Pre-extraction of hemicelluloses and subsequent kraft pulping Part II: Acid- and autohydrolysis

WALEED WAFA AL-DAJANI, ULRIKE W. TSCHIRNER, AND TRYG JENSEN

ABSTRACT: Aspen wood chip samples were subjected to hot water treatments (autohydrolysis) with and without sulfuric acid to extract hemicelluloses. A liquor-to-wood ratio of 4:1 was used at temperatures from 130° to 210°C and H_2SO_4 concentrations in the range from 0% to 1% (w/v), with treatment times up to 4.5 h. Researchers analyzed wood residues and their corresponding hydrolysates, and determined the most suitable conditions for the extraction. Additional information on the suitability of wood residues for pulping purposes is also considered.

Application: Several companies are considering pre-extraction of wood chips with hot water or water/acid before kraft pulping. Our research indicates optimum pre-extraction conditions and the effect on subsequent pulping.

In Part I of this study [1], we examined the alkaline extraction of hemicelluloses from aspen chips. Pretreatment of lignocellulosic materials with water has been considered an excellent option for the extraction of hemicelluloses since no chemicals other than water are involved. Therefore, there are no problems of equipment corrosion, no need for sludge treatments or acid recycling, and there are good yields of sugar solutions and low byproduct formation.

Hydrothermal treatments of xylan-rich materials have been considered environmentally friendly, resulting in a selective release and degradation of the xylan [2]. However, autohydrolysis as well as acid hydrolysis, especially at elevated temperatures, produce undesirable side reactions, reducing the overall yield of hemicellulose recovery and generating inhibitors for a potential subsequent fermentation process [3, 4]. Thus, before the hemicellulose solutions can be used as fermentation feedstock they will require extensive detoxification steps to remove inhibitors [5].

We subjected aspen wood chips to hydrothermal treatments to find the most effective set of conditions for extracting hemicelluloses while leaving high quality cellulosic residue available for pulping processes. We selected aspen because it is a commonly used pulp wood species, and has a comparatively high level of xylan (~18% on o.d. wood). The hydrolysates were analyzed and the results obtained were related to the composition of the starting material.

EXPERIMENTAL

Wood chips

We carried out all our experiments in duplicate, using commercial aspen chips (*Populus tremuloides*). **Table I** shows the chemical composition of the aspen chips. After air-drying, the chips were screened and the fraction passing 1.0" but not 0.5" holes was sorted manually before storage to remove knots and bark.

Component	Weight percent, O.D. basis
Glucan	44.5±0.4
Xylan	17.7±0.2
Galactan	1.3±0.1
Arabinan	0.5±0.1
Mannan	1.7±0.1
Klason lignin	21.1±0.3
Acid-soluble lignin	3.0
Extractives	2.1
Ash	0.5
Acetyl+uronic acids α	7.6

α Determined as the difference to get 100% content.

I. Composition of* Populus tremuloides *aspen wood (as the average of 5 replicate measurements for carbohydrates and Klason lignin).

Pretreatment of wood chips

We investigated two types of pretreatments: autohydrolysis (using deionized water only) and H_2SO_4-pretreatment. A liquor-to-wood ratio of 4:1 was applied. Three sets of conditions were tested as follows:

a) The temperature was raised by 2.3°C/min to a final temperature, at which the pretreatment was interrupted.
Autohydrolysis: Final temperatures investigated were 130°, 150°, 170°, 190°, and 210°C.
H_2SO_4-Pretreatment: Pretreatments with 1.0% H_2SO_4 (w/v) to 130°, 150°, 170°, 190°C, and 210°C.

b) The temperature was raised by 2.5°C/min to a final temperature, at which the pretreatment continued for 1.5, 3.0, and 4.5 h.

Autohydrolysis: Final temperatures investigated were 130°, 140°, 150°, and 160°C.

H_2SO_4-Pretreatment: Pretreatments with 0.01, 0.1, and 1.0% H_2SO_4 (w/v) at 130° and 140°C.

c) Autohydrolysis at 150°C for 4.5 h with recycling of hydrolysate as follows:

1) Autohydrolysis using water for 4.5 h at 150°C.
2) Autohydrolysis using 50% water and 50% hydrolysate from 1.
3) Autohydrolysis using 100% hydrolysate from 1.
4) Autohydrolysis using 100% hydrolysate from 3.

Pulping

We carried out the cooks in stainless steel autoclaves rotating in an electrically-heated mineral oil bath, with a liquor-to-wood ratio of 4:1. After adding the pulping liquor to the chips/residue, we sealed the autoclave and allowed it to rotate at room temperature for 2 h to ensure complete wetting of the chips/residue. Subsequently, the temperature was raised by 3.5°C/min to the final cooking temperature (for the control cook: effective alkali = 21% (as NaOH), sulfidity = 25%, 40 minutes heat-up time to 170°C; 45 minutes at the final temperature of 170°C). We pulped the residues after hemicellulose extraction under slightly different conditions from those used for the control cook (see *Results and Discussion* for cooking parameters and chemical charges). After interrupting the cook, we drained off the black liquor and washed the pulp with deionized water in a water-jet defibrator to liberate the fibers and separate the shives. The material was screened on a 0.15 mm slotted vibratory screen. The screened yield and shive content were determined gravimetrically.

Analyses

The pulp samples were analyzed using standard testing methods: Klason lignin content TAPPI method, T 222 om-23; Kappa number: SCAN-C 1:77; and viscosity of pulp: TAPPI T 230 om-94. The carbohydrate content of chips, chips residues, and pulps was determined using the filtrate obtained after Klason lignin removal. A Waters HPLC system was employed with Waters 1525 Binary Pump, a Waters 717 plus Autosampler, a Waters 2414 Refractive Index Detector and a Breeze software for operation control and data processing. A BIO-RAD De-Ashing Refill Cartridges, 30 × 4.6 mm (guard column) in line with VARIAN MetaCarb 87P, 300 × 7.8 mm (analytical column) was used. The eluant was deionized and degassed water flowing at 0.3 mL/min. The operating pressure was 541 psi and the column temperature was 80°C. The same HPLC system with a Waters 2487 Dual λ Absorbance Detector was used to determine the contents of furfurals at 210 nm in the hydrolysates; 2-furaldehyde (furfural) and 5-(hydroxymethyl)-2-furaldehyde (HMF). A BIO-RAD Cation H Cartridge, 30 × 4.6 mm was used. The eluant was 0.005 M H_2SO_4 flowing at 0.5 mL/min. The operating pressure was 471 psi.

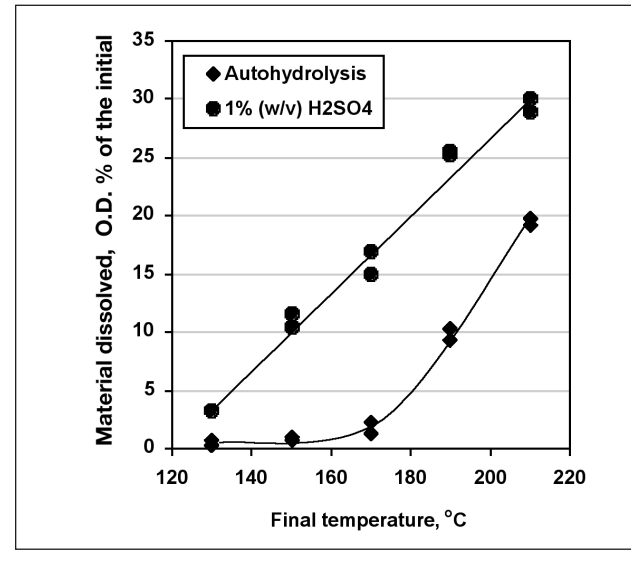
RESULTS AND DISCUSSION

Autohydrolysis and H_2SO_4-hydrolysis to a final temperature

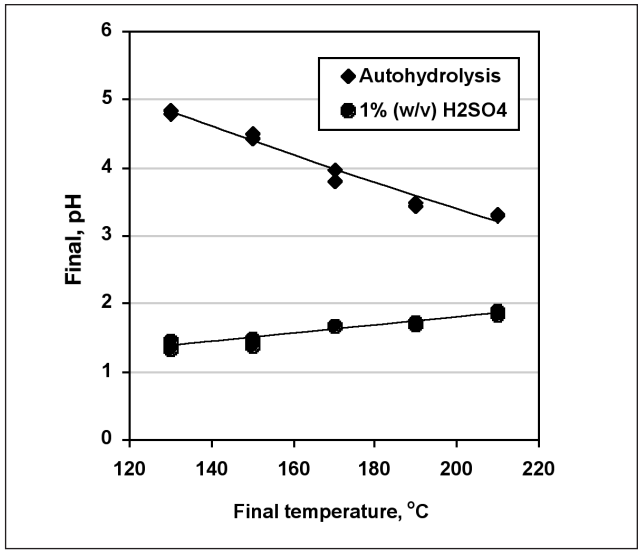
The total content of acetyl and uronic acid groups in aspen shown in Table I is in agreement with the values reported by Timell [6]: 3.7% and 4.3% for acetyl and uronic acid groups, respectively. Acetyl groups split from the hemicellulosic fraction to form acetic acid, thus contributing to the extraction of more hemicelluloses. The final temperatures of hydrolysis investigated in this part were between 130° and 210°C because, first, the extent of hydrolytic reactions was reported to be moderate at temperatures below 100°C [7], and, second, cellulose degradation becomes appreciable at temperatures higher than 210°C [8].

Figure 1 shows the amount of material dissolved during autohydrolysis and H_2SO_4-hydrolysis. This amount was calculated as the difference between the weights of fresh wood chips and that of thoroughly-washed wood residue after the hydrolysis. In the presence of 1% (w/v) H_2SO_4, about 3% of the total material was dissolved when a temperature of 130°C was reached. As shown, this amount continued to rise linearly with time and temperature. For autohydrolysis, however, it was not until a temperature of 170°C was reached that the amount of material dissolved started to increase to a considerable level. In **Fig. 2**, the decreasing pH observed with increasing autohydrolysis temperature is mainly due to the splitting of acetyl groups and the formation of acetic acid. For H_2SO_4-hydrolysis, pH slightly increased because of the formation of acetic acid and the consumption of some H_2SO_4.

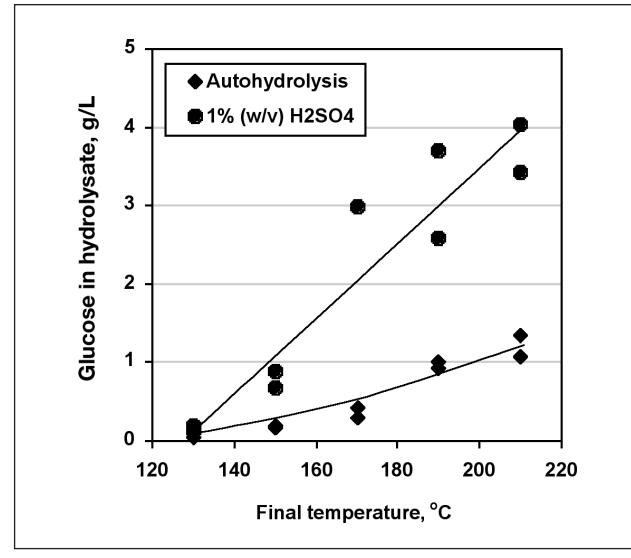
The hydrolysates contain the extracted part of hemicellulose that will subsequently be used for ethanol production. Therefore, it is of great importance to gain information about



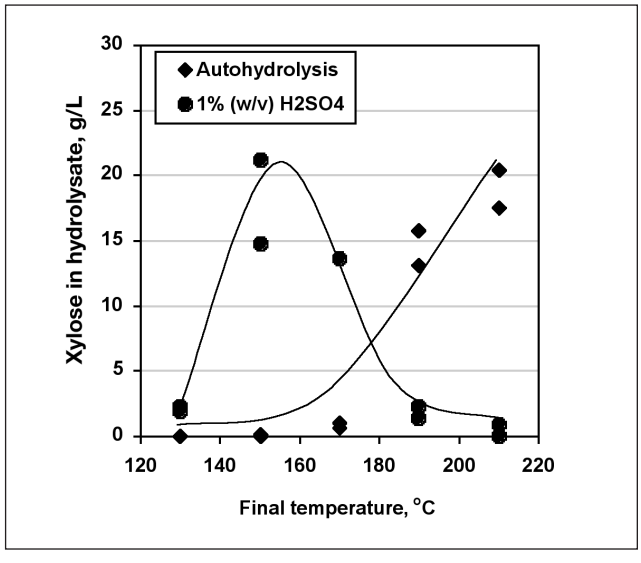
1. The amount dissolved during autohydrolysis and H_2SO_4-hydrolysis of aspen chips to different maximum temperatures.



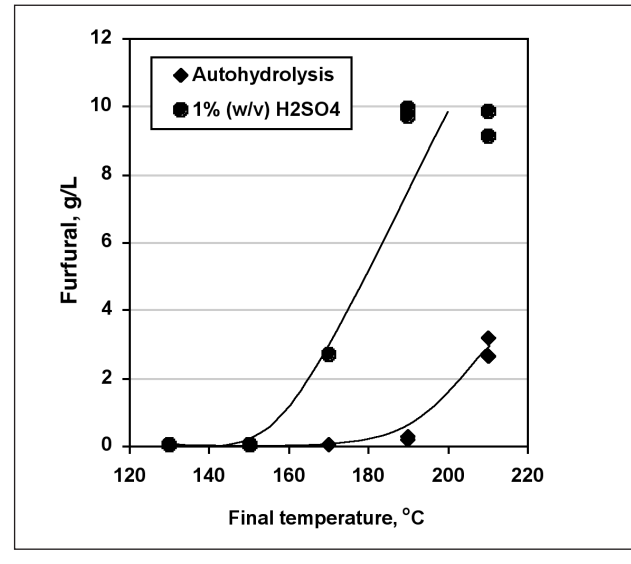
2. Final pH values after autohydrolysis and H_2SO_4-hydrolysis of aspen chips to different maximum temperatures.



4. The amount of glucose present in hydrolysate after autohydrolysis and H_2SO_4-hydrolysis of aspen chips to different maximum temperatures.



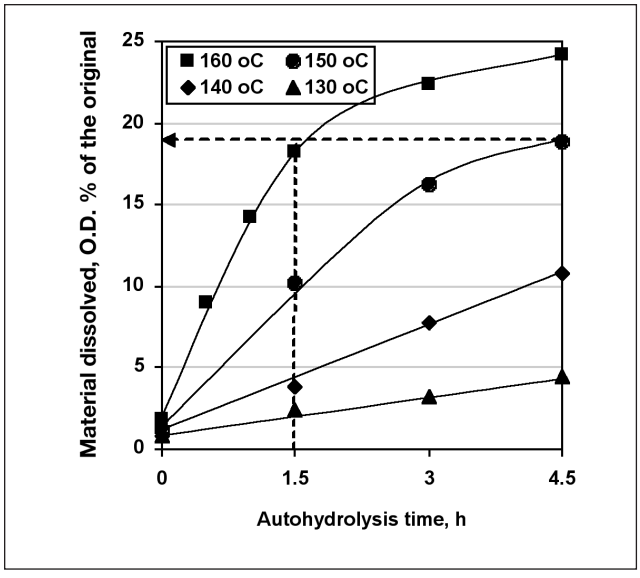
3. The amount of xylose present in hydrolysate after autohydrolysis and H_2SO_4-hydrolysis of aspen chips to different maximum temperatures.



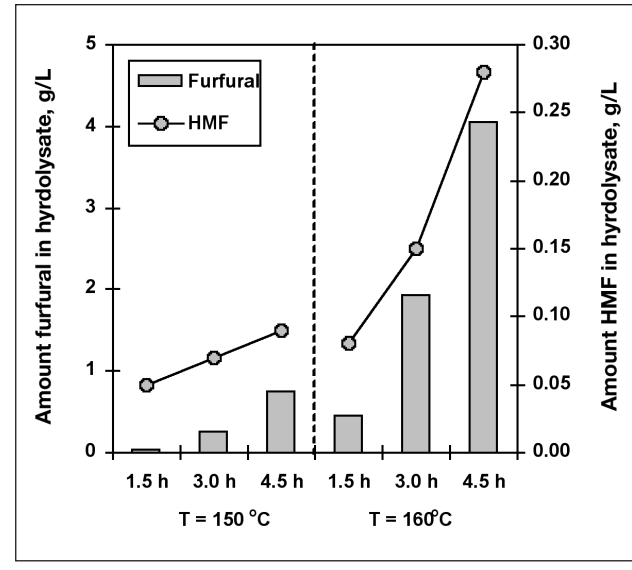
5. The amount of furfural present in hydrolysate after autohydrolysis and H_2SO_4-hydrolysis of aspen chips to different maximum temperatures.

the composition of such hydrolysates. **Figures 3**, **4,** and **5** show the concentrations of xylose, glucose and furfural in the hydrolysates, respectively. Xylose is the most important in this context since it is the major hemicellulosic constituent of aspen (Table I). For autohydrolysis, the concentration of xylose increased continuously with temperature and time until it reached about 20 g/L at 210°C, (Fig. 3). The low concentration of glucose at the same temperature, about 1 g/L (Fig. 4), is an indication of minor degradation of cellulose. The concentration of furfural, a potential fermentation inhibitor, is also low at the same temperature for autohydrolysis, about 2 g/L (Fig. 5). When the hydrolysis was performed in the presence of 1% w/v H_2SO_4, the concentration of xylose in the hydrolysate increased until it reached a maximum at 150°C, about 20 g/L, where it started thereafter to fall sharply to a very small value of < 1 g/L (Fig. 3). This decrease in xylose concentration was accompanied by an increase in both glucose concentration due to more intensive cellulose degradation, up to about 4 g/L at 210°C (Fig. 4), and furfural concentration to about 10 g/L (Fig. 5), due to xylose degradation.

It is well-established that furfural formation from xylose is acid-catalyzed, which explains the initially low furfural levels for autohydrolysis. As seen in Figs. 3-5, the duplicates of 1% w/v H_2SO_4 showed some deviation, especially when the concentrations were high. The reason for this is interferences from other degradation compounds that made the target



6. The amount dissolved during autohydrolysis of aspen chips at different temperatures.



7. The amounts of hydroxymethylfurfural and furfural present in hydrolysate after the autohydrolysis of aspen wood at 150° and 160°C.

peaks in the HPLC chromatogram difficult to integrate.

At this stage, we concluded that a temperature ≈160°C or lower should be used for autohydrolysis in order to have minimal cellulose degradation and furfural formation. In addition, if H_2SO_4 is to be used in the hydrolysis, a temperature of 140°C or lower should be applied.

Autohydrolysis at a constant temperature

We began the second set of hydrolysis experiments at room temperature. The temperature was increased at a rate of 2.5°C/min to a final temperature, at which the hydrolysis continued for 1.5, 3.0, and 4.5 h. The final temperatures investigated were 130°, 140°, 150°, and 160°C.

At each certain final temperature, the amount of dissolved material increased linearly with increasing hydrolysis time (**Fig. 6**). When the amount of dissolved material exceeded 15% of the initial amount, the extraction of more material became more difficult for autohydrolysis at 150° and 160°C. As seen, autohydrolysis at 160°C for 1.5 h dissolved as much material as autohydrolysis at 150°C did in 4.5 h. The concentrations of furfural in the corresponding hydrolysates were 0.45 and 0.75 g/L, respectively (**Fig. 7**). Concentrations of furfural

	Autohydrolysis 150°C, 4.5 h			Autohydrolysis 160°C, 1.5 h		
	Residue, %	Material dissolved, % Cal.α	Exp.β	Residue, %	Material dissolved, % Cal.α	Exp.β
Glucan	43.9	0.6	0.7	44.0	0.5	0.7
Xylan	9.0	8.7	8.9	9.2	8.5	8.7
Galactan	0.4	0.9	0.8	0.4	0.9	0.7
Arabinan	0.1	0.4	0.4	0.1	0.4	0.4
Mannan	1.4	0.3	0.7	1.3	0.4	0.6
Klason lignin	21.1	0.0	1.1	20.4	0.7	1.6
Others$^{\chi}$	5.1	8.1	6.4	6.2	7.0	5.7
Total	**81.0**	**19.0**	**19.0**	**81.6**	**18.4**	**18.4**

α Calculated values = (weight in fresh wood (Table I) – weight in residue).

β Experimental values: determined from the composition of the extracted fraction and the dissolved amount.

χ Includes acid-soluble lignin, extractives, ash, and dissolved and modified carbohydrates.

II. Mass balances over autohydrolysis at 150°C for 4.5 h and 160°C for 1.5 h. Basis: 100 kg chips.

higher than 1 g/L were obtained when autohydrolysis was performed at 160°C for 3 h or longer.

Table II shows the composition of wood residues and dissolved fractions after autohydrolysis of aspen chips at 150° and 160°C for 4.5 and 1.5 h, respectively. About 50% of the total xylan was dissolved in both cases (8.7 and 8.5% out of 17.7% total xylan content). For the purpose of comparison, we determined the composition of the dissolved fraction using two pathways. In the first, we calculated from the difference between the amounts of fresh chips and the thoroughly washed chips residue. In the second, we measured experimentally by freeze-drying a portion of the hydrolysate and then determining its weight and composition.

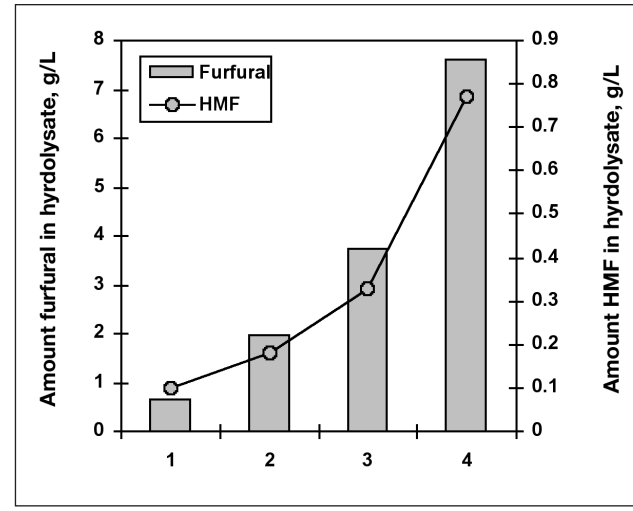
Table II shows that the calculated and experimental xylan contents in the dissolved material are similar, suggesting that no major xylose degradation took place during the autohydrolysis. In addition, the arabinose was easily removed from the xylan-backbone. However, the experimental values for Klason lignin contents were higher than the calculated ones. The lignin remaining in the solid residues after autohydrolysis was reported to have a lower molecular weight than the native one [9], with no structural differences [10]. During autohydrolysis, the reaction of lignin has been reported to undergo two stages [11]: in the first, lignin with low molecular weight and high reactivity is solubilized by breaking lignin-carbohydrate bonds [12], and in the second slower stage, lignin repolymerization takes place in the presence of organic acids released by the treatment to give insoluble condensation products. Others [10, 13] suggested that sugars and/or sugar degradation products (such as furfural) also react with lignin to generate insoluble lignin which results in increased Klason lignin content in the solid residues.

Therefore, the experimental values shown in Table II represent a more accurate estimate of the composition of dissolved material.

Autohydrolysis at a constant temperature with recycling of hydrolysate

Table II shows that autohydrolysis for 4.5 h at 150°C extracts about 50% of the xylan in aspen chips. Based on the liquor:wood ratio used (4:1), the concentration of xylose in the hydrolysate would be 24.6 g/L. Since the theoretical conversion rate of pentoses to ethanol is about 50% [14], the resulting ethanol concentration after fermenting the hydrolysate would be only 12.3 g/L. Therefore, it is desirable to have a higher xylan concentration in the hydrolysate.

In an attempt to increase the concentration of xylan, we used the hydrolysate produced from one autohydrolysis to hydrolyse a new batch of fresh chips. **Figure 8** shows the concentrations of furfural and HMF in the new hydrolysates. Process 1 is the control autohydrolysis of chips with fresh water at 150°C for 4.5 h. In Process 2, fresh chips were hydrolysed under the same conditions with 50% water and 50% hydrolysate produced from Process 1. In Process 3, fresh chips were hydrolysed with 100% hydrolysate produced from Process 1. As seen, the contents of furfural produced were higher for Processes 2 and 3 as compared to Process 1. When the hydrolysate produced from Process 3 was used to hydrolyse fresh chips (Process 4), the concentration of furfural reached a very high level, ~7.5 g/L (Fig. 8.)

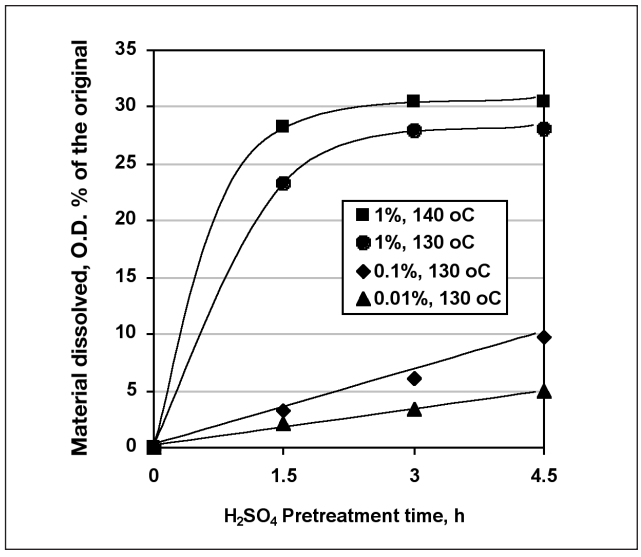


8. The amounts of hydroxymethylfurfural and furfural present in hydrolysate after the autohydrolysis of aspen at 150°C for 4.5 h with recycling of hydrolysate.
1: Autohydrolysis using water for 4 h at 150°C.
2: Autohydrolysis using 50% water and 50% hydrolysate from 1.
3: Autohydrolysis using 100% hydrolysate from 1.
4: Autohydrolysis using 100% hydrolysate from 3.

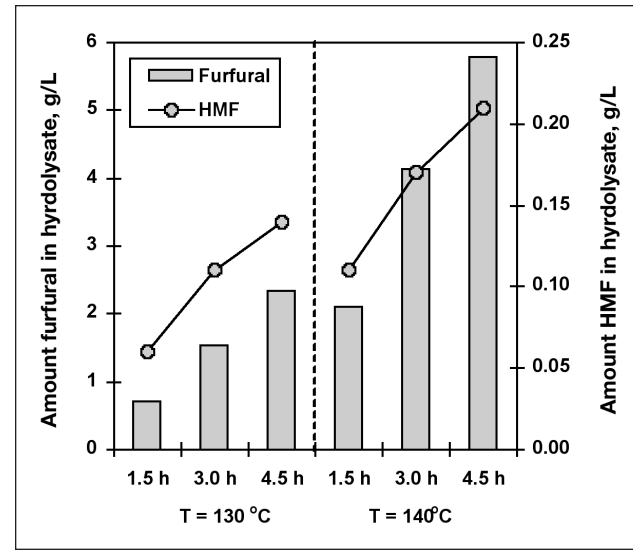
The concentration of HMF in Process 4 was close to 1 g/L, indicating cellulose degradation to some extent. From the amount and composition of chips residue in Process 3, the amount of xylan extracted was theoretically calculated to be 83.6 kg per tonne of chips. This would give an additional 23.4 g xylose/L to the 24.6 g xylose/L originally present in the hydrolysate from Process 1 (neglecting the xylan fraction that was converted into furfural). After freeze-drying the hydrolysate obtained from Process 3 and determining its composition, the xylose concentration appeared to be only 19.2 g/L. This means that almost all the xylan extracted in Process 1 was completely degraded when it was recycled to Process 3. This degradation was intensive and must have given rise to the formation of other products than furfural since the concentration shown in Fig. 8 accounts only for a small fraction of the lost xylan. This again suggests that xylose and its degradation products can react with lignin [10,13].

Hydrolysis with H_2SO_4 at a constant temperature

As in autohydrolysis, hydrolysis with H_2SO_4 was started at room temperature. The temperature was increased at a rate of 2.5°C/min to a final temperature, at which the hydrolysis continued for 1.5, 3.0, and 4.5 h. The temperatures investigated were 130 and 140°C. As seen in **Fig. 9**, the amount of total material dissolved increased with increasing treatment



9. The amount dissolved during the hydrolysis of aspen wood with H_2SO_4 using different concentrations and temperatures.



10. The amounts of hydroxymethylfurfural and furfural present in hydrolysate after the hydrolysis of aspen wood with 1% H_2SO_4.

time at each temperature. Treatment of aspen chips with 0.01% H_2SO_4 at 130°C (Fig. 9) was comparable to autohydrolysis at 130°C (Fig. 6), where both resulted in 5% material dissolution after 4.5 h of hydrolysis. The treatment with 0.1% H_2SO_4 at 130°C was comparable to autohydrolysis at 140°C in the sense that 10% of the material dissolved after 4.5 h of hydrolysis. On the other hand, hydrolysis with 1.0% H_2SO_4 at 130°C dissolved more material than autohydrolysis at 160°C (cf. Figs. 9 and 6), and resulted in the formation of more furfural than autohydrolysis at 150°C (cf. Figs. 10 and 7).

Table III shows the composition of wood residues and dissolved fractions after hydrolysis of aspen chips with 1% H_2SO_4 for 1.5 h at 130° and 140°C. As shown, more xylan was extracted in both cases as compared to autohydrolysis experiments in Table II. Unfortunately, in the presence of sulfuric acid, the acid-catalyzed degradation reactions of carbohydrates are highly favored. Therefore, the real contents of xylan in hydrolysates are expected to be much lower than the calculated ones shown in Table III, especially for the treatment with 1% H_2SO_4 at 140°C.

Pulping of wood residues

As expected, the wood residues obtained after H_2SO_4 treatments were very dark and brittle. Therefore, we used only the residues obtained after autohydrolysis for subsequent pulping. We selected autohydrolysis conditions at 150°C for 4.5 h for pulping experiments, due to the high hemicellulose extraction yield and minimal formation of furfurals under those conditions. The residues had to be washed prior to the pulping so that the acidic reaction products would not reduce the quality of the cooking liquor.

The pulping results of a reference control are compared

	1% H_2SO_4, 130°C, 1.5 h		1% H_2SO_4, 140°C, 1.5 h	
%	Residue	Material dissolved α	Residue	Material dissolved α
Glucan	44.5	0.0	44.4	0.1
Xylan	6.1	11.6	3.1	14.6
Galactan	0.4	0.9	0.5	0.8
Arabinan	0.0	0.5	0.0	0.5
Mannan	1.1	0.6	1.0	0.7
Klason lignin	19.1	2.0	20.3	0.8
Others β	5.5	7.7	2.4	10.8
Total	**76.7**	**23.3**	**71.7**	**28.3**

α Calculated values = (weight in fresh wood (Table I) – weight in residue).

β Includes acid-soluble lignin, extractives, ash and dissolved and modified carbohydrates.

III. Treatment with 1% H_2SO_4 for 1.5 h at 130 and 140°C. Basis: 100 kg chips.

	Aspen control cook	Aspen residue after autohydrolysis		
		shorter pulping time	lower charges of chemicals	lower maximum temperature
Chips/residue OD, kg	100	81 α	81 α	81 α
Effective alkali, % NaOH	21.0	21.0	17.8	21.0
Sulfidity, %	25.0	25.0	26.2	25.0
NaOH, kg	21.0	17.0	14.4	17.0
NaSH, kg	4.2	3.4	3.0	3.4
Pulping: L:W 4:1, 1-hour-impregnation at room temperature. 30°C, 3.5°C/min to $T_{maximum}$				
$T_{maximum}$, °C	170	170	170	160
Time at $T_{maximum}$, min	45	15	45	45
H-factor,	768	308	768	331
Screened yield, %β	53.3	40.9	38.8	39.7
Shives, %β	0.6	0.8	0.4	0.4
Kappa number	17.2	12.5	6.0	7.8
Viscosity, cp	35.9	44.2	33.1	30.5
Klason lignin, %	1.9	2.1	0.7	1.1
Glucan, %	75.8	89.5	88.0	88.1
Xylan, %	18.5	4.6	4.2	4.1

α Amount of residue after autohydrolysis of 100 kg chips (Table II).
β Based on 100 kg aspen chips.

IV. kraft pulping of aspen chips and autohydrolysis wood residue (150°C for 4.5 h). Basis: 100 kg chips.

with three cooks of the autohydrolysis residue in **Table IV**. We adjusted the cooking conditions of the autohydrolysis residues to maintain a low level of rejects (shives) as in the control cook. Although the pulps produced from the residues were prepared under milder conditions than the control cook (cooking for shorter time, using lower charges of chemicals or applying lower maximum temperature), their kappa numbers were much lower than that of the control pulp. All trials to increase the kappa number of the residue pulps resulted in the formation of considerable amounts of shives. As a result, kraft pulping of autohydrolysis residues resulted in a much lower total pulping yield as compared to the control cook (53% vs. about 40% based on the original wood), which is in contrast to previous pulping results after alkaline extraction of aspen chips [1]. Moreover, autohydrolysis of aspen chips afforded pulps with very high glucan (cellulose) content, ~ 90%.

Evidently, a major part of hemicellulose in the residue was dissolved/degraded during subsequent pulping, resulting in pulps with a xylan content < 5%, and this may explain the lower pulping yields obtained. Although we did not investigate the strength properties of the pulps, it is known that pulps with high cellulose/hemicellulose ratio have low tensile index and high tear index, fracture toughness and folding endurance [15], with a potential to collapse on drying and to swell very little on rewetting [16]. This is not surprising, considering the fact that autohydrolysis conditions are slightly acidic (cf. Fig. 2).

During autohydrolysis, hemicellulose is degraded to smaller fragments that are easy to remove in subsequent alkaline pulping stages. Yet more has to be done to fully understand the mechanism for the sugar dissolution reactions involved.

The lower pulping yield after autohydrolysis might be justified by the fact that lower charges of chemicals, shorter cooking time or lower maximum temperature were required to produce a pulp with viscosity similar to the control pulp. Around 19 % of the original wood material was removed during autohydrolysis, half of it xylose that is fermentable to ethanol.

CONCLUSIONS

We made various attempts to extract hemicelluloses from aspen chips by means of autohydrolysis and H_2SO_4 hydrolysis. Autohydrolysis at 150°C for 4.5 h was found to be the most suitable for extracting xylan in reasonable yield without any significant degradation of xylose to furfural. In the presence of H_2SO_4, more hemicellulose is extracted than in autohydrolysis. However, H_2SO_4 gives rise to more conversion of the xylose to furfural, even at lower temperatures, than autohydrolysis. The wood residue after autohydrolysis could be used for the production of kraft pulps with high cellulose content.

Overall pulp yield is lower for the material pre-extracted with hot water, but chemical charges and cooking times could be reduced considerably. **TJ**

ACKNOWLEDGEMENT

This work is a part of the Renewable Energy Research Program financed by the Initiative for Renewable Energy and the Environment (IREE). We also would like to thank Marc von Keitz for his support.

Received: October 21, 2007
Accepted: April 15, 2009

LITERATURE CITED

1. Wafa Al-Dajani, W., and Tschirner, U., *TAPPI J.* 7(6): 3-8 (2008).
2. Garrote, G., Dominiguez, H., and Parajo, J. C., *J. Chem. Technol. Biotechnol.* 74(11): 1101-1109 (1999).
3. Larsson, S., Palmqvist, E., Hahn-Hägerdal, B., Tengborg, C., Stenberg, K., Zacchi, G., and Nilvebrant, N. O., *Enzyme Microb. Technol.* 24: 151-159 (1999).
4. Palmqvist, E., and Hahn-Hägerdal, B., *Bioresource Technology* 74: 25-33 (2000).
5. Olsson, L., and Hahn-Hägerdal, B., *Enzyme Microb. Technol.* 18: 312-331 (1996).
6. Timell, T. E., Wood Sci Technol. 1: 45-70 (1967).
7. Abatzoglou N., Chornet E., Belkacemi K. and Overend R.P., *Chem. Eng. Sci.* 47: 1109-1122 (1992).
8. Heitz M., Carrasco F., Rubio M., Chauvette G., Chornet E., Julian L. and Overend, R.P., *Can. J. Chem. Eng.* 64: 647-650 (1986).
9. Biermann C.J., Schultz T.P. and McGinnis G.D., *J. Wood Chem. Technol.* 4: 111-128 (1984).
10. Heitz M., Capek-Ménard E., Koeberle P.G., Gagné J., Chornet E., Overend, R.P., Taylor J.D. and Yu E., *Bioresources Technol.* 35: 23-32 (1991).
11. Lora J.H. and Wayman M., *Tappi J.* 61: 47-50 (1978).
12. Burstcher E., Bobleter O., Schwald W., Concin R. and Binder, H., *J. Chrom.* 390: 401-412 (1987).
13. Aoyama M., Seki K. and Saito N., *Holzforschung.* 49: 193-196 (1995).
14. Lee T.H., Kim M.Y., Ryu Y.W. and Seo J.H., J. *Microbiol. Biotechnol.* 11: 384-388 (2001).
15. Molin, U., and Teder, A., *Nordic Pulp Paper Res. J.* 17(1), 14-19, 28 (2002).
16. Moss, P. A., and Pere, J., *Nordic Pulp Paper Res. J.* 21(1), 8-12 (2006).

INSIGHTS FROM THE AUTHORS

We chose this topic to research because the maximum utilization of all the constituents of wood is of great importance for all existing pulp and paper mills. The efficient extraction of hemicelluloses is a prime concern for increasing the revenue and profit streams for the industry. Part I of our research was published in *TAPPI JOURNAL* (June 2008) and focuses on alkaline extraction.

The most difficult challenge we faced in Part II of our study was the extraction of hemicelluloses without a decrease from the rate of pulp yielded without extraction. We addressed this issue by adjusting the pulping conditions.

We found that while autohydrolysis or hot water treatment results in a good hemicellulose extraction rate, subsequent pulping of the residue might not be feasible in terms of yield and fiber quality.

The next step is continued testing to improve extraction conditions and pulp yield.

Tschirner

Wafa-Dajani

Jensen

Tschirner is a professor and Wafa Al-Dajani is a postdoctoral research associate in the department of bioproducts and biosystems engineering of the University of Minnesota, St. Paul, Minn. Jensen is currently with Imation Corp., Oakdale, Minn. For more information on this research, email Tschirner at ulrike@umn.edu.