Research Article

Unique steel belt press technology for high strength papers from high yield pulp

Tove Joelsson[1,2] · Anna Svedberg[2] · Sven Norgren[2] · Gunilla Pettersson[1] · Jan-Erik Berg[1] · Cherryleen Garcia-Lindgren[3] · Per Engstrand[1]

Received: 8 February 2021 / Accepted: 31 March 2021
Published online: 16 April 2021

Abstract
The dry strength properties of hot-pressed moist paper improved as stiff high-yield pulp fibers soften and the sheet density increased. Very high wet strength was also achieved without adding strengthening agents. This research focuses on a new hot-pressing methodology based on a steel belt-based pilot cylinder press with infrared heating. The heated steel belt transports the moist paper into the cylinder nip with two adjacent steel rollers with adjustable nip pressure. The temperature ranges up to 300 °C, maximum speed is 5 m/min, maximum pulling force from the steel belt is 70 kN and the line load in the two press nips is 15 kN/m each. High peak pressures are possible due to the hard press nip between steel rolls and steel belt, allowing a good heat transfer to the paper. The long dwell time allows strained drying of the paper which results to high density and high wet strength. Paper samples from high-yield pulps were tested at different nip pressures, temperatures and machine speeds while the dry content was kept constant at about 63%. High nip pressure showed the largest effect on densification and dry strength. While high temperature and long dwell time seem to be most important in achieving high wet strength.

Keywords Hot-pressing · Steel-belt · High yield pulp · Density · Dry strength · Wet strength

1 Introduction

Hot-pressing techniques have been developed since the end of the 1920s, starting from the Mason's invention of the hardboard called Masonite [1–3]. In this single stage press drying, a wet and coarse TMP (thermomechanical pulp) was pressed between a gloss platen of 220 °C and a coarse wire hot plate of 150 °C. Until the 1970s the wet pressing technique was only used for producing hardboard. The development of press drying of paper material started in 1973 in Sweden using 70% yield unbleached kraft for producing liner and later even TMP in order to reduce the stiffness of lignin rich fibers [4]. Later, efficient wet pressing in papermaking became an indispensable technique for obtaining an economically feasible process before the paper web enters the energy-intensive drying part.

It was gradually understood that not only dryness and density could develop but also strength properties if the temperature was raised above 100 °C during pressing i. e. press drying. Press drying of moist paper at high web temperature added compressive forces and reduced the stiffness of the fibers, as wood components are softened. This led to increased density by enhanced consolidation

✉ Tove Joelsson, tove.joelsson@more.se; Anna Svedberg, anna.svedberg@more.se; Sven Norgren, sven.norgren@more.se; Gunilla Pettersson, gunilla.pettersson@miun.se; Jan-Erik Berg, jan-erik.berg@miun.se; Cherryleen Garcia-Lindgren, cherryleen.garcia-lindgren@ipco.com; Per Engstrand, per.engstrand@miun.se | [1]Mid Sweden University, Holmgatan 10, 851 70 Sundsvall, Sweden. [2]MoRe Research Örnsköldsvik AB, Hörneborgsvägen 10, 892 50 Domsjö, Sweden. [3]IPCO Sweden AB, 2453-B Västra Verken, 81181 Sandviken, Sweden.

of constituent components and improved strength, especially in lignin-rich paper [5, 6].

Impulse drying, as an improved wet pressing technique, was invented by Douglas Wahren in 1973 and patented in 1982 [7]. The concept was to achieve a high heat transfer to a paper web by passing it between a heated roll and a cold felt-covered roll. In modern impulse drying, the press roll is externally heated and the felt-covered roll is a press shoe with extended nip. Realistic values show a dwell time of 5–50 ms, a peak pressure of 3–8 MPa and the surface temperature of the roll is 200–400 °C [8, 9]. A great deal of research has been done on the EuroFex pilot paper machine at RISE, Stockholm which is equipped with two impulse units [10]. Later, this technique was further improved by introducing a thin metal band which transferred the heat more efficiently to the paper web [8]. The impulse technique, however, never came into industrial scale because of delamination and adsorption problems.

The Condebelt process was developed in 1975–1985 and its first industrial use was in 1996. The drying rate in the press section was further improved by evaporation when the web was in direct contact with a heated metal belt on the top side. On the bottom side, the water condenses through a cold felt fabric or wire and on to a cooled metal belt. The temperature range of the upper side is 120–180 °C and the cold bottom side is 60–90 °C, while the pressure range is 0.05–0.7 MPa. The Condebelt section can be about 20 m long. This technique improves the strength properties at same time, preserves the bulk and bending stiffness. The Condebelt was implemented in some commercial board machines in 1996 [11].

Another development of press drying is the highly efficient dryer called BoostDryer by Voith. This technique consists of a specially designed cylinder, where the outer periphery is pressurized by water. The web runs directly on the heated drying cylinder and is held in close contact by a fine wire and a steel belt cooled with water. The incoming web dryness is about 60% and the cylinder surface temperature is 120–160 °C; pressure is 0.6–1.2 MPa and the dwell time 10–15 s. This technique was never implemented on a commercial scale [12].

There is potential in hot-pressing moist paper at high temperatures, especially in terms of enhanced strength properties. Most particularly with increased wet strength without the need of strength additives due to the presence of lignin. It is a promising way to improve strength in paper material based on HYP where stiff lignin coated fibers need to be softened to consolidate in order to facilitate enhanced bonding in the fiber network.

At Mid Sweden University, FSCN's researchers have shown recently how strength properties for HYP based paper sheets could significantly be improved as the lignin is softened and thereby fiber structure densified by means of hot-pressing [13–15]. It has also been demonstrated how wet strength increased due to high pressing temperature, well above the softening temperature of lignin and due to increased lignin content [16, 17]. These trials were performed on an oil heated test cylinder press equipped with a felted web carrying the paper sample through the press nip. The maximum temperature of the cylinder press is 200 °C, the nip of a constant pressure about 6 MPa, and a dwell time of about 1.5 s and 70 s in nip pressure and under felted web respectively at the rate of 1 m/min.

These studies were due to equipment design limited to a maximum temperature of 200 °C, but as the results indicate an increase in strength with increasing temperature it should be possible to further develop strength properties of HYP based papers. In order to study hot-pressing at higher temperatures in a well-controlled way we developed the new type of lab-scale hot pressing machine presented here. The design is based on the technology described above based on research performed at Mid Sweden University combined with key knowledge of steel belt technologies from IPCO AB (earlier Sandvik Process Systems AB).

The new hot-pressing equipment consists of a cylinder press with two roll-nips and an infrared heated steel belt. The heater is placed underneath the belt just before the first nip, allowing paper sheets (or a paper web) to enter the nip at a well-controlled temperature. After the first nip the sheet is locked between the cylinder and the steel band and can enter a second nip after about 0.4 m whereafter the sheet is locked between the band and the cylinder for 0.77 m until the band leaves the cylinder and the paper samples are extracted. The total paper to cylinder contact length is thus 1.17 m. The contact time between belt and cylinder is important as it is necessary to maintain high enough temperature and pressure until the papersheet is dry enough avoid the well-known "spring back" effect of high yield pulp based sheets.

The new design may also prevent delamination that can occur when a large enough amount of superheated water evaporates and flashes into vapor in a rapidly opening nip as in case of impulse drying. The reduced risk of delamination may be due to the low density, i.e. open structures of HYP based paper sheets allow water vapor to expand. Moreover, the compression time at high temperature is quite long so that vapor pressure will drops in a slow and controlled way. The moisture content should preferable be below 50%, preferably at about 65%. The advantages of using a steel belt is that it is more temperature resistant than fabrics and that higher temperature can be used, which is important to further developing the mechanical properties for paper based on high yield pulp. Other advantages of a steel belt compared to fabric is the nice smooth surface and the low compression—stretch that gives a hard and short nip.

The new equipment is designed to perform tests related to hot-pressing of lignin rich material in such way that the dry and wet strength maxima can be achieved. Additionally, the equipment will be used to improve the fundamental understanding of optimization of physical properties of HYP based materials. Major hot-pressing variables such as temperature, pressure, moisture content and residence time can be adjusted more easily compared to earlier equipment.

The new steel belt press is located at MoRe Research AB due to a unique combination of excellent pilot equipment competence and knowledgeable technical personnel. Several other industrial partners, such as Holmen, SCA, Stora Enso and Valmet, are also engaged in the research.

2 Experimental

2.1 Material

Paper sheets were prepared from high temperature-chemithermomechanical pulp (HT-CTMP) from Norway Spruce of CSF 630 ml with a yield of 95% produced by SCA's Östrand mill in Sweden. The pulp was bleached with peroxide and flash dried to 91.8% dry content. All laboratory work, sheet preparation, hot-pressing and analysis, were performed at the laboratory of MoRe Research Örnsköldsvik AB. Table 1 shows the characterization of the pulp used in this research study. The carbohydrates were analyzed with ion chromatography according to SCAN-CM 71:09. The method for calculating cellulose and hemicellulose is according to KA 10.314, which is an internal method at MoRe Research (Eqs. 1 and 2).

$$Cellulose\,(\%) = Glucose\,(\%)\,of\,Carbohydrates - \frac{Mannose\,(\%)\,of\,Carbohydrates}{3} \tag{1}$$

$$Hemicellulose\,(\%) = 100\,(\%) - Cellulose\,(\%) \tag{2}$$

Cellulose, hemicellulose, lignin, acetone extract and acid soluble lignin content are calculated as percentage of the total weight. The fiber data was analyzed by PulpEye instrument according to ISO 16065-2.

Table 1 Pulp characterization

Pulp	HT-CTMP
Cellulose (%) (KA 10.314)	48.2
Hemicellulose (%) (KA 10.314)	24.4
Lignin (Klason) (%) (T222)	26.2
Acetone extract (%) (ISO 14453)	0.19
CFS freeness (ml) ISO 5267-1, -2	630
Fiber length (mm) ISO 16065-2	1.66
Fiber width (µm) ISO 16065-2	32
Shive content (Sum/g) ISO 16065-2	112
Fines (%) ISO 16065-2	29.0
State of pulp, dry (%) ISO 638	91.8

2.2 Methods and experimental plan

2.2.1 Pulp preparation

The characterization of the pulp covers a broad range of properties, e.g. freeness, content of cellulose, hemicellulose, lignin, fines and shive, average fiber length and fiber width, all summarized in Table 1. The pulp was hot-disintegrated according to ISO 5263-3: 2004 prior to making paper sheets. No chemicals were added to the pulp furnishes.

2.2.2 Sheet preparation

Handsheets were prepared in a Rapid Köthen (RK) sheet former, Paper Testing Instruments (PTI), Pettenbach, Austria, according to ISO 5269-2:2004. The fiber suspension was 6.0 g/l. Sheets with a grammage of 100 g/m^2 were formed after vigorous aeration of the fiber suspension just before sheet preparation. The sheets were then press dried at 100 kPa pressure under restrained conditions at 90 °C until they reached about 63% dryness content. The handmade laboratory paper sheets made in the RK equipment had no fiber orientation. The paper sheets were stored in well-sealed plastic bags for approximately 24 h in room temperature before hot-pressing in the rotating cylinder press.

2.2.3 Sheet testing

Sheet testing was carried out after conditioning according to ISO 187 and grammage according to ISO 536, density according to ISO 534. Tensile strength was conducted according to ISO 1924-3. Wet tensile strength was measured according to ISO 3781.

2.2.4 Press drying equipment

The trials were performed on the new pilot hot-pressing machine with steel belt, which was installed in late 2018 at MoRe Research Örnsköldsvik AB (Fig. 1). The pilot machine

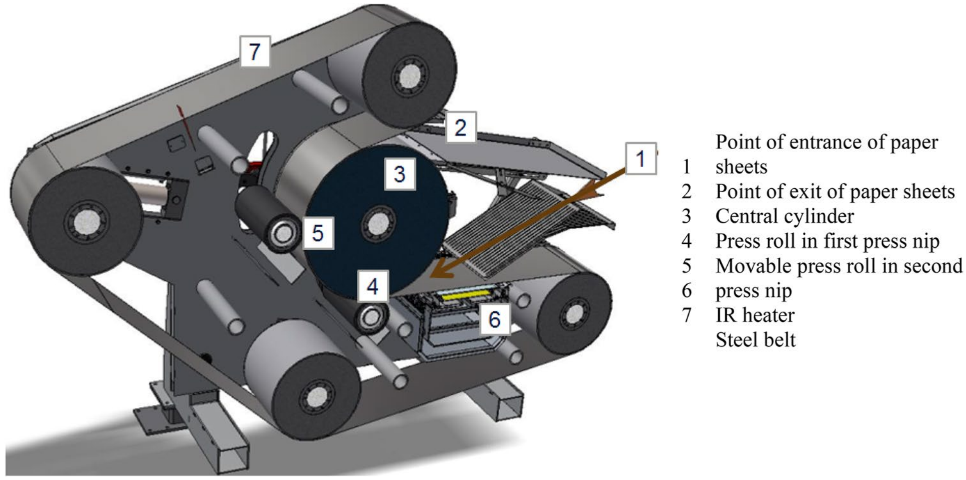


Fig. 1 Rotating press machine, with IR heated steel belt. With permission, a drawing from IPCO AB

has one central cylinder and two press rolls making up two press nips. A moving heated steel belt carries the paper material, which is in direct contact with the unheated central cylinder. Vertically, underneath the steel belt and the central cylinder is the first press roll. The second press roll is on a movable distance from the first one. The steel belt is heated with an infrared heating system about a distance of 20 cm from the first nip. Running the machine at a chosen temperature, the central cylinder will be equally heated within 40 min. The maximum temperature in the first nip is about 300 °C. The heat will be transferred through the steel belt into the paper sheet and the water in the moist paper material will be pressed out and evaporate in the nip. As the heated steel belt is covering the central cylinder for 1.17 m (the arc length) the dwell time will be long, giving a bone dry paper after the pressing. It is known that adsorption and delamination problems may occur at certain conditions [9]. To avoid adsorption problems in the present experiments, thin blotters were used on both sides of the paper sheet tested. Neither delamination nor adsorption was observed with this procedure. The diameter of the cylinder and the press rolls is 0.8 m and 0.2 m respectively. The maximum speed is 5 m/min and the maximum line load is 15 kN/m for each press nips as the maximum load on press roll is 6 kN. The applied pulling force on the steel belt may be adjustable between 10 and 70 kN and this gives a pressure on the central cylinder between 0.03 and 0.21 MPa. The dwell time at the press nip is between 27 and 240 ms and for the steel belt between 14 and 140 s. The steel belt has a width of 400 mm, thickness of 0.8 mm and covers 46.7% of the total cylinder perimeter of 2.5 m. The total weight of the machine is 2500 kg, length 3.3 m and width 1.6 m (Fig. 1).

2.2.5 Press machine settings and experimental set up

The nip length in the press nip without paper sample was measured in room temperature with sensor films from Fuji/Prescale and was estimated to be about 2 mm. The actual press nip length is somewhat different measured with paper samples because both width and thickness of the sample have effect as well as the crown effect at elevated temperature. Due to measuring difficulties in present study with samples and the varying high temperature the calculations are based on the geometry at room temperature without samples. We assume that the results in relation to each other can explain some effects of the changes in process variables. In this trial we calculated the mean pressure by using the 2 mm nip length and this resulted in 3.75 MPa (rounded to 4 MPa) and 7.5 MPa (rounded to 8 MPa) when the applied force was 3 kN and 6 kN respectively.

Experiments with seven trial points were performed at machine settings according to Table 2. HT-CTMP based paper sheets of 100 g/m^2 and a dry content of approximately 63% were formed on the RK. The HT-CTMP pulp was characterized as shown in Table 1. The final dryness of about 93% minimum (bone dry) was important for the dimensional stability and physical properties of the paper. Due to this the test point (T1) was run 3 times at the temperature of 100 °C and 3 m/min in order to reach dry content of 93%, which affected the results. The temperature was measured just before the first press nip. The trials were run at speeds of 3 and 4.3 m/min, which gave in press nip dwell times of 40 and 28 ms respectively. The applied pressure in the two press nips gave a mean pressure of about 4 and about 8 MPa. The pressure of the belt was 0.15 MPa through all the trial points. The arc length of the steel belt coating the central cylinder was 1.173 m giving a dwell time or after hold of 23.5 s and 16.4 s for the speed of 3 m/min and 4.3 m/min respectively. In Fig. 2 the pressure and

Table 2 Trial set-up with trial points Tp1 to Tp7

		T1	Tp2	Tp3	Tp4	Tp5	Tp6	Tp7
Speed	m/min	3	3	3	3	3	3	4.3
Temperature	°C	100	200	200	260	260	300	300
Force press roll (nip 1, 2)	kN	0	3	3, 3	3	3, 3	6	6, 6
Mean pressure (nip 1, 2)	MPa	0	4	4, 4	4	4, 4	8	8, 8
Dwell time (nip)	ms	0	40	40	40	40	40	28
Press impulse (nip)	kPa s	0	150	150	150	150	300	209
Press impulse (steel belt)	MPa s	3.5	3.5	3.5	3.5	3.5	3.5	2.5
Steel belt pulling force	kN	50	50	50	50	50	50	50
Steel belt pressure	MPa	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Steel belt dwell time	s	23.5	23.5	23.5	23.5	23.5	23.5	16.4

The paper sample in T1 was run 3 times in order to become bone dry at the exit

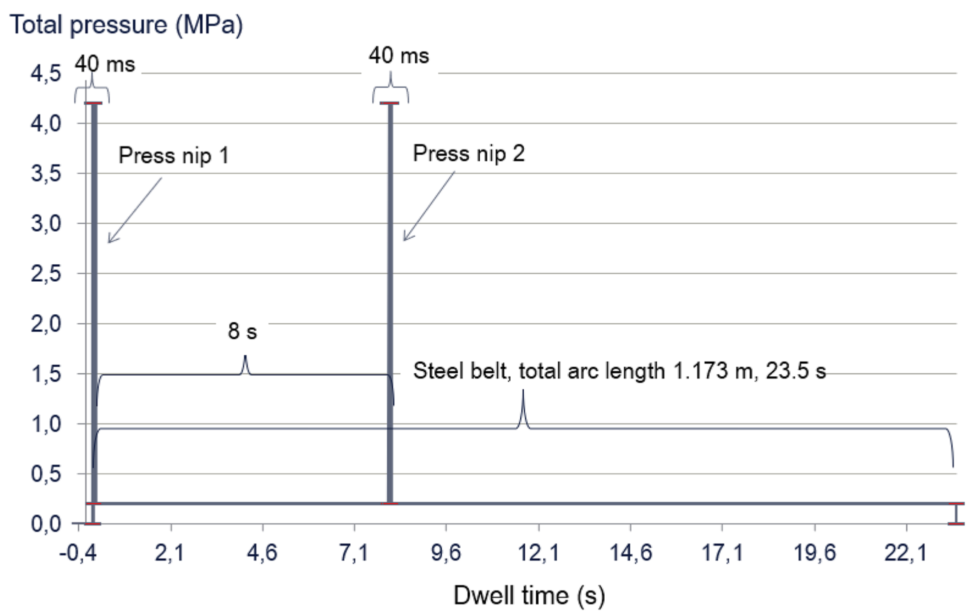


Fig. 2 The total pressure as a function of dwell time at a speed of 3 m/min

dwell time is schematically drawn for the machine speed of 3 m/min.

The pressure impulse can be increased over the time factor if the pressure is limited or vice versa, Eq. 3.

$$\textit{Pressing impulse}, I, [\text{Pa s}] = \frac{L}{v} = P \times t \tag{3}$$

L is the line load (force per unite width) in press nip **v** is the speed of the steel belt. P is the mean pressure and t is the dwell time (press time).

The paper sheet enters the steel belt at time 0 and a pressure from steel belt as well as from first press nip is applied simultaneously. After about 8 s the paper sample enters the second nip. The dwell time in the nips are equally long, 40 ms. After the second press nip the paper sample is in pressure of steel belt for another 15.38 s, after which it leaves the steel belt and the central cylinder (Fig. 2).

3 Results

The following results belong to the first step in optimizing the process variables on the new steel belt based dynamic pilot hot-press machine. The test points where all run at same steel belt tension and run at 3 m/min, test point with 2 nips á 8 MPa was run at 4.3 m/min. The dry content of the paper sheets was about 63%. Results here will also be compared to earlier studies performed on felted web oil heated cylinder press [16, 17].

Analyzing the paper sheets, showed that increasing load pressure increased density in the paper, while increasing temperature alone did not change density significantly (Fig. 3). This is evident when comparing the result of press nip of 4 MPa with two nips of same and equally comparing press nip of 8 MPa with two nips of same. Two press nips increase the density by 20–30% and the increase of

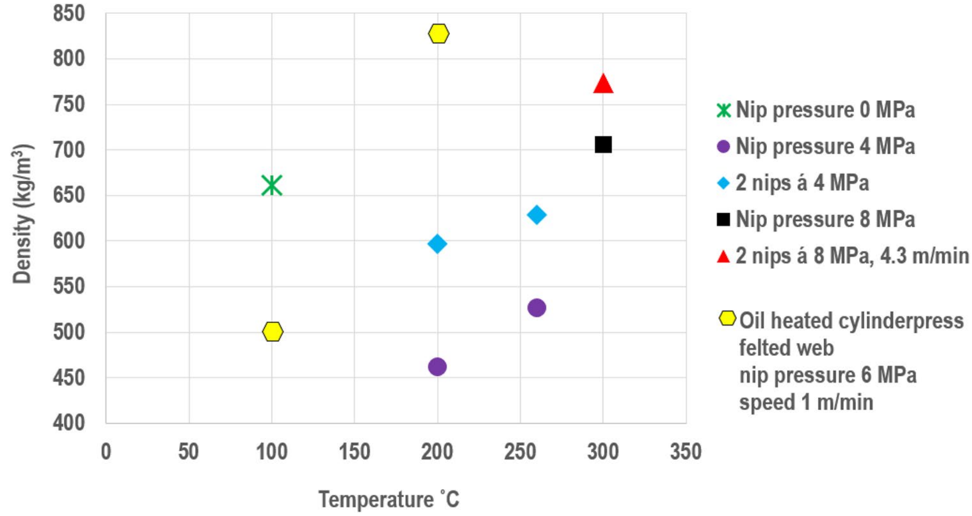


Fig. 3 Density as a function temperature in press nip. The trial points Nip pressure 0 MPa, 4 MPa, 8 MPa and 2 nips á 4 MPa were run at a speed of 3 m/min

50 °C in temperature increase the density by 5–14%. The test point with two press nips at 8 MPa was run at a higher speed resulting in shorter pressing time which may be the reason for only a slight increase in density. The reference is run at low temperature without load pressure in the nips but run three times in order to achieve bone dry sheets. Consequently, the dwell time of steel belt of 3*23.5 s at 0.15 MPa, resulted in a rather high density of 661 kg/m^3. At 100 °C and at 200 °C the present results can be compared to earlier results from tests on the felted web oil heated cylinder press. At 100 °C the load (0.15 MPa) of the steel belt run three times at a pressing time of 23.5 s per run (total 70.5 s), gives much higher density than the run at the oil heated cylinder press where the run was performed at 1 m/min giving a pressing time of felted web of 70 s. The pressure of the steel belt (0.15 MPa) is probably higher than that of the felted web. At 200 °C the result of the steel-belt based press machine run at 3 m/min show a much lower compressibility due to much shorter pressing time and a somewhat lower load in press nip compared to the felted oil heated cylinder press. The density reached by the felted web pressing machine at 1 m/min was 830 kg/m^3 at 200 °C compared to the 774 kg/m^3 at 300 °C, which was run with the steel belt pressing machine at 4.3 m/min. The pressing time was 1.5 s and 70 s compared to 28 ms and 16.4 s for the dwell time of nip pressure and steel felted web/steel belt respectively for each. The shorter pressing time was here compensated by higher temperature.

The dry tensile strength increased by increasing the density. According to this study a second press nip does not improve further the strength property, but perhaps compensate slightly the shorter pressing time. A temperature of 300 °C gave a strength value about equal to that of 200 °C at a much shorter pressing time, 40 ms and after hold of 23.5 s compared to 1.5 s and after hold 70 s. The high density of the test point at 100 °C seems not to have had influence on the tensile index. The reason for this is somewhat unclear. The test point at 200 °C is though clear in the sense that a longer pressing time has a great influence on the development of dry strength (Fig. 4).

It was observed that the wet strength property is most sensitive to increased temperature and pressing time as shown in Fig. 5. It is evident that high temperature is required to reach high wet strength. Even here the dwell time is important as seen in the case of test point at 8 MPa at two different speed. The same can be observed when the test point at 200 °C is compared to the earlier result from felted oil heated press cylinder. Here the wet strength was 16 kNm/kg compared to 3 kNm/kg at a pressing time in nip of 1.5 s and 40 ms respectively. When increasing the pressing temperature to 300 °C and still reducing the pressing time from 2.5 s to 28 ms at a somewhat higher load pressure the wet strength index is improved and reaches as high as 22 kNm/kg.

4 Discussion

Evaporation, delamination and adsorption are phenomena that are critical in the press drying technology. In the present equipment, the moist paper sample was run between a hot solid metal belt and an unheated steel cylinder, and therefore no absorbing surfaces present. Most of the water was displaced immediately by rapid flashing/evaporation in the entrance of the first press nip. After the press nip, there was little room for expansion because of the tension of the steel belt. The load from the steel belt was 0.15 MPa and the residence time was 23.5 s, which held the paper sample under pressure until it passed 1.17 m (the arc length of cylinder) before leaving the cylinder at a dryness of about 93%. The nip length of 2 mm gave a mean

Fig. 4 Tensile index as a function of temperature in press nip

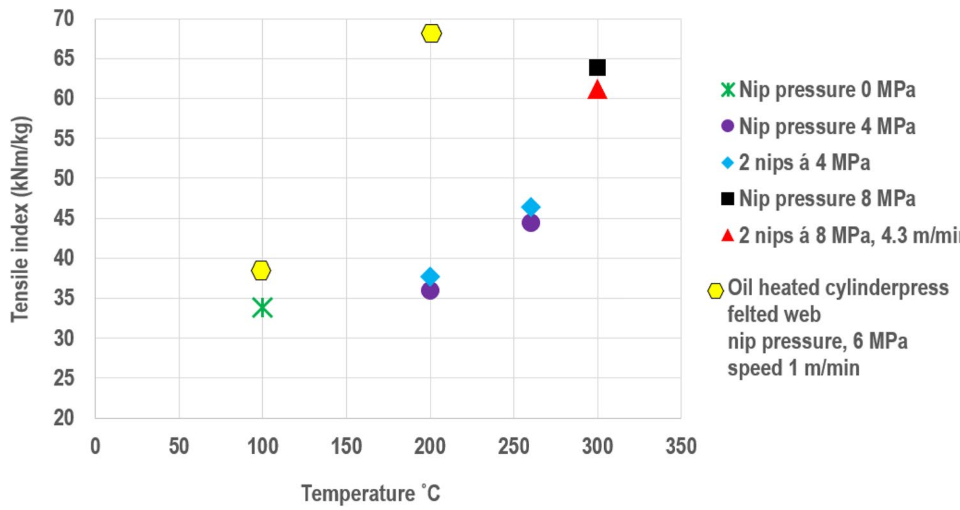
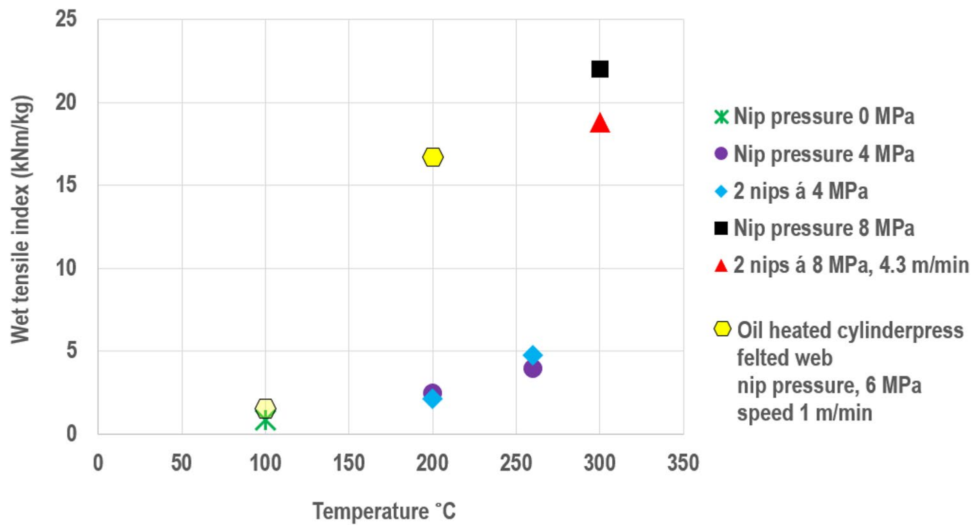


Fig. 5 Tensile index wet as a function of temperature



pressure of about 4–8 MPa. This gave a short dwell time in the hard nip but a long dwell time or after hold between the steel belt and the central cylinder.

To avoid adhesion of the moist paper sample to the steel surfaces, thin, porous blotters were used on both sides. There was no delamination observed, probably due to the long residence time provided by the steel belt on the lignin-rich paper sample. The second press nip did not increase paper strength to the same extent as the first press nip. One probable reason may be that the moisture content was already drastically reduced in the first nip and thereby also the plasticizing effect of water on the lignin. Another reason may be an assumed reduction in temperature as the distance from the infrared heater increases. The density, though, significantly increased by the second press nip. It is postulated by Goring in 1963 that that the drying process creates hydrogen bonds between fibers by auto-contraction [18, 19].

The test point, which was run at a higher speed at 4.3 m/min (in order not to burn the paper sample) and the temperature of 300 °C rendered in a much shorter dwell time, about 28 ms in nip and 16.5 s in afterhold. This reduced the effect of compressing the fiber matrix of the lignin-rich paper to enhance the physical paper properties, especially the wet strength. The importance of residence time was stressed by Horn and Setterholm in their experiments on a continuous press dryer with high yield hardwood pulp [20]. The The results for the physical properties illustrate the effect of temperature, load pressure in the two press nips and the steel belt pressure well. Density increased significantly by increasing pressure, but slightly more easily as the temperature increased. The reference trial point without nip pressure and only 100 °C had to be run 3 times to reach complete dryness. The values in density and tensile strength reached the same levels as compared to the results from earlier trials (ref. Joelsson et al. 2018) on the cylinder drying press.

Wet strength measured as wet tensile index, increased largely to a level of 22 kNm/kg, as the pressing temperature reached 300 °C and the nip pressure to about 8 MPa. The exact value was not possible to measure. The density here was above 700 kg/m^3. This level of wet strength is much higher with this equipment compared to earlier hot-pressing techniques.

5 Conclusions

In this work we have demonstrated a new steel belt based hot-pressing technique for developing strong and water-resistant lignin-rich paper material. Important advantages have been discovered during these trials.

- Setting variables were fast and easy in terms of temperature, pressure, one and two press nips, steel belt tension and speed.
- Effect of dwell time and press load were also easy to evaluate on the strength properties of the resulting paper sheets.
- Delamination can be avoided. High temperature and long dwell time of the steel belt pressure is preferable. It was critical that the outgoing paper sample was bone dry to avoid spring back effect.
- Highest wet strength was achieved by highest temperature and highest pressure.
- A second press nip did not further improve significantly neither the dry strength nor the wet strength.

This study concludes that the new hot-pressing technology enables the use of HYP to be used in strong and specifically wet strong paper materials without adding strengthening chemicals. With this hot-pressing technique paper sheets pressed at high temperature, about 300 °C and high pressure, more than 8 MPa at a pressing time of 40 ms and an after hold of 23.5 s, reached a wet strength of 22 kNm/kg. This wet strength value is in the lower region of commercial wet strong paper. The hot-pressing technique is therefore a unique way of producing environmental-friendly packaging material with demands on wet stability without adding strengthening agents.

Acknowledgements We gratefully acknowledge financial support from the Knowledge Foundation (KKS) with FORIC (Forest as Resource Industrial Research College, a part of Treesearch), the Kempe Foundation, IPCO AB, MoRe Research Örnsköldsvik AB, and Mid Sweden University. We would also like to thank the laboratory personnel at MoRe for their excellent cooperation.

Funding Open access funding provided by Mid Sweden University.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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