Impact of Pulp Consistency on Refining Process Conducted under Constant Intensity Determined by SEL and SEC Factors

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Specific Edge Load (SEL) and Specific Energy Consumption (SEC) are nowadays the most popular parameters for defining the intensity of pulp refining. As a result, these factors are widely used in industrial practice. The purpose of this research was to determine limitations connected with use of these parameters during bleached kraft pulp refining. Performed tests showed that, despite keeping the SEL and SEC at constant level, changes of pulp refiner consistency always modified the character of the refining process. Obtained results showed that neither SEL nor SEC are fully reliable parameters to describe and to control the refining process.

Keywords: Pulp, refining; Specific Edge Load (SEL); Specific Energy Consumption (SEC); WRV; Tensile index

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INTRODUCTION

Pulp refining is one of the most important unit operations in paper technology because it directly influences the papermaking ability of pulp fibers. Phenomena that occur during the refining process are very sophisticated and complicated. As a result, this operation has not been fully described mathematically yet. General rules and important technological aspects for operating pulp refiners are known; however, there is no universal refining theory, which would comprehensively explain the mechanism of the process and would improve the precise control of refiner operations.

It is worth mentioning that the contemporary refining theory was developed by Emerton (1957). The theory was based on the author's own experience and the knowledge of that time. The theory was rather qualitative and therefore did not provide a quantitative relationship. Nevertheless, the Emerton theory made a large step towards the systematization of refining effects. Among other things, this theory comprises the phenomena related to formation and breakage of hydrogen bonds and interactions between cellulose and water molecules, including the important role of water surface tension.

The Emerton theory was significantly complemented by the work of Ebeling and Hietanen (1990). Based on the authors' literature review, they analyzed some phenomena occurring during the refining and classified them as primary refining effects (*e.g.* external and internal fibrillation, fibre shortening). The main disadvantage of both mentioned works is their qualitative character, which cannot form the basis of a quantitative mathematical model for pulp refining.

A lack of a universally accepted quantitative description of pulp refining reflects the complexity, and, to some extent, the unpredictability of phenomena occurring during this process. One of the reasons for this situation is a fact that papermaking pulp is a highly heterogeneous lignocellulosic material. As a result, there are not any satisfactory mathematical equations that unambiguously predict pulp properties on the basis of refining parameters.

At the moment, only a few criteria, which describe refining processes, exist and are universally accepted by the scientists. The most popular criteria are cutting edge length (CEL) and specific edge load (SEL), which were introduced by Wultsch and Flucher (1958) and later supplemented by Brecht and Siewert (1966). Apart from that, specific energy consumption (SEC) is also commonly used.

CEL is defined as,

$$\mathrm{CEL} = z_R \cdot z_S \cdot l \cdot \frac{n}{60}, \quad [\mathrm{m/s}] \tag{1}$$

where z_R is the number of rotor bars, z_S is the number of stator bars, l is the bar effective length [m], and n is the rotational speed of refiner rotor [rpm]. On the other hand, SEL can be calculated according to the formula:

$$\mathrm{SEL} = \frac{P_{net}}{\mathrm{CEL}}, \quad [\mathrm{J/m}] \tag{2}$$

where P_{net} is the effective refining power [W] and CEL is the cutting edge length [m/s].

SEL defines the amount of effective refining energy transferred by the edges of refining elements to the refining zone. SEL is currently considered to be the most reliable parameter when analyzing refining processes (Koskenhely and Paulapuro 2005; Karlström *et al*. 2008; Desarada 2010). Selecting SEL as the most useful parameter is also demonstrated by test results on the change of the amount of energy transferred by refining bars in a refiner (Martinez and Kerekes 1994; Khlebnikov *et al*. 1969; Goncharov 1971). The tests show that the highest amount of energy is transferred to the refining zone at the time when the edge of the rotor bar is directly close to the leading edge of the stator bar. By comparison, the amount of the energy being transferred to the refining zone when the edge of the rotor bar moves over the surface of the stator bar is significantly lower. This allows one to conclude that the refining effects are mostly obtained in the initial stage of passing between rotor and stator edges. Numerous tests show that this general rule can be successfully used for process optimization (Olejnik 2011).

The main disadvantage of SEL, and later introduced specific surface load (SSL) factor (Lumiainen 1990), is that both do not take into consideration the obvious impact of consistency and pulp flow in the refining zone. Among others, this was proved by Croney *et al.* (1999) who found inaccuracy in correlation between SEL and paper strength properties. That is why in the industrial conditions SEC (specific energy consumption) is used additionally:

$$\mathrm{SEC} = \frac{P_{net}}{q_m \cdot \frac{c_F}{100} \cdot \rho}, \text{ [kWh/ton of dry matter]} \tag{3}$$

where P_{net} is the effective (net) refining power [kW], q_m is the pulp flow through refining zone [m^3/h], c_F is the consistency of refined stock [%], and ρ is the stock density [ton/m^3].

SEC expresses the amount of refining energy received by the specified amount of refined stock during a single pass through the refining zone, and it can also be considered as a measure of refining intensity. For this purpose, in the present work, it has been marked as $\mathrm{SEC_{SP}}$ (single-pass SEC).

It must be emphasized that many scientists (Danforth 1969; Stevens 1981; Kerekes 1990) characterize the refining process as a combination of the number of impacts per unit mass and the intensity of each impact. Both parameters are responsible for refining specific energy consumption according to Eq. 4,

$$E = N \cdot I, \text{ [kWh/ton of dry matter]} \tag{4}$$

where E is the energy per mass [kWh/ton], N is the number of impacts/mass [ton^{-1}], and I is the energy per impact [kWh].

Equivalent refining action can be obtained when N and I of each refiner are equal. N and I can be linked to the most important technological refining factors (*e.g.* flow through the refining zone, pulp consistency, and its density). This relationship can be described as in Eq. 5,

$$E = \left(\frac{C}{q_m}\right) \cdot \left(\frac{P_{net}}{C}\right) \tag{5}$$

where:

$$N = \left(\frac{C}{q_m}\right) \qquad I = \left(\frac{P_{net}}{C}\right)$$

In these expressions, "C" is the so-called C-factor which expresses the probability of a fibre being impacted in a refining zone. The most advanced mathematical description of C-factor has been developed by Kerekes (1990). For example, the simplified C-factor for conical refiner is given by Eq. 6,

$$C = 8 \cdot \pi^2 \cdot G \cdot D \cdot \rho \cdot c_F \cdot l_F \cdot z^3 \cdot n \cdot (1 + 2 \cdot \tan\phi) \cdot \left[R_1^2 \cdot L + L^2 \cdot R_1 \cdot \sin\phi + \left(\frac{L^3}{3}\right) \sin^2\phi\right] / w \cdot (1 + D) \tag{6}$$

where G is the width of grooves [m], D is the depth of grooves [m], l_F is the fibre length [m], z is the number of bars [-], n is the rotational velocity of refiner [rev./s], ϕ is the bar angle, R_1 is the radius of smaller conical rotor [m], L is the length of the refining zone [m], and w is the coarseness of fibres [kg/m].

It is worth mentioning that under typical industrial conditions, the dimensions of the refiner filling and the rotational speed are usually constant; therefore Eq. 6 can be simplified as follows,

$$C = K \cdot \frac{\rho \cdot c_F \cdot l_F}{w} \tag{7}$$

where K is a constant factor for given construction of a refiner and its rotational speed.

Equation 7 clearly points out that for a given industrial refiner, pulp consistency and its density, fibre length, and coarseness are the most important parameters which affect the refining operation. Since fibre length and coarseness change during the progress of refining, the C-factor is, in fact, a variable (Batchelor 1999). This also could result in continuous fluctuations of N and I factors. Consequently, even if refining is conducted under constant consistency and constant net power, fibre treatment in the refining zone changes during the refining progress. It can be stated that the C-factor provides a lot of information about the refining process. Unfortunately, it is also difficult to apply as a precise refining control method under industrial conditions. In order to obtain constant refining intensity, permanent measurement of fibre length and coarseness should be carried out. All above descriptions of the refining process are, in general, energy-based. There are also force-based attempts to characterize the refining intensity (Batchelor *et al.* 1997; Kerekes 2011). These theories are even more sophisticated and complex. Accordingly, they usually provide only estimate values and still call for further investigations.

All of the above reasons contribute to the fact that C-factor and force-based refining intensity are not yet as popular as the less precise but simpler SEL and SEC factors that are widely used even in scientific research (Koskenhely and Paulapuro 2005; Wang and Paulapuro 2005; Lundin *et al.* 2008). Nevertheless, the possibility of application of C-factor has been shown by Welch and Kerekes (1994) and Croney *et al.* (1999). In the present work, the most popular SEL and SEC factors were used for refining intensity control.

The impact of consistency on refining progress in low consistency refining (2 to 8%) is still discussed in the scientific literature. Analyzing Eq. 5 and 7, it can be shown that for a given refining device and under constant refining net power, higher pulp consistency causes an increase of N factor (higher number of impacts promotes fibrillation). Lower consistency, in turn, results in an I factor increase and promotes cutting action.

The effect of pulp consistency was experimentally studied by Brecht and Siewert (1966). For consistencies from 2% to 6%, they found no effect. Also Batchelor (2001), in his work related to the effects of flocculation and floc trapping on fibre treatment during low consistency refining in Escher-Wyss conical refiner, did not find any significant impact of pulp consistency on refining process. He did not mention whether pulp flow control was used and how the refining process was controlled in order to obtain the same N and I values. On the other hand, Manfredi, Villela and da Silva (1986) found significant differences between 2 and 5% consistency for eucalyptus pulp refining. Several modern books related to paper technology (Annergren and Hagen 2009; Holik 2006; Baker 2000) do not explain this effect at all.

On the basis of the above discussion, a series of experiments were done with reference to limitations connected with application of SEL and SEC_{SP}, including consistency changes. As a working hypothesis, it was assumed that with keeping a constant method for energy transfer in the refining zone (SEL=const.) or constant proportion of effective energy stream in the refining zone to the stream of refined cellulose fibres (SEC_{SP}=const.), constant refining conditions should be obtained. This hypothesis would be substantiated by comparable refined pulp properties and paper properties made from these pulps.

EXPERIMENTAL

Materials

Market bleached kraft softwood (pine) pulp was used in the experiments. Pulp was delivered in the form of dry sheets. The average moisture content was 7.4%. Initial pulp properties are shown in Table. 1.

Table 1. Initial Pulp Properties

NaOH Concentration, %	1	5	10	17.5	20
Solubility in NaOH, %	0.82	5.25	13.28	13.42	13.36
Amount of α-cellulose, %	86.6				
Intrinsic viscosity ml/g	680				
DP (Degree of Polymerization)	981				

Methods

The refining process was performed in a pilot plant (Fig. 1). The plant was equipped with an Escher-Wyss conical refiner R1L working as a semi-continuous system (refined pulp passed through the refiner zone multiple times). The plant had a computer system for measuring the pulp flow. Pulp flow control was based on precise time measurements of pulp level change in the upper tank. A capacitance level sensor was used for this purpose.

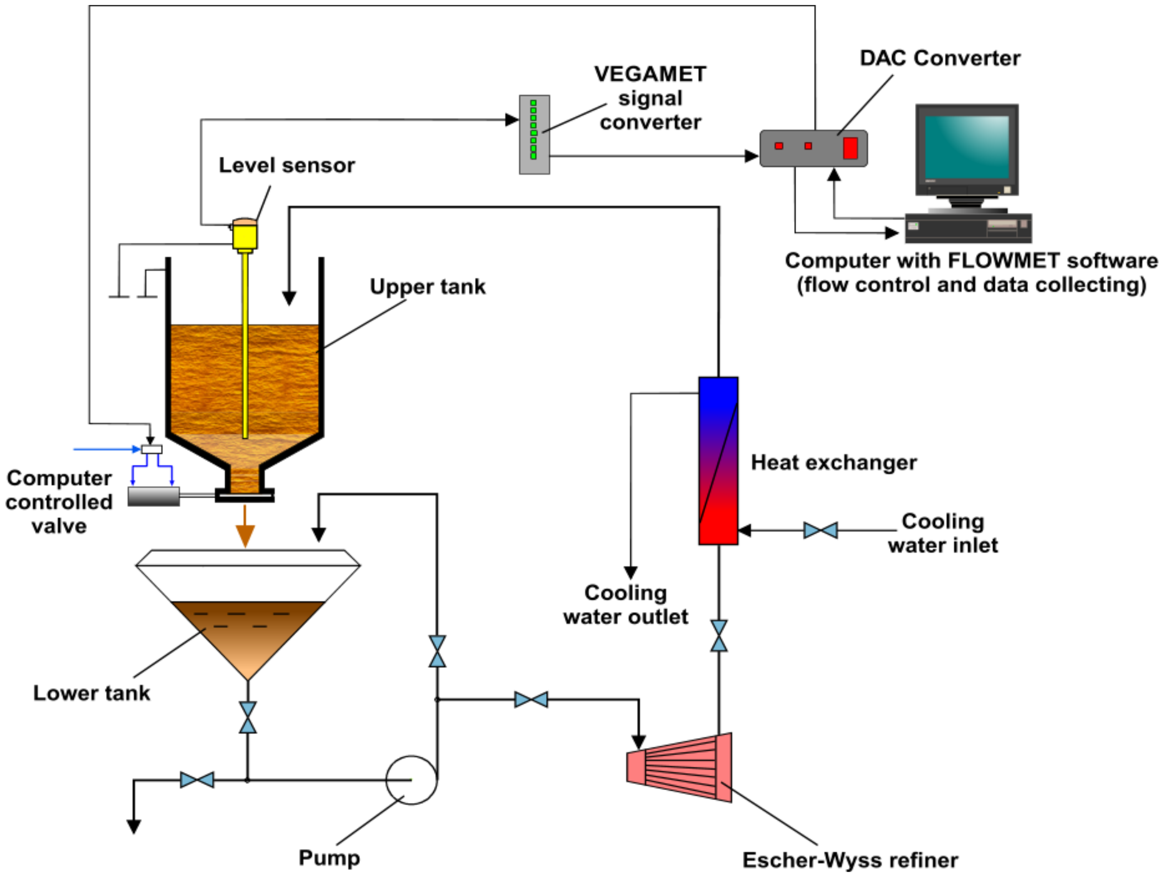

Fig. 1. Schematic diagram of pulp refining pilot plant

SEL and SEC_{SP} factors were used to control the refining intensity. Specific energy consumption (SEC) for every single pulp pass through the refining zone in a given experiment was also kept constant. This factor was further denoted by the SEC_{SP} abbreviation, whereas total specific energy consumption, a sum of the passes multiplied by single pass specific energy consumption (SEC_{SP}), was denoted by the SEC_T abbreviation. Each experiment started with the determination of the no-load power (measured for the refiner working with the pulp and maximum refiner gap opening). A heat exchanger was used to cool the pulp slurry such that refining did not exceed 35 ^oC. A single volume of refined pulp was set at 130 dm^3. The refining sequences were carried out in accordance to the scheme presented in Table 2.

Table 2. Refining Parameters for Each Experiment

	Parameters					
	q_m	n	c_F	P_{net}	SEL	SEC_{SP}
1.	const.	variable	const.	variable	const.	variable
2.	const.	const.	variable	const.	const.	variable
3.	variable	const.	const.	variable	variable	const.
	const.	const.	variable	variable	variable	const.

The tests of refined pulp and laboratory paper handsheets were performed in accordance to current ISO standards. Water retention value (WRV) determinations were performed using a centrifugal method according to the SCAN-C 102 XE standard. A centrifugal force of 3000 g for 15 min was used. The Kajaani FS-200 analyzer was used to measure the length-weighted average fibre length. Laboratory paper sheets of 75 g/m^2 were formed in a Rapid-Köthen apparatus, according to standard EN ISO 5259-2:2001. Samples were then conditioned at 23 ^{o}C and 50% RH, according to standard ISO 187:1990. All the determinations of paper properties were performed according to specific ISO standards.

RESULTS AND DISCUSSION

The results of this study were analyzed on the basis of two pulp properties (*i.e*. WRV and length-weighted average fibre length) and one property of paper made from the refined pulp (*i.e*. tensile index). For the purpose of this publication and to facilitate the analyses of experimental data, two general cases were selected regarding the test results obtained with a constant value of SEL and the constant value of SEC_{SP}.

Case a) SEL = constant and SEC_{SP} ≠ constant

In order to verify the SEL theory, a refining sequence was done at a constant value of this parameter. The proper ratio between refiner loading with effective (net) power (P_{net}) and rotor refiner speed was selected in order to obtain a constant SEL value factor for different CEL values. This part of the experiment was done with one pulp consistency value during refining. The other part of the experiment (within discussed case a) was performed for a constant P_{net} value and constant rotor refiner speed, whereas the pulp consistency during refining was varied. In all cases, SEC_{SP} in the refining zone increased along with an increase in P_{net} or along with a decrease in pulp consistency.

Figure 2 shows that the changes in the WRV of the fibres depended on the consumed effective refining energy for experiments made at constant consistency and at variable refiner loading with effective power and rotor speed (with SEL=const.). It can be clearly seen that all experimental points were placed along one curve. This means that with SEL kept constant, the WRV of the fibres were identical for a given effective refining energy, regardless of applied combination of refining loading and rotor speed. A similar situation is presented in Fig. 3.

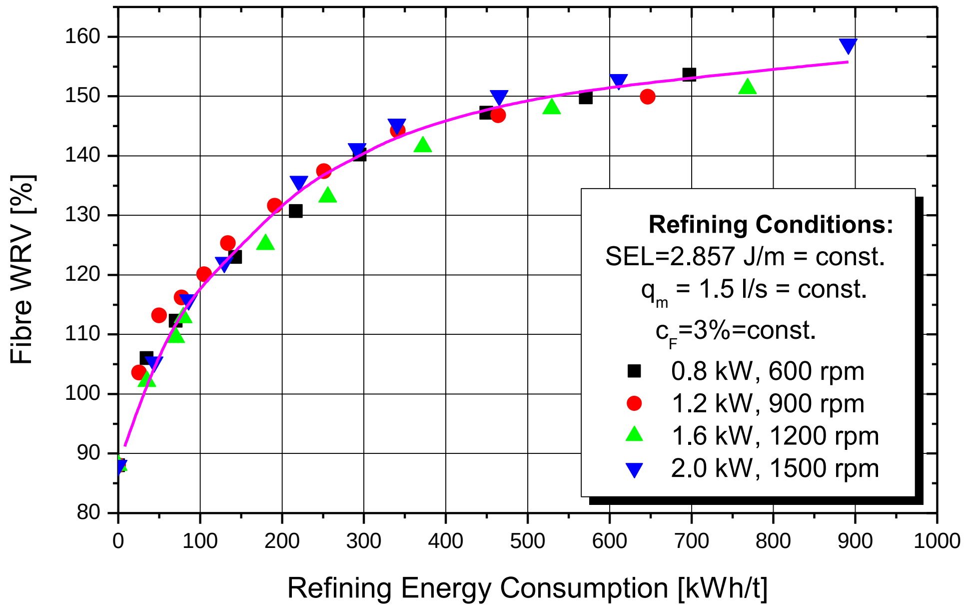

Fig. 2. Changes of fibre WRV value *vs*. specific energy consumption for constant SEL values and constant pulp consistency

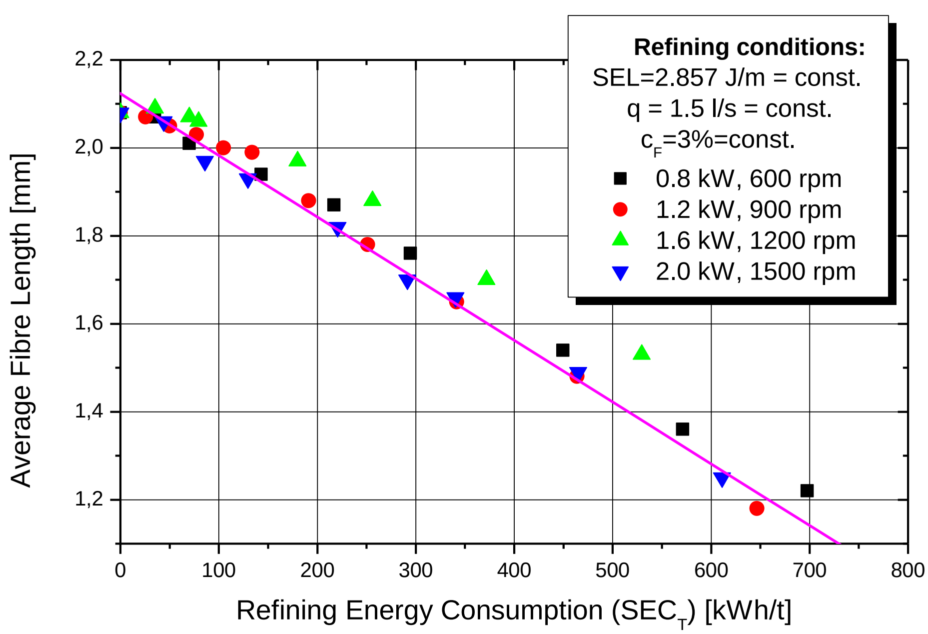

Fig. 3. Changes of length-weighted average fibre length *vs.* specific energy consumption for constant SEL values and constant pulp consistency

Figure 3 shows changes in the average fibre length as a function of consumed effective refining energy for refinings of various intensities. Obtained results demonstrated that the rate of the fibre length drop was proportional to the specific energy consumption only. Figures 2 and 3 demonstrate that the SEL theory was correct in the range of variables tested.

From a practical point-of-view, final paper strength properties obtained from pulp refining is the most important effect. Figure 4 shows changes in paper tensile index made from pulp refined in the same conditions. The results showed that the same tensile index was obtained, regardless of used combination of P_{net} and n. Therefore, it can be concluded that when maintaining a constant value of SEL and constant consistency of the pulp, constant intensity in the refining zone is achieved.

As a result, it is possible to obtain identical properties of refined pulp, which results in similar paper strength properties. This effect is obtained despite different SEC_{SP} values.

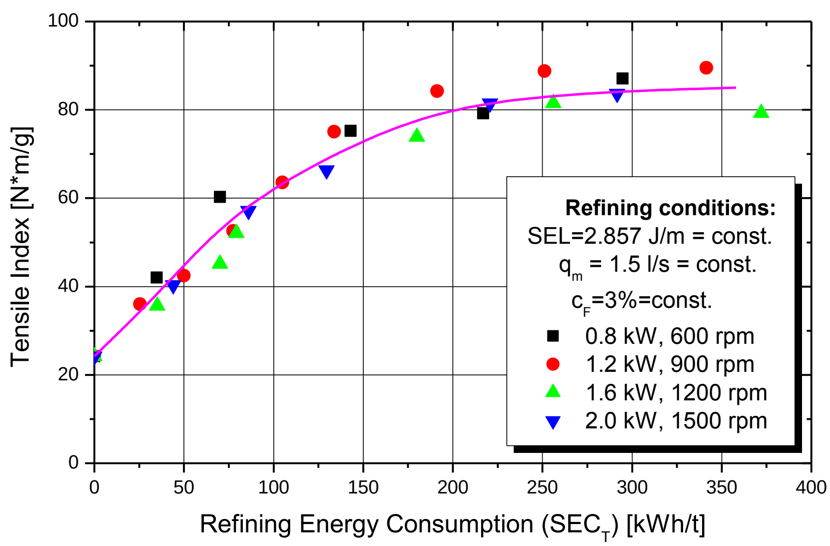

Fig. 4. Changes of tensile index *vs.* specific energy consumption for constant SEL values and constant pulp consistency

Obviously, at higher bar loading with effective power, the refining will take a shorter time. This is explained by constant properties of refined pulp with different SEC_{SP}. The pulp receives more energy, but the refining is performed proportionally faster.

As constant conditions of fibre treatment are maintained, comparable pulp and paper strength are obtained for comparable consumption of effective energy. This is also confirmed by the comparable bulk changes of all laboratory paper samples prepared from pulps refined at constant SEL value (Fig. 5). Based on the obtained results, it can be concluded that the SEC_{SP} parameter does not thoroughly describe the refining mechanism when refiner load and/or rotational speed of rotor are changed, even if consistency and pulp flow in the refining line are constant. In such a case, SEL is a more reliable control parameter.

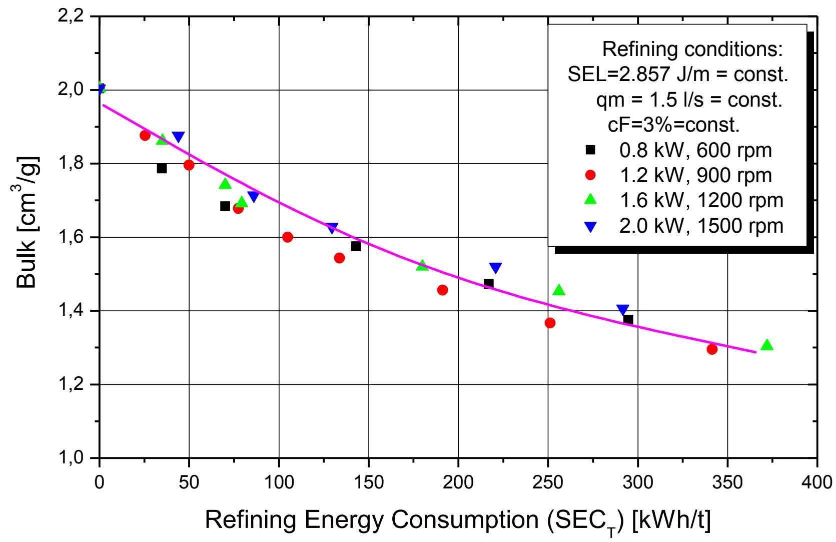

Fig. 5. Changes of bulk *vs*. specific energy consumption for constant SEL values and constant pulp consistency

The second series of the tests of the discussed case examined how refining consistency influences the process despite maintaining constant SEL value. Figure 6 shows changes in the WRV depending on the consumed effective refining energy. The shape of the curves was characteristic to typical changes to this parameter, whereas there were differences in the increase in WRV. It can be clearly observed that WRV increase was the fastest for the pulp refined at the lowest consistency. On the other hand, the lowest WRV were obtained for the pulp refined with the highest consistency. Observed results can be explained by the fact that along with the increase in consistency of refined pulp, the refining energy was distributed on larger number of fibres. As a result, real refining intensity was lower.

Figure 7 presents changes in average fibre length depending on the consumed effective refining energy. It was noticed that for the same amount of specific refining energy, fibre shortening was faster for the lower consistency values. This confirmed the fact that even for constant SEL value but lower refining consistency, real refining intensity is higher. These results are also in accordance with C-factor theory.

Significant differences in refining intensity were also confirmed by Fig. 8, where changes in tensile index of handsheets made from pulp refined at different consistency are shown. It is interesting that despite higher fibre WRV, handsheet tensile index was worse at the lower refining consistency. Along with the lower refining consistency, the tensile index was increasing slower, and the asymptotic, maximum value of handsheet tensile index was also lower.

It can be concluded that for higher intensity in the refining zone, the papers of lower properties were obtained. Probably, the conditions applied were too harsh for relatively small amount of fibres. This resulted in substantial damage already in the initial stage of refining that could not be compensated in any other way.

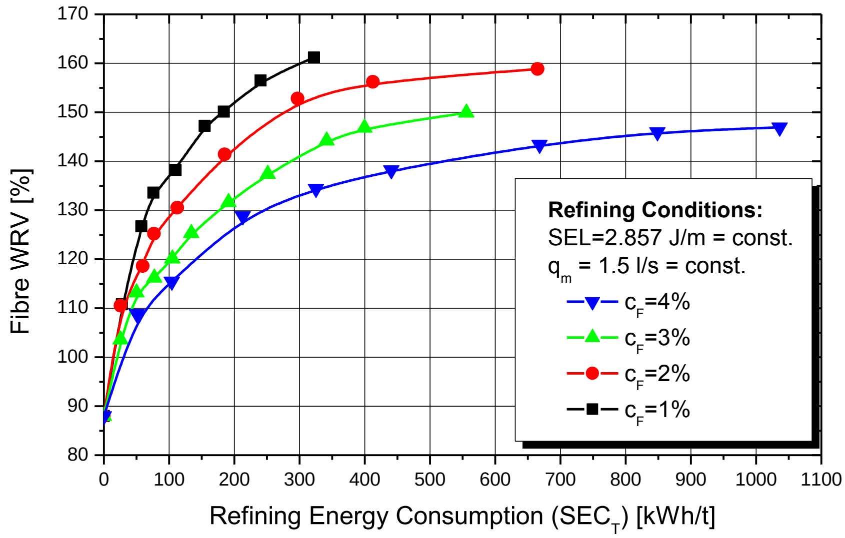

Fig. 6. Changes of fibre WRV value *vs.* specific energy consumption for constant SEL values and different pulp consistencies

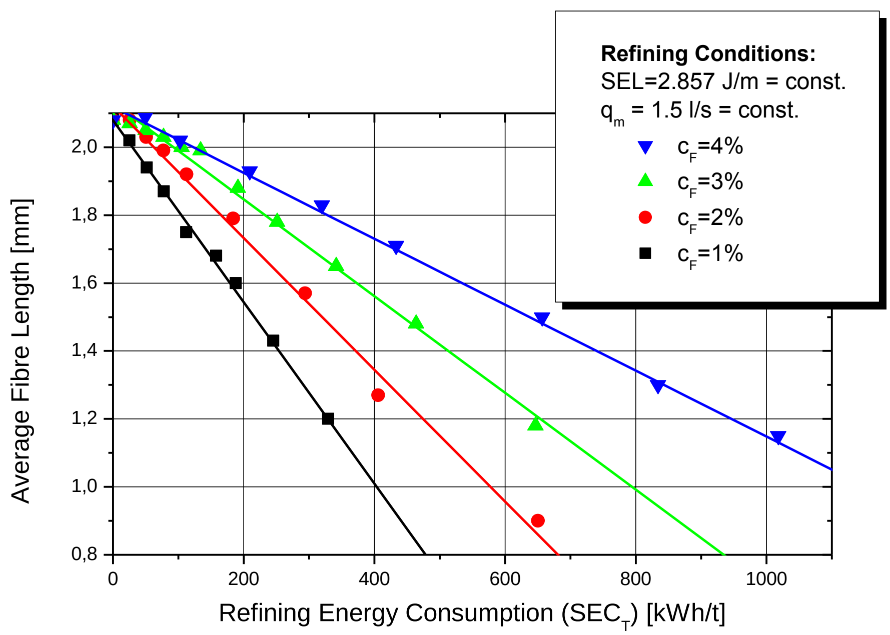

Fig. 7. Changes of length-weighted average fibre length *vs.* specific energy consumption for constant SEL values and different pulp consistencies

Differences in bulk of tested papers are shown in Fig. 9. The fastest decrease of this parameter was observed for papers made from pulp refined at the lowest consistency. It can be concluded that refiner pulp consistency is a very important variable for the refining process, and the fact that it is not included in the SEL theory is a serious disadvantage.

In case of consistency changes during refining, the SEL factor does not indicate the possibility to obtain different refining effects. In such a case, SEC_{SP} can be a parameter which signals various conditions in the refining zone.

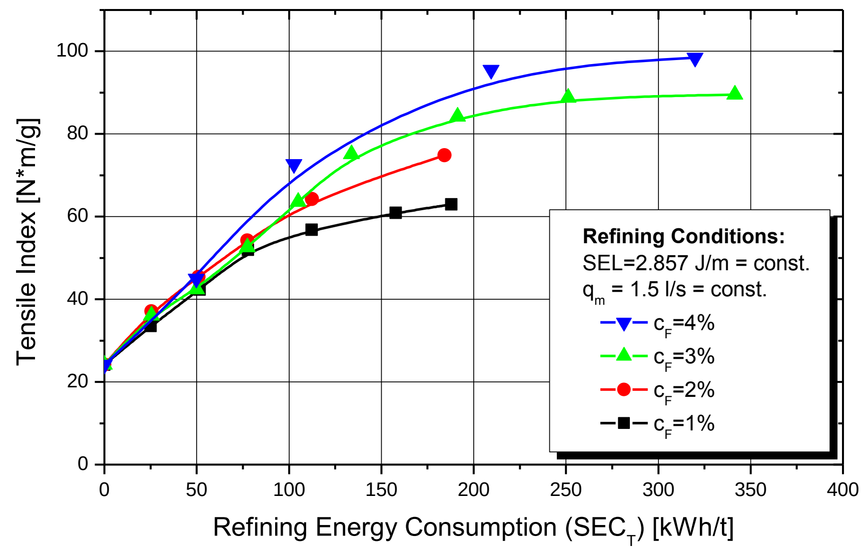

Fig. 8. Changes of tensile index *vs.* specific energy consumption for constant SEL values and different pulp consistencies

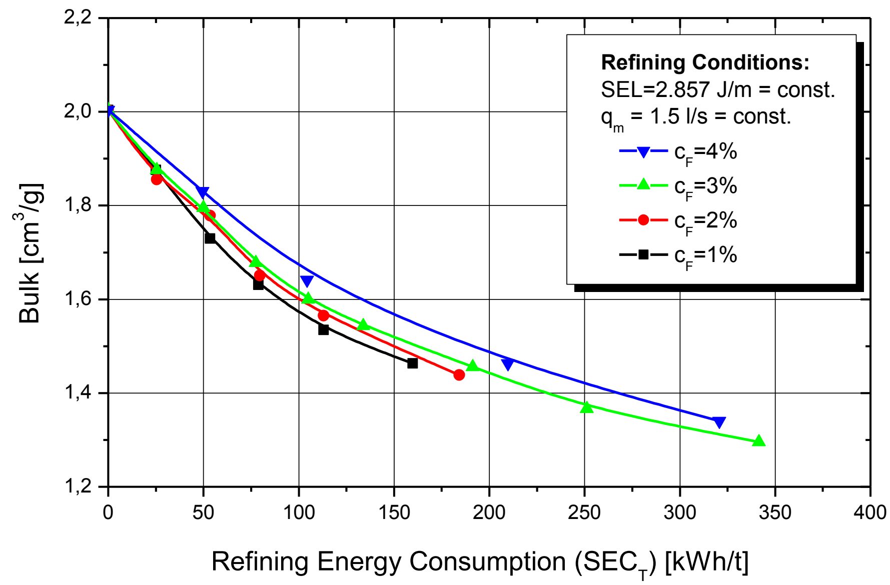

Fig. 9. Changes of bulk *vs*. specific energy consumption for constant SEL values and different pulp consistencies

Case b) SEL ≠ constant and SEC_{SP} = constant

In order to define the reliability of SEC_{SP} as a supplementary parameter to SEL, a refining sequence was performed with a constant SEC_{SP} in the refining zone. Two series of tests were carried out for this case. In the first series, pulp refining consistency was kept constant, whereas a constant SEC_{SP} value was obtained by proper selection of values for refiner loading and refined pulp flow through the refining zone. In the second series, a constant SEC_{SP} value was obtained by keeping constant refined pulp flow and proper refiner loading to pulp refiner consistency ratio. SEL factor was changing in both series.

Figure 10 illustrates changes in the fibers' WRV for each refining from the first series where SEC_{SP} and pulp consistency were constant.

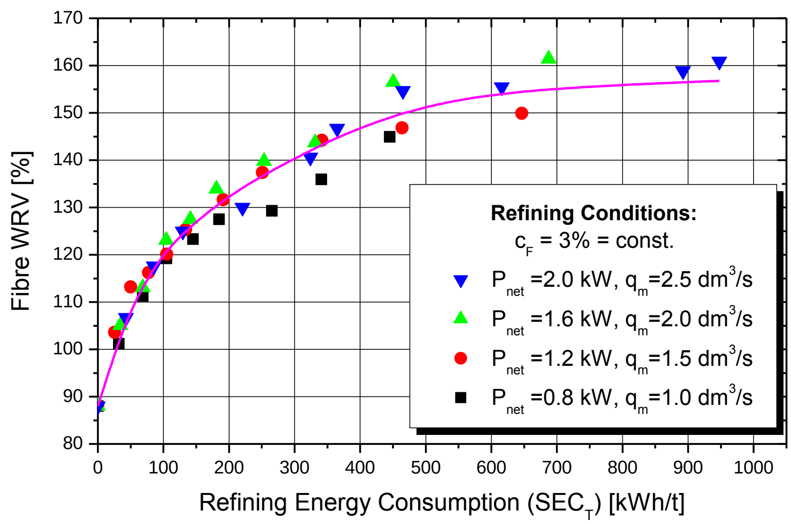

Fig. 10. Changes of fibre WRV value *vs.* specific energy consumption for constant SEC_{SP} value (7.4 kWh/t) and constant pulp consistency

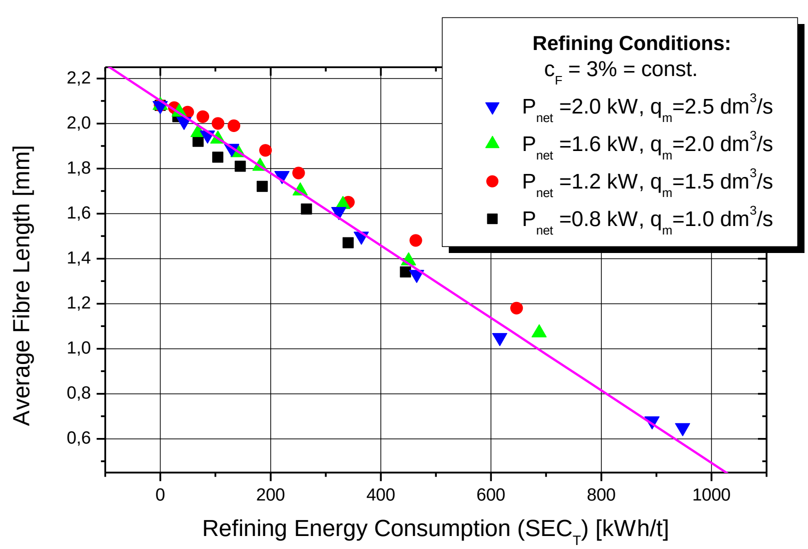

Fig. 11. Changes of length-weighted average fibre length *vs.* specific energy consumption for constant SEC_{SP} value (7.4 kWh/t) and constant pulp consistency

It can be noted that, for given values of effective refining energy consumption, the same values of WRV were achieved regardless of used combination of refiner load and pulp flow. Changes of average fibre length (Fig. 9) confirmed that constant refining conditions were obtained despite different values of SEL. The fact that refining conditions were constant is also confirmed by Fig. 12, where changes in tensile index of paper as a function of effective refining energy are shown. Also, similar changes for bulk (Fig. 13) confirm that when pulp flow in refining zone is changed proportionally to net power and consistency is constant, SEC_{SP} may be successfully used as a supplement to SEL factor.

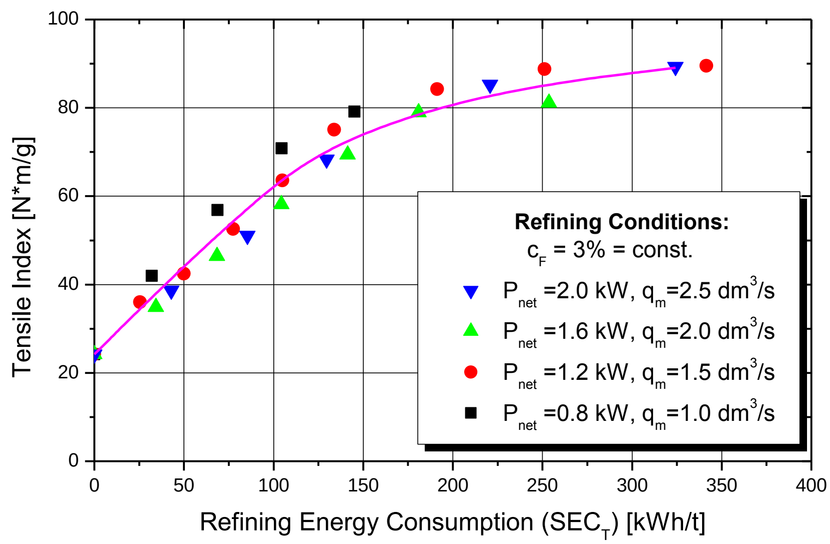

Fig. 12. Changes of tensile index *vs.* refining energy consumption for constant SEC_{SP} value (7.4 kWh/t) and constant pulp consistency

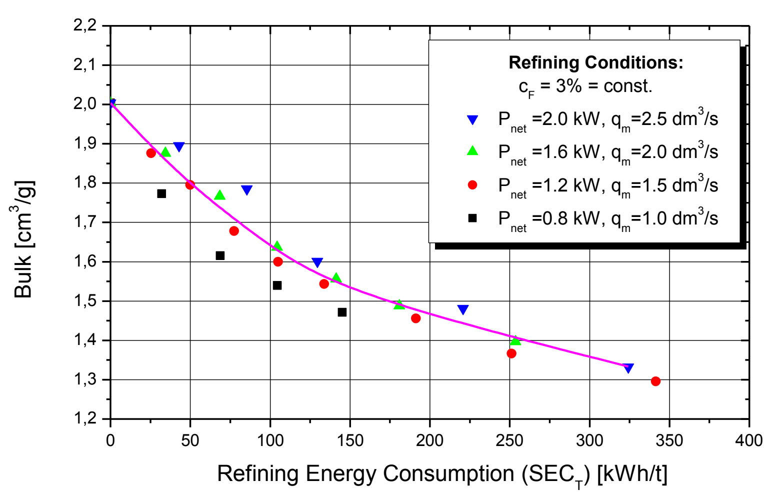

Fig. 13. Changes of bulk *vs.* refining energy consumption for constant SEC_{SP} value (7.4 kWh/t) and constant pulp consistency

Since tests of the refining process that were carried out with constant SEL value and with variable refiner pulp consistency showed inconsistent results for this parameter, it was decided to examine if SEC_{SP} will be a more reliable parameter in such a case. Figure 14 shows changes in the WRV of fibres as a function of net specific energy consumption for constant SEC_{SP} value and different pulp consistencies.

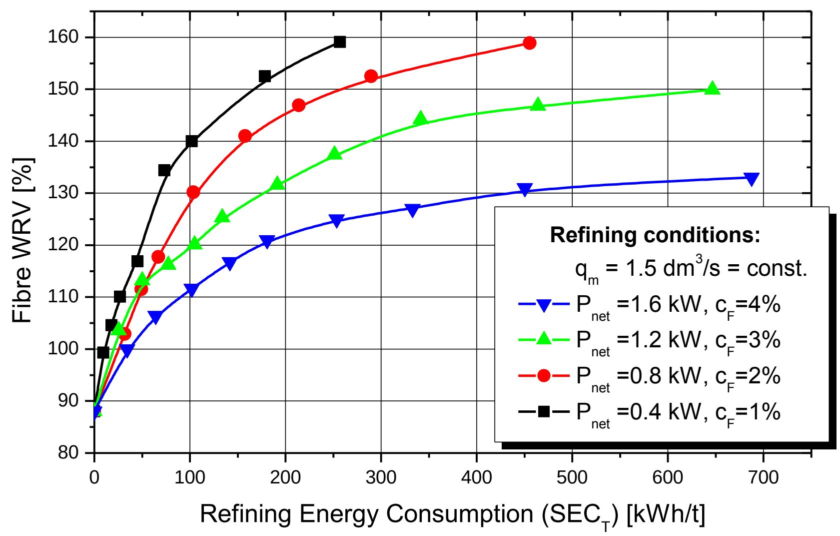

Fig. 14. Changes of fibre WRV value vs. specific energy consumption for constant SEC_{SP} value in refining zone and different pulp consistencies

Despite a constant SEC_{SP} value, an increase of WRV of fibres was higher for lower refiner pulp consistency. For the highest pulp consistency, the increase of WRV was the slowest and the asymptotic WRV was the lowest. These results were similar to the results obtained for the refining sequence carried out at a constant specific edge load (SEL) and variable pulp refiner consistency; however, in this case, specific consumption of effective energy in the refining zone was not constant. The results indicated the high significance of pulp refiner consistency to the discussed process. It is also worth mentioning the fact that despite relatively low loading of the refiner with effective power at 1% refiner consistency, the obtained effect of WRV changes was very high in relation to the next values of used loadings and consistencies.

Figure 15 shows changes in the average fibre length as a function of consumed effective refining energy. Surprisingly, the rate of the fibre length drop was proportional to the specific energy consumption and was not dependent upon the pulp refiner consistency values.

Changes in handsheet tensile index from pulps refined at constant SEC_{SP} value at variable refiner consistency are shown in Fig. 16. It was observed that changes of tensile index were not similar. Tensile index increased faster for pulp refined with lower consistency. Obtained curves also showed that the asymptotic tensile index values at refiner consistencies of 3% and 4% were similar; however, at refiner consistency of 3%, the highest value was achieved more efficiently (with lower consumption of specific effective refining energy). For the presented case it can be stated that the optimum refining conditions were achieved at pulp refiner consistency of 3%.

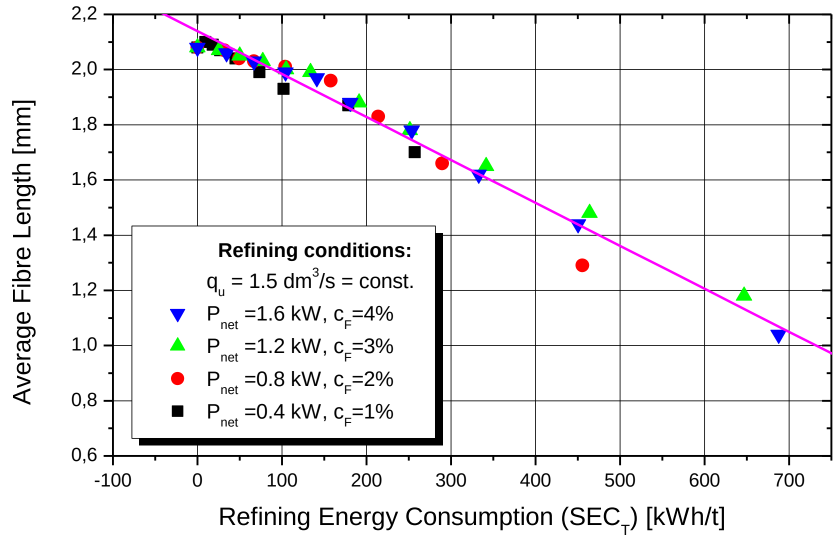

Fig. 15. Changes of average fibre length *vs*. specific energy consumption for constant SEC_{SP} value in refining zone and different pulp consistencies

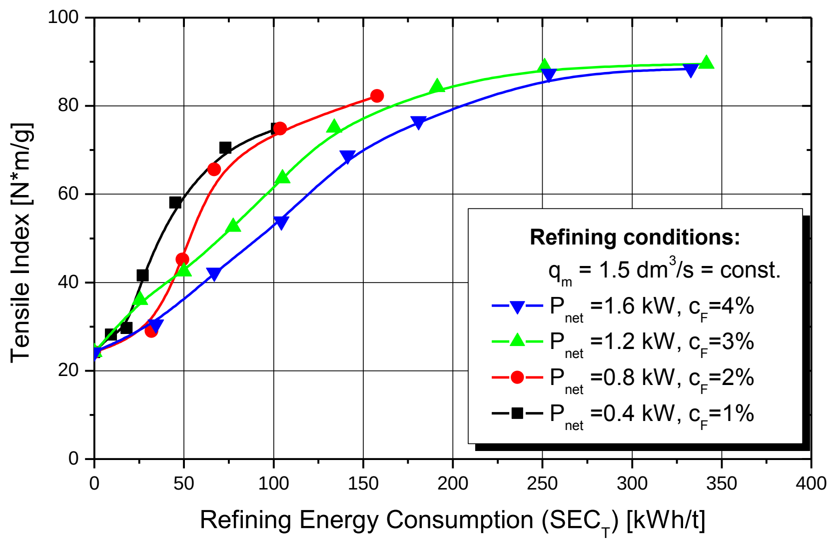

Fig. 16. Changes of breaking length *vs*. specific energy consumption for constant SEC_{SP} value in refining zone and different pulp consistencies

Finally, significant differences in bulk of tested laboratory paper samples (Fig. 17) make it possible to presume that in the case of consistency changes of refined pulp, SEC_{SP} is not a reliable parameter and it cannot be considered as the definitive measure of refining intensity.

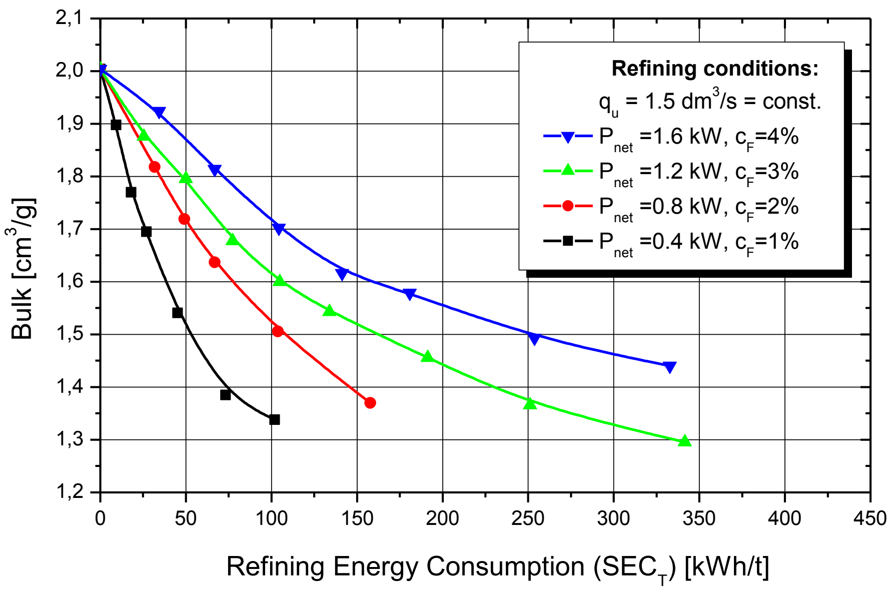

Fig. 17. Changes of bulk vs. specific energy consumption for constant SEC_{SP} value in refining zone and different pulp consistencies

CONCLUSIONS

1. The obtained results showed that despite maintaining SEL or SEC_{SP} at a constant level, refining effects for bleached Kraft softwood pulp were different in each case when the consistency was not kept constant.

2. It can be concluded that refiner pulp consistency changes resulted in different refining process flows, including differences in WRV and average fibre length values. In such cases, neither SEL nor SEC_{SP} were reliable parameters to thoroughly describe and control the refining process.

3. Considering industrial process, it can be stated that it was possible to change the overall productivity of the refining line in a paper mill, simultaneously maintaining constant conditions of refining using SEL or SEC_{SP} factors, but only when refined pulp consistency was constant. The conditions can be formulated as follows:

SEL = const. for $n \neq$ const., q_m = const., c_F = const. $P_{net} \neq$ const.
SEC_{SP} = const. for n = const., $q_m \neq$ const., c_F = const. $P_{net} \neq$ const.

4. In summary, results of the present work confirm the need for the improvement of current SEL/SEC based refining control systems by more advanced systems (based on C-factor, for example). It is also worth mentioning that none of the mathematical descriptions of the refining process quantifies the most important refining effect, namely internal fibrillation. Further research should be undertaken in order to solve this problem.

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