensor decreased. This suggests that the process conditions and the fibre separation might be different if a change in the load is obtained by a change in plate gap or in dilution water flow rate. The maximal force, however, might not be the variable of highest interest and further studies on this are needed.

For TEST2, where step changes in the FZ conditions were targeted, extremely high values of estimated pulp consistencies after the FZ were obtained. The set-points of the first operating point in TEST2 were repeated twice. The composite pulp samples from the latter two had lower specific energy and higher tensile index and higher fibre length than at the first one. Most likely, these differences are related to the difference in pulp consistency after the FZ. The consistency was highest during the period of the first of these composite pulp samples and the cause of this might have been variations in chip dry content. Moreover, the estimated force at the position of the third temperature sensor in the FZ differed, with higher values at the two latter of these periods. This might also be related to the differences in tensile index in between these three composite pulp samples.

For TEST4, in which three operating points with different production rates were included, small differences in estimated pulp consistency after the FZ were observed. During the same test, the measured pulp consistency after the CZ showed relatively large differences. This suggests that it was the conditions in the CZ that were most affected by the production rate changes in this test.

At the third operating point during TEST5, a successive decrease in motor load was observed, although no set-point changes were applied. Tensile index decreased with the decrease in motor load and thereby the relation between tensile index and specific energy was as expected. The most probable reason for the decrease in motor load at this operation point was that additional water was introduced, for example by changes in the dry content of the chips.

Taken together, the results from these tests illustrate, by use of estimated internal variables like refining zone pulp consistency, a nonlinear behaviour of the refining process with respect to tensile index and specific energy consumption. Clearly, it is most beneficial to operate the refiner using refiner conditions where the tensile index is increased with increasing specific energy. As already stated, the consistency after the FZ is a variable of high importance to reach high TI/SE ratio values. This suggests that the installation of temperature measurements along the entire refining zone radius is especially important in a CD refiner as it enables estimation of pulp consistency after the FZ.

Conclusions

These studies on relations between process operating conditions and obtained pulp properties considering a CD 82 TMP chip refiner have shown that:

A CD-refiner has a process performance similar to that of a two-stage refiner set-up. The tests indicated that pulp consistency in both zones is important to obtain high Tl/SE.

High consistency after the FZ was very high in some of the tests, considerably higher than after the CD zone. This resulted High consistency after the FZ resulted in lower values in both tensile index and fibre length, as well as higher specific energy, which resulted in a low TI/SE ratio. Measurement of the temperature profile and estimation of pulp consistency using the extended entropy model could be used to identify when the refiner is operating at such undesired conditions.

The pulp consistency had a larger effect on the TI/SE ratio than the fibre residence time in these tests. The negative effect of high consistency (in the consistency range of these tests) on the TI/SE ratio might have exceeded the assumed positive effect of the increased production rate.

Higher production rate resulted in shorter residence time in spite of considerably higher pulp consistency. This indicates that the production rate influenced the fibre residence time more than the pulp consistency did.

The increased dilution water to the FZ had much larger influence on refiner load and fibre residence time than the increase dilution water to the CD zone.

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Appendix

Table 3: Data from TEST1.

Composite Pulp Sample	1	2	3	4	5	6	7	8	9	10
Load, MW	19.2	18.7	18.5	19.0	18.5	18.6	18.7	18.7	18.5	18.3
Gap FZ, mm	1.53	1.53	1.54	1.49	1.53	1.54	1.53	1.53	1.55	1.57
Gap CD, mm	0.86	0.85	0.87	0.85	0.85	0.85	0.86	0.85	0.85	0.86
Dil. water FZ, l/s	3.26	3.25	3.27	3.25	3.26	3.27	3.26	3.27	3.26	3.26
Dil. water CD, l/s	4.76	4.76	4.76	4.76	4.76	4.76	4.76	4.76	4.76	4.76
Prod., admt/h	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4
SE., kWh/admt	1437	1401	1381	1422	1382	1394	1395	1396	1388	1372
Calc. conc. FZ, %	60.7	59.5	59.0	60.9	59.1	59.4	59.3	59.1	59.0	58.7
Calc. conc. CD, %	47.2	46.1	45.3	46.7	45.3	45.6	45.7	45.8	45.4	45.0
Tot. res. time, s	1.23	1.22	1.21	1.23	1.21	1.21	1.21	1.21	1.21	1.21
Res. time ratio FZ/CD	1.14	1.16	1.18	1.16	1.18	1.17	1.17	1.17	1.18	1.19
Force FZ 3, N	1.15	1.16	1.16	1.14	1.16	1.14	1.17	1.15	1.16	1.14
Pulp conc., %	47.0	44.8	44.5	43.9	45.2	44.0	44.4	44.2	42.8	44.7
Freeness, ml CSF	240	253	265	243	260	246	261	255	258	269
Fiber length (ww), mm	2.38	2.41	2.43	2.42	2.48	2.41	2.41	2.42	2.48	2.41
CWT, µm	8.0	8.1	8.0	8.1	8.1	8.0	8.0	8.0	8.0	7.9
Fibrillation, %	5.74	5.76	5.71	5.76	5.78	5.86	5.78	5.83	5.79	5.77
Curl, %	13.7	13.5	13.6	13.8	13.7	13.8	13.8	13.7	13.8	13.8
Somerville, %	1.78	1.98	1.96	1.96	1.98	1.97	1.97	2.06	2.04	2.03
Density, kg/m^3	319	313	317	325	321	320	321	324	323	325
Tensile index, Nm/g	29.3	28.2	28.4	29.6	27.5	28.0	28.5	28.0	27.9	27.8
Elongation, %	1.83	1.77	1.78	1.81	1.69	1.71	1.74	1.71	1.70	1.76
Tear index, mNm^2/g	7.02	6.90	7.06	7.09	7.26	7.10	7.27	7.19	7.20	6.90
Light scatt. coeff. m^2/kg	42.8	41.7	41.8	42.7	42.0	41.8	42.2	41.9	42.0	41.5

Table 4: Data from TEST2.

Composite Pulp Sample	21	22	23	24	25	26	27	28	29
Load, MW	23.7	24.6	24.9	23.3	21.9	23.1	24.2	24.2	21.4
Gap FZ, mm	1.35	1.20	1.05	1.21	1.37	1.35	1.36	1.35	1.36
Gap CD, mm	0.78	0.79	0.78	0.77	0.77	0.79	0.78	0.75	0.78
Dil. water FZ, l/s	3.42	3.43	3.43	3.43	3.43	3.36	3.26	3.17	3.43
Dil. water CD, l/s	5.23	5.24	5.24	5.23	5.23	5.23	5.23	5.24	5.23
Prod., admt/h	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9
SE., kWh/admt	1493	1552	1569	1473	1381	1457	1525	1527	1353
Calc. conc. FZ, %	76.7	84.3	89.8	77.9	69.3	75.9	81.0	82.0	68.2
Calc. conc. CD, %	60.0	64.1	65.4	58.9	53.7	58.6	64.0	65.3	52.3
Tot. res. time, s	1.23	1.28	1.30	1.23	1.17	1.22	1.28	1.30	1.15
Res. time ratio FZ/CD	1.03	0.98	0.97	1.04	1.11	1.05	1.00	0.99	1.13
Force FZ 3, N	1.11	1.20	1.26	1.19	1.21	1.15	1.11	1.13	1.26
Pulp conc., %	57.6	61.0	62.6	57.0	53.5	58.9	62.5	64.2	53.8
Freeness, ml CSF	198	192	182	197	225	202	192	193	230
Fiber length (ww), mm	2.11	1.96	1.92	2.15	2.29	2.20	2.03	2.01	2.31
CWT, μm	7.8	8.0	7.8	7.9	7.8	8.0	7.9	7.9	8.0
Fibrillation, %	5.43	5.64	5.62	5.39	5.56	5.82	6.06	5.67	5.62
Curl, %	14.1	13.6	13.5	13.6	13.6	13.9	13.8	13.4	13.6
Somerville, %	1.61	1.15	1.04	1.46	1.78	1.44	1.32	1.34	1.79
Density, kg/m^3	329	352	362	343	330	343	348	358	326
Tensile index, Nm/g	27.7	27.2	28.0	30.1	29.7	29.6	27.3	27.1	29.1
Elongation, %	1.78	1.71	1.73	1.82	1.73	1.79	1.78	1.73	1.83
Tear index, mNm^2/g	6.37	5.72	5.86	6.72	7.21	6.88	5.95	6.11	7.27
Light scatt. coeff. m^2/kg	45.3	47.7	48.1	45.9	43.2	45.5	47.0	47.8	43.5

Table 5: Data from TEST3.

Composite Pulp Sample	31	32	33	34
Load, MW	22.4	22.1	22.1	21.9
Gap FZ, mm	1.23	1.24	1.22	1.23
Gap CD, mm	0.63	0.57	0.63	0.64
Dil. water FZ, l/s	3.78	3.79	3.78	3.79
Dil. water CD, l/s	5.12	5.11	5.12	5.06
Prod., admt/h	15.0	15.0	15.0	15.0
SE., kWh/admt	1496	1476	1470	1463
Calc. conc. FZ, %	60.7	58.0	59.8	59.5
Calc. conc. CD, %	50.6	49.6	49.4	49.5
Tot. res. time, s	1.03	1.15	1.15	1.15
Res. time ratio FZ/CD	1.13	0.99	0.99	0.99
Force FZ 3, N	1.23	1.28	1.27	1.25
Pulp conc., %	51.4	51.4	50.8	50.8
Freeness, ml CSF	214	212	213	220
Fiber length (ww), mm	2.22	2.21	2.28	2.20
CWT, μm	7.9	7.9	7.8	7.9
Fibrillation, %	5.48	5.31	5.72	5.72
Curl, %	14.5	13.7	14.8	14.0
Somerville, %	1.78	1.88	1.75	1.86
Density, kg/m^3	316	328	337	340
Tensile index, Nm/g	26.8	26.3	27.8	27.9
Elongation, %	1.78	1.71	1.77	1.78
Tear index, mNm^2/g	6.42	6.36	6.82	6.79
Light scatt. coeff. m^2/kg	44.0	44.2	43.8	43.9

Table 6: Data from TEST4.

Composite Pulp Sample	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
Load, MW	19.7	19.6	19.7	19.5	19.6	21.5	21.5	21.6	21.3	21.3	22.5	22.5	22.3	22.4	22.5
Gap FZ, mm	1.48	1.48	1.48	1.49	1.48	1.48	1.47	1.47	1.48	1.48	1.49	1.48	1.48	1.48	1.48
Gap CD, mm	1.14	1.14	1.13	1.13	1.14	1.15	1.15	1.15	1.15	1.14	1.11	1.12	1.14	1.14	1.13
Dil. water FZ, l/s	3.39	3.39	3.39	3.39	3.40	3.41	3.40	3.40	3.39	3.39	3.38	3.41	3.40	3.43	3.38
Dil. water CD, l/s	3.89	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.89	3.88	3.89	3.88	3.89	3.88
Prod., admt/h	12.5	12.5	12.5	12.5	12.5	14.4	14.4	14.4	14.4	14.4	15.9	15.9	15.9	15.9	15.9
SE., kWh/admt	1580	1566	1578	1564	1568	1490	1494	1497	1478	1482	1418	1415	1403	1410	1418
Calc. conc. FZ, %	75.5	75.0	75.0	74.1	74.2	76.0	76.4	76.5	75.2	75.6	76.6	76.2	75.8	75.6	77.6
Calc. conc. CD, %	–	58.6	58.6	57.6	57.7	64.5	64.9	65.2	63.9	64.2	65.9	65.4	65.0	65.3	66.1
Tot. res. time, s	1.59	1.58	1.58	1.57	1.57	1.47	1.48	1.48	1.46	1.47	1.36	1.35	1.35	1.35	1.36
Res. time ratio FZ/CD	0.85	0.85	0.85	0.86	0.86	0.80	0.80	0.80	0.81	0.81	0.80	0.80	0.80	0.80	0.80
Force FZ 3, N	0.56	0.55	0.56	0.58	0.58	0.79	0.78	0.80	0.78	0.79	0.99	1.02	1.00	0.99	0.99
Pulp conc., %	56.7	63.2	60.3	58.9	58.8	67.7	68.5	70.4	64.0	65.8	70.8	73.2	70.9	69.5	75.8
Freeness, ml CSF	183	198	190	191	194	235	235	260	226	253	303	327	295	280	307
Fiber length (ww), mm	2.34	2.33	2.32	2.33	2.32	2.31	2.31	2.28	2.30	2.31	2.33	2.34	2.34	2.36	2.28
CWT, μm	7.6	7.7	7.8	7.7	7.7	7.9	7.9	8.0	7.9	7.9	8.1	8.2	8.0	8.0	8.3
Fibrillation, %	6.7	6.47	6.42	6.38	6.6	6.13	6.24	6.18	6.09	6.19	6.15	6.12	6.28	6.15	5.97
Curl, %	15.3	15.1	15.1	14.9	15.4	14.4	14.6	14.5	14.6	14.6	14.6	14.6	15.0	14.8	14.2
Somerville, %	0.88	0.92	0.85	0.78	0.95	1.26	1.27	1.22	1.32	1.28	1.40	1.54	1.43	1.39	1.34
Density, kg/m^3	362	355	360	360	364	341	352	350	356	346	336	337	339	350	339
Tensile index, Nm/g	34.4	31.6	33.1	32.9	32.9	28.1	28.6	28.0	30.5	28.4	25.5	24.5	27.2	28.1	24.9
Elongation, %	1.92	1.83	1.86	1.91	1.88	1.75	1.66	1.67	1.71	1.69	1.53	1.56	1.63	1.68	1.56
Tear index, mNm^2/g	7.47	7.22	7.59	7.31	7.37	7.16	6.95	6.48	6.93	6.61	6.19	6.23	6.55	6.83	6.06
Light scatt. coeff. m^2/kg	47.5	47.4	47.3	47.1	47.3	46.0	47.1	47.4	47.3	46.4	45.2	44.6	45.2	45.4	44.9

Table 7: Data from TEST5.

Composite Pulp Sample	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64
Load, MW	21.9	22.3	22.1	22.1	22.6	18.4	18.1	18.5	18.9	18.7	20.0	19.0	18.8	17.6	17.4
Gap FZ, mm	0.87	0.87	0.86	0.86	0.87	0.85	0.85	0.86	0.86	0.86	0.85	0.86	0.85	0.85	0.86
Gap CD, mm	0.67	0.67	0.67	0.67	0.65	0.65	0.64	0.65	0.65	0.65	0.67	0.66	0.66	0.65	0.65
Dil. water FZ, l/s	3.29	3.28	3.28	3.28	3.28	3.51	3.51	3.51	3.51	3.51	3.51	3.51	3.51	3.51	3.52
Dil. water CD, l/s	4.69	4.70	4.70	4.69	4.70	4.69	4.69	4.69	4.69	4.69	4.45	4.44	4.45	4.44	4.44
Prod., admt/h	14.2	14.2	14.2	14.2	14.2	14.3	14.3	14.3	14.3	14.3	14.2	14.2	14.2	14.2	14.2
SE., kWh/admt	1540	1568	1555	1555	1588	1285	1264	1297	1321	1306	1407	1339	1322	1243	1223
Calc. conc. FZ, %	61.2	62.5	62.1	62.2	62.5	53.4	52.9	53.6	54.3	53.9	56.4	54.6	54.2	52.4	51.9
Calc. conc. CD, %	57.7	59.2	58.4	58.5	60.4	45.4	44.7	45.7	46.8	46.2	51.5	48.8	48.1	45.2	44.5
Tot. res. time, s	1.16	1.17	1.17	1.17	1.18	1.04	1.03	1.04	1.05	1.05	1.10	1.07	1.06	1.04	1.03
Res. time ratio FZ/CD	0.94	0.92	0.93	0.93	0.90	1.11	1.13	1.11	1.09	1.10	1.01	1.05	1.06	1.11	1.12
Force FZ 3, N	1.56	1.64	1.62	1.63	1.68	1.28	1.27	1.30	1.32	1.31	1.42	1.29	1.30	1.25	1.26
Pulp conc., %	59.0	61.2	59.6	60.7	61.4	45.0	43.7	45.5	48.0	48.6	49.0	49.7	48.7	44.3	44.4
Freeness, ml CSF	190	194	194	203	205	262	270	259	252	253	214	235	244	286	295
Fiber length (ww), mm	2.29	2.24	2.22	2.24	2.19	2.33	2.39	2.39	2.34	2.37	2.34	2.38	2.35	2.33	2.38
CWT, μm	7.8	7.8	7.9	7.8	8.0	7.8	7.8	7.8	7.8	7.9	7.9	7.8	7.7	7.6	7.7
Fibrillation, %	6.3	6.3	6.4	6.29	6.2	5.92	6.03	6.05	6.03	6.12	6.16	6.05	6.04	5.91	6.12
Curl, %	14.7	14.5	14.5	14.9	14.4	13.7	14.0	13.6	14.0	13.9	14.2	13.9	14.1	13.8	13.9
Somerville, %	0.86	0.76	0.75	0.80	0.64	1.75	2.00	1.66	1.75	1.72	1.32	1.42	1.75	2.24	2.28
Density, kg/m^3	372	375	376	381	373	333	329	340	340	338	348	333	329	331	327
Tensile index, Nm/g	34.2	33.8	33.9	33.5	32.1	27.9	26.8	28.5	29.1	28.8	31.2	29.0	27.2	26.0	25.8
Elongation, %	1.80	1.83	1.81	1.91	1.82	1.76	1.71	1.76	1.81	1.76	1.85	1.78	1.78	1.68	1.75
Tear index, mNm^2/g	7.44	7.51	7.74	7.54	7.12	7.18	6.88	7.16	7.14	7.10	7.35	7.26	6.92	6.75	6.44
Light scatt. coeff. m^2/kg	46.6	47.2	47.1	46.5	47.1	43.2	43.0	42.8	43.4	43.5	44.5	43.5	43.1	42.0	41.9

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