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Refining systems for sack paper pulp: Part I HC refining under pressurised conditions and subsuequent LC refining

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KEYWORDS: Airflow resistance, Fibre length, LC refining, Pressurised HC refining, Sack paper, Shape factor, Strain at break, Tensile energy absorption index

SUMMARY: Unbleached kraft pulp for sack paper is usually refined in a high consistency process followed by low consistency refining in order to achieve the desired paper properties, such as a high strain at break and high tensile energy absorption at low airflow resistance. In this study, conventional atmospheric high consistency refining is compared to pressurised high consistency refining after preheating to 125°C and 175°C. After the high consistency refining stage, the pulp samples were refined in a low consistency process in a laboratory Escher-Wyss refiner.

The results show that the highest levels of tensile energy absorption and strain at break were achieved with curled and kinked fibres refined in a pressurised refiner at 175°C at a relatively low refining energy input, before the low consistency refining stage. These results were obtained at low airflow resistance, which is advantageous for sack paper. The disadvantage of the pressurised high consistency refining process is a loss in tensile strength. Paper properties were evaluated on freely dried as well as ISO sheets.

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The increasing availability of alternative packaging materials on the market means that producers of kraft sack paper are under pressure to remain competitive. This has resulted in increased efforts to improve the properties of kraft sack paper and to lower the costs of production.

Paper sacks are exposed to fast filling processes. It is therefore important that the sack paper can withstand the forces during filling and at the same time have a low airflow resistance (Gurley) in order to prevent a high pressure from building up in the sack. Paper properties such as strain at break and tensile energy absorption index (TEA-index) at low airflow resistance are of great importance for predicting how the sack will perform in practice.

To improve the extensibility of sack paper, the kraft pulp used is commonly refined in a high consistency (HC) refining stage before low consistency (LC) refining. During the HC refining, the fibres become curled and kinked due to a transfer of stresses between fibres (Miller 1998, Hartler 1995). HC refining also creates micro compressed zones in the fibre walls (Page 1966). The micro compression phenomenon has been described as a plastic deformation in the fibrillar structure of the cell wall (Hartler 1995). The transfer of stress from fibre to fibre during beating at a high pulp solid content is recognised as the causal mechanism of micro compression (Page 1985). Fibres with micro compressed zones improve the extensibility of the sheet (Miller 1998, Omholt 1999).

According to previous research (Gullichsen and Paulapuro 1998, Scott-Kerr 1997), the pulp solid content during HC refining must be higher than 30% in order to achieve the desired effect on the properties of pulp and sheets. Due to fibre interaction, the compressive stresses are greater at higher consistency in refining, and the number of micro compressed zones therefore increases as the solid content is increased (Page 1966). Since HC refining creates curled and kinked fibres, which give a low sheet density, the HC refining stage must be followed by a LC refining stage (Gullichsen and Paulapuro 1998) in order to straighten out the fibres and to increase the sheet density in the final sheet of paper (Gullichsen and Paulapuro 1998, Scott-Kerr 1997), in order to achieve the highest possible tensile strength.

The introduction of curl and micro compressions has a large impact on the properties of the paper. Fibre curl mainly influences the tensile strength and bulk of the sheet, as the curl makes the fibres less effective in carrying loads. The fibre network becomes less activated, with relatively few bonds, and it is more easily broken under straining, which gives a low tensile index (Hartler 1995, Omholt 1999). On the other hand, a very large number of micro compressions in a HC-refined chemical pulp give a greater elongation in sack paper (Hartler 1995).

It is well known that very curly fibres are created from lignin rich fibres in thermo mechanical pulping (TMP), a pressurised HC refining process (Beath 1966). The intention with this study was to evaluate if the unbleached kraft pulp fibres behave in the same way as TMP fibres and whether the properties for sack paper can be further improved if conventional atmospheric HC refining is replaced by pressurised HC refining. After HC refining in a pilot plant, the pulp samples were refined in a LC refining stage in a laboratory Escher-Wyss refiner. Fibre properties such as shape and length were evaluated using an optical fibre analyser, STFI FiberMaster (Karlsson 1999). Physical properties were measured on hand-made sheets.

Experimental

Pulp

All the pulps used in these experiments were commercially produced, unbleached and non-dried kraft pulp from

Mondi Packaging Dynäs AB. The pulps were manufactured from a wood mix of approximately 50% spruce and 50% pine with a Kappa No. of approximately 43, which corresponds to a yield of 50%. The pulps were collected from a twin-roll press prior to the HC refining stage in the mill at different times for the two trials. The solid content was approximately 35% and the pH was approximately 9.

HC_{atm} refining

A reference trial with conventional atmospheric HC refining (HC_{atm} refining) was carried out at the Metso Paper R&D Centre in Sundsvall, Sweden. The objective was to evaluate how refining energy and pulp solid content during HC_{atm} refining affect fibre and sheet properties.

Pulp was fed to a single disc refiner at a rate of 1 kg/min. The refiner was equipped with 20-inch segments type 5821S and the refiner speed was 1500 rpm. The pulp from the mill had a solid content of 35% and was gently diluted in three batches to solid content level of 30%, 25% and 20% respectively with white water taken from the mill, *Fig 1*. These four different batches of pulp were refined in the atmospheric refiner using two or three levels of refining energy. The discharge temperature was about 100°C.

HC_{press} refining

The main trial in a pressurised 20-inch pilot refiner (HC_{press} refiner) was also carried out at the Metso Paper R&D Centre, *Fig 1*. Pulp was fed through a plug screw (compression ratio 1:4) at a rate of 1 kg/min to a pressurised thermo-mixer. The preheating time in the pressurised thermo-mixer was short, approximately 30 sec. From the thermo-mixer the pulp was fed to the single disc refiner. The refiner was equipped with 20-inch segments type 5821S and the refiner speed was 1500 rpm. The pulp from the mill had a solid content of 35% and was refined at 125°C (170 kPa) and 175°C (830 kPa) and four levels of refining energy.

LC refining

For low consistency refining an Escher-Wyss conical refiner at the SCA Technology Centre was used to simulate the low consistency refining process used by commercial producers of sack paper. The pulp was refined according to a SCA standard method. Pulp consistency during refining was approximately 2% and the edge load was 1.26 Ws/m. The pulp suspension was recirculated until the target level of refining energy was obtained.

Fibre and pulp analysis

The length-weighted average fibre length and shape factor were determined in non-dried pulp samples, with an optical fibre analyser, FiberMaster (Karlsson 1999). The pulp was defibrated in cold water according to the SCAN-C 18:65 method before analysis. The results from each sample were based on data from approximately 10 000 fibres. Fibres are defined as particles with a length/width ratio greater than 4. The definition of the shape factor is the projected fibre length divided by the true fibre length, i.e. a completely straight fibre has a shape factor of 100%. The Water Retention Value and drainability (SR number) were determined in accordance with the SCAN-C 62:00 and ISO 5267-1 methods respectively.

Sheet properties

Sheets were made according to the ISO-M 5:67 method and the physical properties of the paper were tested according to SCAN-C 28:76. Freely dried sheets were made by hand as ordinary ISO-sheets until the point of stacking. Placing a pressing plate at the bottom followed by two dry blotters, a couching blotter, the laboratory sheet and three dry blotters composed the stack. This was repeated for each laboratory sheet and a second pressing plate was placed on top of the stack. The sheets were pressed at 490 kPa for four minutes, then all the blotters were removed and the sheets were dried between Teflon wires on a drying drum. The temperature was 60±5°C and the drying time was approximately two hours.

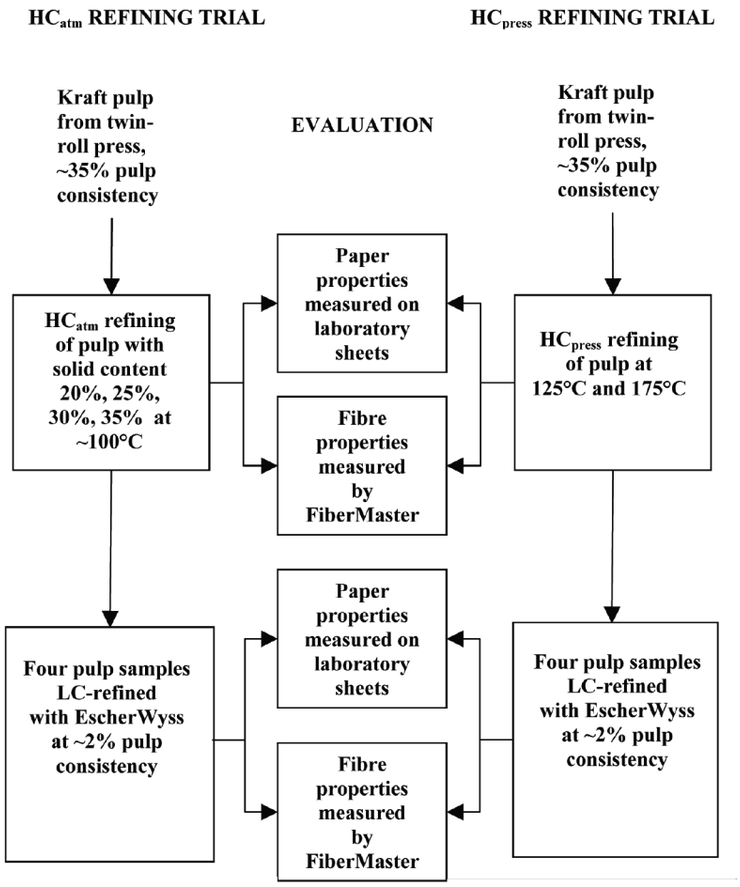

Fig 1. Block scheme for the HC_{atm} and HC_{press} refining trials.

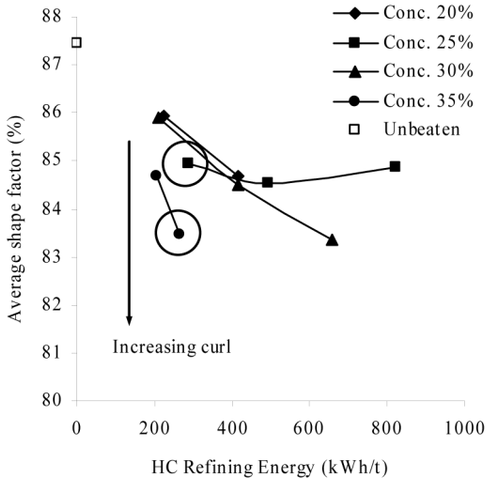

Fig 2. Average shape factor versus HC_{atm} refining energy at different pulp concentrations. Circled samples were used for subsequent LC refining.

Table 1. Pulp and hand-made ISO sheet data from HC_{atm}–refined pulp.

Pulp conc./Energy consumption (%/kWh/t)	SR	Density (kg/m³)	Tensile index (kNm/kg)	Tensile energy abs-index (J/kg)	Strain at break (%)	Tensile stiffness-index (MNm/kg)	Airflow resistance (Gurley) (s/100 ml)	Average fibre length (mm)
Unrefined	13,0	602	45,6	880	2,7	5,6	1,2	2,19
20/223	15,0	673	57,3	1440	3,5	6,3	2,4	2,10
20/415	15,0	693	61,6	1720	3,9	6,4	2,2	2,12
25/287	15,0	683	60,0	1540	3,6	6,5	2,1	2,16
25/495	15,5	702	61,1	1740	4,0	6,3	2,3	2,09
25/820	16,5	712	61,4	1860	4,2	6,2	2,2	2,04
30/209	14,0	648	53,9	1230	3,2	6,1	1,6	2,11
30/415	15,0	668	53,2	1390	3,6	5,9	1,1	1,97
30/657	15,0	679	53,7	1490	3,8	5,8	0,9	2,09
35/205	13,0	610	40,0	840	2,9	4,9	0,7	2,16
35/267	13,0	610	43,7	1120	3,5	5,2	0,6	2,04

Table 2. Pulp and hand-made ISO sheet data for HC_{atm}–refined pulp and subsequent LC refining.

Energy consumption in Escher-Wyss (kWh/t)	SR	Density (kg/m³)	Tensile index (kNm/kg)	Tensile energy abs-index (J/kg)	Strain at break (%)	Tensile stiffness-index (MNm/kg)	Airflow resistance (Gurley) (s/100 ml)
Pulp HC refined at 100 °C, 25% and 287 kWh/t							
0	15,0	681	59,5	1600	3,8	5,7	2,5
22	16,5	701	74,7	1820	3,6	6,7	4,1
45	17,5	706	81,4	1820	3,4	7,1	7,0
69	22,0	729	87,5	1890	3,3	8,0	14,0
96	28,0	745	93,3	2010	3,3	8,4	34,0
111	32,0	756	96,8	2030	3,2	8,7	67,4
Pulp HC refined at 100 °C, 35% and 267 kWh/t							
0	14,0	623	41,7	990	3,2	5,1	0,6
22	14,5	644	60,4	1580	3,7	6,2	1,0
45	16,5	648	67,8	1690	3,6	6,5	1,8
69	19,5	676	77,1	1810	3,5	7,2	4,4
96	25,0	698	83,0	2040	3,6	7,4	12,1
115	31,0	718	86,0	1980	3,4	7,9	30,8

Result and Discussion

Conventional HC_{atm} refining and subsequent LC refining

HC_{atm} refining

The length-weighted fibre length was only slightly changed during the HC_{atm} refining, *Table 1*. The length-weighted shape factor decreased with increasing pulp consistency and increasing refining energy, *Fig 2*. The greatest amount of curled fibres occurred at the highest pulp consistency and highest refining energy. This is a result of fibre interactions under greater compressive stress due to higher stock consistency and is in agreement with earlier findings (Page 1966).

The physical properties of ISO sheets from the HC_{atm} refined pulp are given in *Table 1*. Denser sheets and a higher tensile index were achieved by refining at lower pulp consistencies, e.g. 20% and 25%, due to less curled fibres. Pulp refined at the highest consistency, 35%, had an even lower tensile index than the unbeaten pulp. The density and tensile index increased with increasing refining energy except for the pulp that was refined at a consistency of 35%, for which the density was unchanged.

All the pulp samples showed a higher strain at break after HC_{atm} refining and the TEA-index increased with increasing refining energy during refining.

LC refining

LC refining was performed on two samples of pulp from the HC_{atm} refining trial. These two samples were chosen because they were HC_{atm}-refined using approximately the same refining energy, 275 kWh/t, but at different pulp consistencies, 25% and 35% respectively. These pulp samples covered most of the variation of fibre shape, *Fig 2*. The samples are marked with circles in *Fig 2*.

Table 2 shows the properties of the ISO sheets from HC_{atm}- and LC-refined pulp samples. Denser sheets with higher tensile strength were achieved from pulp that was HC_{atm}-refined at a lower pulp consistency in the first stage. The density and tensile index increased with increasing refining energy during the LC refining. The strain at break of the pulp that was HC_{atm}-refined at a pulp consistency of 25% decreased with increasing LC refining but for pulp HC_{atm}-refined at a consistency of 35% the strain at break initially increase up to a fairly constant level. This result agrees with previous research (Gullichsen and Paulapuro 1998, Scott-Kerr 1997), and confirms that the pulp consistency during HC_{atm} refining must be more than 30% in order to achieve the desired effect on the properties of the pulp and paper sheets. As a result of fibre interaction, the compressive stresses are greater in refining at a high consistency. The TEA-index increased with increasing LC refining for both pulp samples. Sheets made of pulp that had been HC_{atm}-refined at 35% pulp solid content have a larger percentage increase in TEA-index during LC refining.

These results were as expected and in agreement with those reported from the previous research, i.e. a HC_{atm} refining stage improves the TEA-index of the final sheet after LC refining, which is explained as being due to the presence of a larger number of micro compressions in the

fibre wall. Internal and external fibrillation of the fibre is required to develop a high tensile strength, and this is best achieved through low solid content refining (Scott-Kerr 1997, Kibblewhite 1972). An increase in fibre-to-fibre interactions in the sheet structure increases the sheet strength, strain at break and elastic modulus. On the other hand, the introduction of curl and micro compressions increases strain at break, but lowers the dry tensile strength and the elastic modulus. This explanation has also been suggested for wet webs, where it seems that curl and micro compressions are more important than in dry sheets, (Seth 1983). When the increase in strain at break due to the HC_{atm} refining treatment starts to level off at a refining energy above approximately 250 kWh/t, the strength of the sheet may have been reduced to such an extent, due to increased fibre curl, reduced swelling or a reduced bonded area, that the stretch potential of the fibres before rupture can no longer be utilised (Omholt 1999).

HC_{press} refining and subsequent LC refining

In an attempt to apply TMP technology in order to strengthen the positive effects of HC_{atm} refining of the unbleached kraft pulp, the pulp was preheated to 125ºC and 175ºC before the HC_{press} refining stage. The trial was carried out on a new batch of kraft pulp which seems to have a different character than the pulp used in the previous conventional HC_{atm} trial. However the strength properties of unrefined kraft pulps, cf. *Table 1* and *3*, change considerably as a result of even gentle mechanical treatment i.e. small change in SR values around 13-15 (Gullichsen and Paulapuro 1998).

HC_{press} refining

The length-weighted fibre length was relatively unchanged during the HC_{press} refining at 125ºC, *Table 3*. Some fibre shortening occurred in the pulp which was HC_{press}-refined at 175ºC, as the fibre length decreased with increased refining energy. The length-weighted shape factor was sharply dropped after refining with a low refining energy in pulp that was preheated and refined at 125ºC and 175ºC. The shape factor increased with increasing refining energy during HC_{press} refining, which is remarkable, *Fig 3*. The largest amounts of curled fibres were found after HC_{press} refining at 175ºC with the lowest refining energy. These results are opposite to the results from the conventional HC_{atm} refining (cf. *Fig 2* and *3*), where the shape factor decreased with increasing refining energy during HC_{atm} refining. The reason for this behaviour during HC_{press} refining may be that the fibres are already curled during the kneading at high temperature and under pressure in the plug screw prior to entering the refiner. The fibres are then straightened out during the HC_{press} refining.

The water retention value, *Fig 4*, increased with increasing HC_{atm} refining energy at 100ºC and HC_{press} at 125ºC. The water-retaining capability of a pulp is influenced by many factors such as internal fibrillation and fibre wall delamination, which increase the fibre swelling and improve the bonding properties of the fibres (Mohlin 1992). In HC_{press} refining at 175ºC, the water

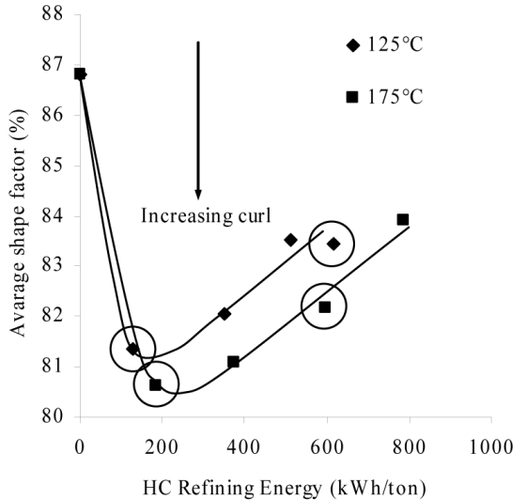

Fig 3. Average shape factor versus HC_{press} refining energy at different temperatures. Circled samples were used for subsequent LC refining.

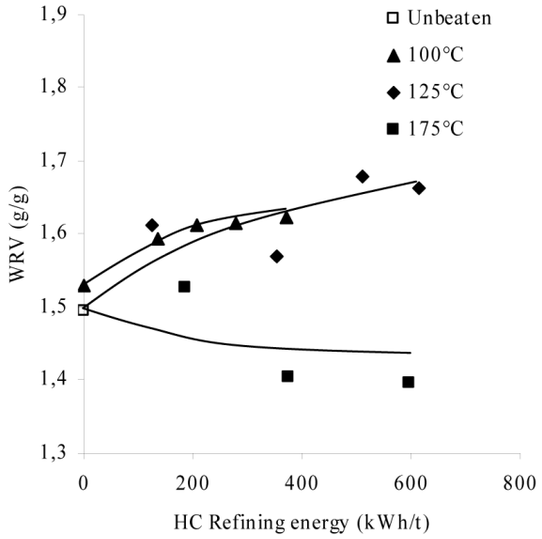

Fig 4. Water retention value versus HC_{atm} and HC_{press} refining energy at different temperatures.

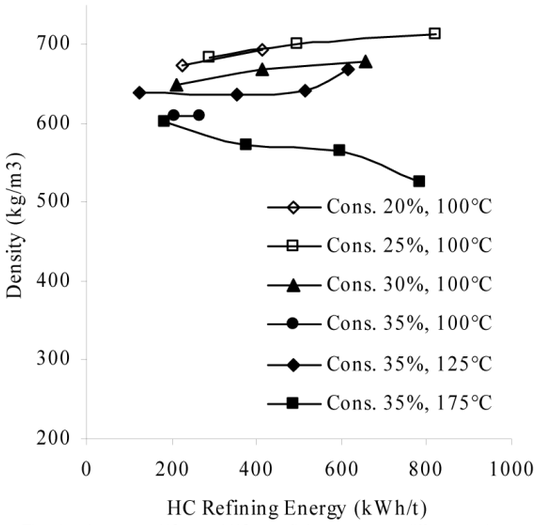

Fig 5. The density versus HC_{atm} and HC_{press} refining energy at different pulp concentrations and temperatures.

retention value decreased with increased refining energy. The progress of the water retention value decrease can be visualised as being a function of drying, i.e. the development of hornification and loss of swelling ability due to water removal (Carlsson 1984, Weise 1997, 1998). The explanation may be that higher refining temperature leads to a higher compression in the plug screw due to higher pressure in the thermomixer, so more water is squeezed out of the pulp during kneading in the plug screw. The combination of high pressure, high temperature and high consistency during refining leads to an effect similar to hornification. Generally, most strength properties decrease due to hornification, probably because of a lower density of the sheets made from dried pulp fibres (Carlsson 1984).

The properties of the ISO sheets from HC_{press}-refined pulp are shown in *Table 3*. *Fig 5* shows that the sheet density increased slightly with increasing HC_{atm} refining, but that it was relatively unchanged during HC_{press} refining at 125ºC. The density decreased in the pulp that was HC_{press}-refined at 175ºC, even though the fibres were straightened with increasing refining energy during the HC_{press} refining, (cf. *Fig 2* and *3*).

The strain at break increased with increasing refining energy during HC_{press} refining at both temperatures, even though the shape factor increased. Sheets made of pulp that was HC_{press}-refined at 125ºC showed the highest strain at break and the highest tensile index. The tensile index increased with increasing refining energy in pulp which was HC_{press}-refined at 125ºC, whereas that of sheets made of pulp which was HC_{press}-refined at 175ºC was almost the same as that of sheets made of unrefined pulp. The TEA-index increased with increasing refining energy at both temperatures, but sheets made of pulp which was HC_{press}-refined at 125ºC had a higher TEA-index.

It thus seems that the higher HC_{press} refining temperature, 175ºC, had a negative effect on the pulp fibres. The fibre length decreased and the strain at break, tensile index, tensile energy absorption index and density were lower compared to the results from HC refining at a lower temperature. This is probably an effect of hornification as the changes in water retention value and physical paper properties agree with the effects of hornification shown in earlier research (Carlsson 1984). An earlier study by Page (1996) shows the effect of quite low temperatures (15ºC, 20ºC and 35ºC) and solid content (5%, 15% and 20%) during the treatment of dried unbleached kraft pulp in a PFI mill. It was found that solid content had a far greater influence than temperature on stretch. Our study shows, however, that the higher temperatures that have been used have a permanent effect on the physical properties of paper. This behaviour might be explained by the softening of lignin at the higher refining temperature. The pulp solid content has not been varied in this study of the effects of HC_{press} refining.

Table 3. Pulp and hand-made ISO sheet data for HC_{press}-refined pulp.

Pulp temp./Energy consumption (ºC/kWh/t)	Pulp consistency (%)	SR	Density (kg/m3)	Tensile index (kNm/kg)	Tensile energy abs-index (J/kg)	Strain at break (%)	Tensile stiffness-index (MNm/kg)	Airflow resistance (Gurley) (s/100 ml)	Average fibre length (mm)
Unrefined	35,0	12,0	507	24,7	390	2,1	4,0	0,5	2,12
125/126	33,9	14,5	638	35,5	1030	3,7	4,3	0,6	1,96
125/353	31,3	14,0	637	33,3	1120	4,3	3,9	0,5	1,97
125/512	27,7	15,0	642	37,8	1260	4,4	4,2	0,6	1,97
125/615	29,0	15,0	668	49,6	1620	4,4	5,3	0,9	1,92
175/184	30,0	14,0	603	24,2	570	3,0	3,2	0,4	1,92
175/376	32,9	13,0	573	21,0	640	3,8	2,7	0,3	1,84
175/597	40,3	14,0	565	26,0	650	3,2	3,3	0,3	1,79
175/785	36,9	14,5	527	23,7	730	3,9	3,0	0,3	1,67

Table 4. Pulp and hand-made ISO sheet data for HC_{press}-refined pulp and subsequent LC refining.

Energy consumption in Escher-Wyss (kWh/t)	SR	Density (kg/m3)	Tensile index (kNm/kg)	Tensile energy abs-index (J/kg)	Strain at break (%)	Tensile stiffness-index (MNm/kg)	Airflow resistance (Gurley) (s/100 ml)	Average fibre length (mm)
HC_{press}-refined pulp at 125 °C and 126 kWh/t								
0	13,5	638	35,5	1030	3,8	4,3	0,6	1,95
45	16	680	59,9	1590	3,6	5,9	1,4	1,86
69	19,5	699	69,1	1800	3,8	6,5	3,4	1,79
96	24	716	77,3	2040	3,9	6,9	8,3	1,66
125	33	745	82,2	2100	3,7	7,4	27,7	1,61
HC_{press}-refined pulp at 125 °C 615 kWh/t								
0	15,5	668	49,6	1620	4,4	5,3	0,9	1,98
22	17,5	678	63,5	1880	4,1	6,5	1,3	1,89
45	22	703	74	2150	4,1	6,8	3,5	1,81
69	28,5	723	81,5	2220	3,9	7,6	10,2	1,681
82	39	741	87,9	2400	3,9	7,8	36,2	1,57
HC_{press}-refined pulp at 175 °C and 184 kWh/t								
0	14	603	24,2	570	3,0	3,2	0,4	2,27
56	17	656	51,7	1660	4,4	5,1	1,5	2,19
80	20,5	675	60	1940	4,5	5,6	3,4	2,17
106	24	688	64,2	1970	4,3	5,9	6,3	2,10
134	32	711	71	2260	4,5	6,2	17,8	2,10
HC_{press}-refined pulp at 175 °C and 597 kWh/t								
0	14	565	26	650	3,2	3,3	0,3	2,15
59	19	634	51	1680	4,5	5,2	1	2,09
85	22	645	55,8	1920	4,7	5,4	2	2,02
113	27	660	59,9	2000	4,6	5,8	4,6	2,01
144	34	682	65,2	2220	4,7	6,1	12,7	1,93

LC refining

LC refining was performed on four samples of pulp after the HC_{press} refining. The four pulp samples are marked with circles, *Fig 3*. Two of these samples were HC_{press}-refined at 125ºC and the other two at 175ºC. Pulp samples that had been refined at two different levels of refining energy were selected.

The length-weighted fibre length was relatively unchanged during LC refining of the pulp that had been HC_{press}-refined at 175ºC in the first

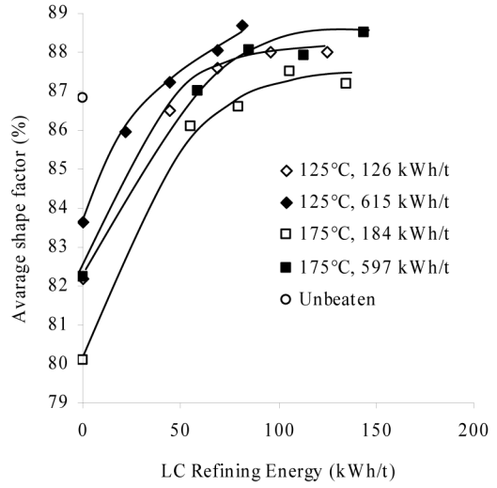

Fig 6. Average shape factor versus LC refining energy after HC_{press} refining at different temperatures and levels of energy consumption.

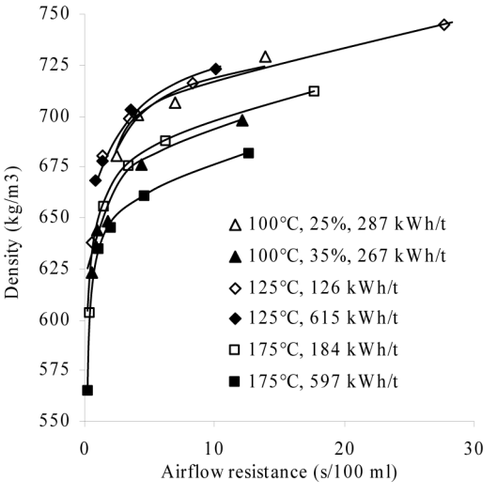

Fig 7. Density versus airflow resistance (Gurley) after HC_{atm} and HC_{press} refining (at different temperatures and levels of energy consumption) and LC refining. Measured on ISO sheets.

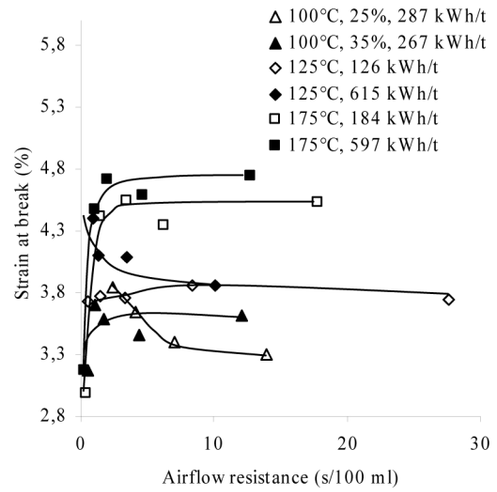

Fig 8. Strain at break versus airflow resistance (Gurley) after HC_{atm} and HC_{press} refining (at different temperatures and levels of energy consumption) and LC refining. Measured on ISO sheets.

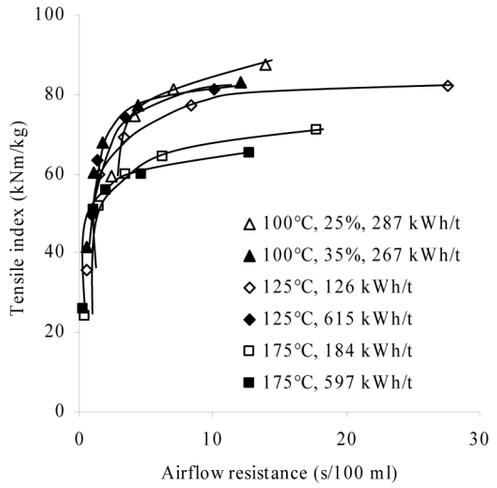

Fig 9. Tensile index versus airflow resistance (Gurley) after HC_{atm} and HC_{press} refining (at different temperatures and levels of energy consumption) and LC refining. Measured on ISO sheets.

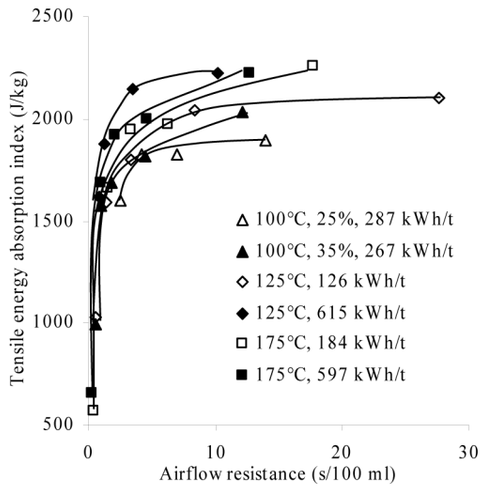

Fig 10. Tensile energy abs-index versus airflow resistance (Gurley) after HC_{atm} and HC_{press} refining (at different temperatures and levels of energy consumption) and LC refining. Measured on ISO sheets.

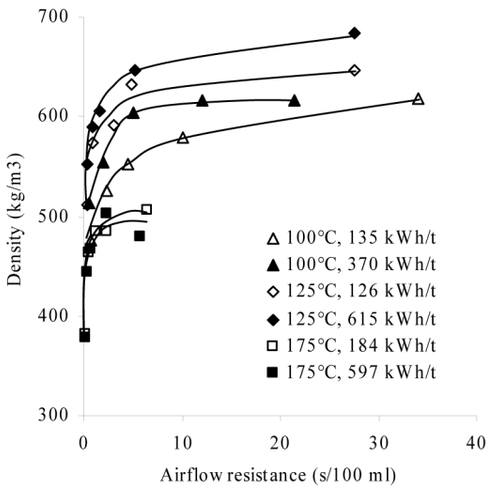

Fig 11. Density versus airflow resistance (Gurley) after HC_{atm} and HC_{press} refining (at different temperatures and levels of energy consumption) and LC refining. Measured on freely dried sheets.

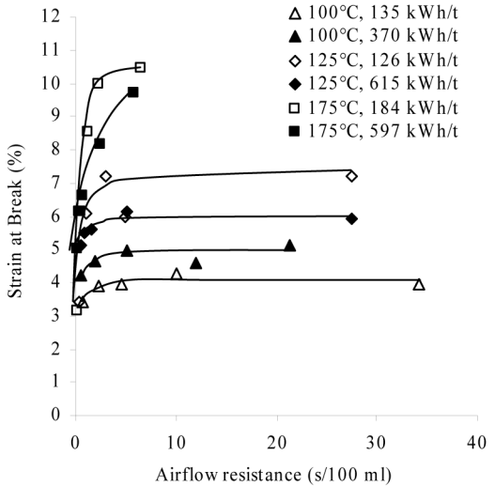

Fig 12. Strain at break versus airflow resistance (Gurley) after HC_{atm} and HC_{press} refining (at different temperatures and levels of energy consumption) and LC refining. Measured on freely dried sheets.

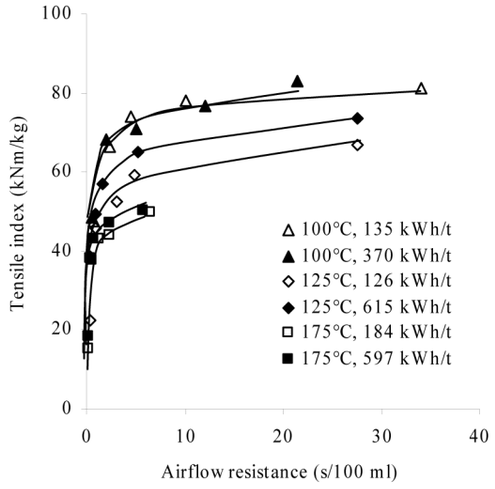

Fig 13. Tensile index versus airflow resistance (Gurley) after HC_{atm} and HC_{press} refining (at different temperatures and levels of energy consumption) and LC refining. Measured on freely dried sheets.

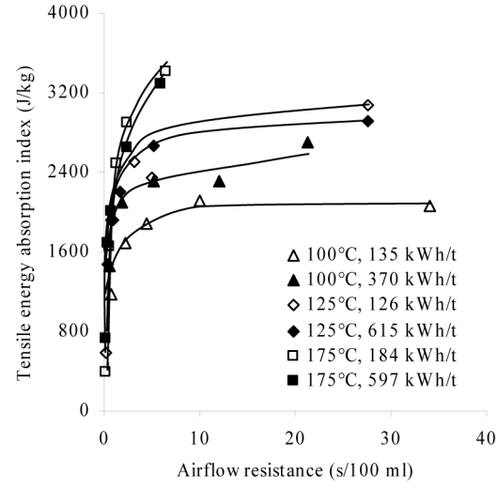

Fig 14. Tensile energy abs-index versus airflow resistance (Gurley) after HC_{atm} and HC_{press} refining (at different temperatures and levels of energy consumption) and LC refining. Measured on freely dried sheets.

stage, *Table 4*. The length of fibres that had been treated at 125ºC in the HC_{press} refining stage was lower and it decreased slightly with increasing refining energy during LC refining. This could be due to a straightening out of the fibres, as the fibres that were HC_{press}-refined at 175ºC were more curled than the fibres that were HC_{press}-refined at 125ºC.

The length-weighted shape factor increased with increasing refining energy during the LC refining for all pulps, *Fig 6*. The fibres that had been HC_{press}-refined at 175ºC using low refining energy (184 kWh/t) retained most curled fibres during LC refining.

The results of the testing of ISO sheets are shown in *Table 4* and in *Fig 7-10*, where the results are compared to the results after conventional HC_{atm} refining at 100ºC. The density increased with increasing LC refining, the most dense sheets were obtained from pulp that had been HC_{press}-refined at 125ºC. Pulp that had been HC_{press}-refined at 175ºC using a low refining energy (184 kWh/t) had a higher density after LC refining than pulp that had been HC_{press}-refined at 175ºC using a higher refining energy (597 kWh/t). The strain at break increased with increasing refining energy in pulps that had been HC_{press}-refined both at 125ºC and 175ºC. The greatest increase occurred already at very low airflow resistance values. The best development of strain at break was achieved for fibres that had been HC_{press}-refined at 175ºC. The development of strain at break during LC refining was much better in pulp that had been HC_{press}-refined than HC_{atm}-refined. The tensile index increased with increasing LC beating. Sheets made of pulp that had been HC_{atm}-refined at 100ºC and at a low pulp solid content showed the best tensile index development. The tensile index was lower, when the HC refining stage was performed under pressurised than under atmospheric conditions. The TEA-index increased with increasing LC beating for all pulp samples. The TEA-index was higher when the HC refining stage was performed under pressurised than under atmospheric conditions. Apart from the normal LC refining effects, the effect of LC refining is a straighter fibre. The straighter fibre results in a denser sheet structure with more fibre-to-fibre contact and thus higher strength and a more activated network with higher stiffness and normally lower strain at break. The most important part of the normal LC refining effect is the internal fibrillation which supposedly makes the fibre more flexible, resulting in a larger bonded area per contact point and thus higher strength.

The ability to stretch is determined to a large extent by the shrinkage, which occurs in the sheet during drying. When a high strain at break is needed, e.g. in sack paper, attempts should be made to increase the paper shrinkage (Htun 1981, Page 1971, Wahlström 1999). The tensile index increases and strain at break decreases with increasing strain during drying. This means that the more a sheet shrinks freely, the higher strain at break is achieved in the paper (Wahlström 1999). To investigate this behaviour, freely dried hand-made sheets were made from six pulp samples from the trials with HC_{atm} and HC_{press} refining in the first stage. The effect on pulp and sheet pro-

Table 5. Pulp and hand-made freely dried sheet data from HC_{atm}- and HC_{press}-refined pulp and subsequent LC refining.

Energy consumption in Escher-Wyss (kWh/t)	SR	Density (kg/m3)	Tensile index (kNm/kg)	Tensile energy abs-index (J/kg)	Strain at break (%)	Tensile stiffness-index (MNm/kg)	Airflow resistance (Gurley) (s/100 ml)
HC_{atm}-refined pulp at 100°C and 135 kWh/t							
0	15	476	47,6	1170	3,4	4,9	0,7
30	17,5	525	66,2	1700	3,9	5,7	2,3
70	21	552	74,2	1890	3,9	6,1	4,5
90	24,5	579	77,9	2110	4,3	6,1	10
110	33	619	81,4	2070	4,0	6,6	34,1
HC_{atm}-refined pulp at 100°C and 370 kWh/t							
0	16,5	513	48,2	1470	4,2	2,4	0,6
30	19,5	553	68,3	2110	4,6	3,1	1,9
50	22	605	71,1	2310	5,0	3,3	5,1
80	28	617	76,7	2310	4,6	3,8	12,0
90	32	616	82,8	2710	5,1	3,7	21,4
HC_{press}-refined pulp at 125 °C and 126 kWh/t							
0	13,5	512	22,6	590	3,4	2,7	0,3
45	16	574	45,7	1920	6,1	3,7	1
69	19,5	592	52,5	2500	7,2	3,8	3,1
96	24	633	59	2340	6,0	4,6	5
125	33	646	66,9	3080	7,2	4,6	27,6
HC_{press}-refined pulp at 125 °C 615 kWh/t							
0	15,5	552	38,5	1470	5,1	3,9	0,5
22	17,5	589	49,2	1920	5,5	4,3	0,8
45	22	606	57	2210	5,6	4,8	1,6
69	28,5	647	64,8	2670	6,1	5,1	5,2
82	39	683	73,5	2910	5,9	5,8	27,6
HC_{press}-refined pulp at 175 °C and 184 kWh/t							
0	14	382	15,4	390	3,2	1,8	0,2
55	17	463	37,6	1660	6,1	3,1	0,6
80	205	486	43,2	2490	8,5	2,6	1,2
106	24	484	44	2890	10,0	2,2	2,4
134	32	505	49,6	3410	10,4	2,7	6,5
HC_{press}-refined pulp at 175 °C and 597 kWh/t							
0	14	377	18,6	730	5,0	2,0	0,2
59	19	444	38,3	1690	6,1	3,2	0,4
85	22	468	42,9	2000	6,6	3,4	0,8
113	27	503	47,3	2660	8,2	3,4	2,4
144	34	479	50,4	3290	9,7	3,2	5,9

perties from HC_{atm} and HC_{press} refining are compared and shown in *Table 5*. Some physical properties are evaluated as a function of the airflow resistance in *Fig 11-14*.

Density increases with increasing LC beating. The densest sheets were achieved from pulp that had been HC_{press}-refined at 125°C. The freely dried sheets had a lower density than the ISO sheets. The strain at break increased with increasing beating in pulp that was either HC_{atm}- or HC_{press}- refined. The greatest increase occurred, as before, at very low airflow resistance values. The by far best development of strain at break was achieved for fibres that were HC_{press}-refined at 175°C. The strain at break on these samples was twice that of the ISO sheets. The strain at break is obviously highly dependent on how the sheet is dried. The most interesting aspect is that there is a great difference in strain at break between pulp that is HC_{press}-refined at 175°C or 125°C and pulp that is HC_{atm}-refined. The pulp that showed the best development of strain at break was the pulp refined using the lowest refining energy, 184 kWh/t, in HC_{press} refining at 175°C.

The tensile index increased with increasing LC beating. The pulp that had been HC_{atm}-refined at 100°C showed the best development of tensile index. This is probably a result of less damaged fibres during HC_{atm} refining. The tensile index was much lower for all the samples compared with the ISO-sheets.

The TEA-index increased with increasing LC beating in all the pulp samples. The best development of TEA-index was achieved in fibres that had been HC_{press}-refined at 175°C. However, the pulp sample that was HC_{press}-refined using the lowest refining energy was still the most stretchable. Compared to the results for the ISO sheets, the TEA-index was considerably higher, especially in the pulp samples that had been HC_{press}-refined at 175°C.

These results were somewhat unexpected, as the sheet properties after the HC_{press} refining stage were inferior to the sheet properties after HC_{atm} refining, *Table 1* and *3*. The strain at break and TEA-index, especially for fibres refined at 175°C, had very high values even at very low airflow resistance. This is a very desirable combination of properties for sack paper.

Conclusion

Refining of unbleached kraft pulp in a pressurised HC refiner (HC_{press} refiner) at a high temperature leads to a higher degree of curled fibres than in an atmospheric HC refiner (HC_{atm} refiner). However, it is possible that most of the fibre curl arises already during the treatment in the plug screw in the inlet to the pressurised system.

The water retention value increased for pulp HC_{atm}-refined and HC_{press}-refined at 125°C. Pulp samples HC_{press}-refined at 175°C showed a decrease in water retention value, which indicates a permanent change in the fibre wall with properties similar to hornified fibres.

The evaluation of ISO sheets shows that a refining system that starts with HC_{press} refining produces pulp with a higher strain at break and higher tensile energy absorption index (TEA-index) than that produced in an atmospheric system. On the other hand, the tensile index is somewhat higher in systems that start with a HC_{atm} refining stage. The highest TEA-index in this study was found in freely dried, hand-made sheets produced from fibres HC_{press} refined at 175°C and subsequent LC refining. The result was achieved at a very low airflow resistance, which is very important for high quality sack paper. The highest strain at break was also achieved in freely dried, hand-made sheets produced from fibres

HC_{press} refined at 175ºC and subsequent LC refining. This result was also achieved at a very low airflow resistance.

In order to attain these results, the refining energy during HC_{press} refining was low compared to the refining energy used to produce pulp with a high TEA-index and high strain at break in an atmospheric system. The tensile index was not, however, as high in pulp samples HC_{press} refined at 175ºC and thereafter beaten in a LC stage. The highest tensile index was achieved in pulp samples refined in a conventional HC_{atm} refiner and thereafter LC refined.

A HC_{press} refining stage makes it possible to produce pulp for kraft sack paper with a high strain at break and high TEA-index at low airflow resistance using relatively low refining energy during refining.

Further Investigations

This study indicates a possibility to replace the HC_{atm} refining stage with pulp treatment in a plug screw at high temperature and achieve the same effects. This will be reported in "Refining systems for sack paper pulp, Part II" (submitted to Nordic Pulp and Paper Research Journal). It is also of importance to understand the fundamentals of what happens in the fibre walls under conditions of HC_{press} refining. This has been studied with NMR technique. To investigate the role of lignin, in achieving the effects shown in the present study, bleached kraft pulp has been HC_{press} refined. New methods using chemical additives to improve the bond strength of paper made from fibres that have been treated to achieve a high strain at break level in pressurised systems have been studied. Forthcoming papers intend to report the results from these studies.

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