CHARACTERISTICS OF ACOUSTIC EMISSIONS FROM DEHYDRATING WOOD RELATED TO SHRINKAGE PROCESSES

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Abstract

Cavitation events in water-conducting elements of wood and dehydration cracks caused by wood-shrinkage processes induce acoustic emissions (AEs) in the high-frequency range. The aim of this study was to relate spectral features of AEs from dehydrating Norway spruce (Picea abies (L.) Karst.) trunkwood to shrinkage processes. Wood shrinkage in the radial direction was assessed by load cells. Resonant 150 kHz, 60 kHz and broadband transducers (operating range 50-200 kHz, 35-100 kHz and 100-1000 kHz, respectively) were used to detect AEs at the same time on standard size samples (5 or 10 cm (length) x 6 mm (radial) x 6 mm (tangential)). Two different shrinkage processes were detected, where the first shrinkage period was termed “tension shrinkage”. Shrinkage caused by high tensions is a phenomenon observed also in field measurements and is practically used for drought stress measurements of living trees. The final shrinkage process started at relative water contents around the “fiber saturation point”, where most of the cell lumina contain no water, but walls are fully saturated with liquid. The onset of the rapid rise in tension shrinkage coincided with the decrease of the first rapid rise of the total AE rate (r = 0.99). The valley between the last two AE peaks was located at the onset of the final shrinkage process. Characteristics for AEs during the tension shrinkage period were higher proportions of AEs with very high amplitudes (> 60 dB) and lower frequency components. Therefore, the highest relative AE energies (pVs) were measured during this stage. AEs during the final shrinkage period showed lower amplitudes, lower energy values and higher frequency components.

Keywords: Lumber drying, wood shrinkage, peak amplitude, frequency, AE transducers

Introduction

Norway spruce wood consists of 90% of small water conducting elements with a diameter of about 10-40 µm and a length of 1-4 mm (tracheids). Water in tracheids exists in three states; first, as “free” liquid water, second, as water vapor and within the tracheids, and third, as chemically “bound” water in the cell wall matrix [1]. „Free” water in the tracheids of the sapwood is transported under tension, requiring high mechanical strength of the cell walls in order to avoid implosion, and hydraulic safety against breakage of the water column (cavitation). During periods of drought stress decreases in the stem diameter of living trees can be observed [2-3]. These shrinkage processes are supposed to induce internal checking in living trees [4]. Stem diameter changes are caused by hydrostatic tension forces resulting in a decrease in diameter of the conducting elements, which still contain “free” water. The breakage of the water column is induced when the tension stress increases above a certain threshold. Once cavitated, the conduit does not conduct water any longer and the hydraulic conductivity of the plant is reduced, leading to impairment of water supply of the crown [5]. Cavitations induce AEs with the highest amplitudes in the range of 100-300 kHz, which are used to detect periods of drought stress non-destructively [2].
AE testing is also an established method for optimizing lumber drying conditions, where the analysis of the amplitude or energy distribution of AE signals has been successfully used to pinpoint wood checking [6-7]. Most of these tests are not performed on fully saturated wood, where still all conducting elements contain “free” water, but on “green” wood at varying moisture contents. When cell lumina contain no water, but cell walls are fully saturated with liquid (“fiber saturation point”), further dehydration leads to a shrinkage process, which can induce drying checks. Drying checks develop because the fiber saturation point is reached far earlier in the shell than in the core of a specimen and because wood is an anisotropic material concerning shrinkage (radial = in direction of the annual rings: tangential = 1 : 1.5) [7-8]. Nevertheless, combined shrinkage and AE tests are rare in AE literature on wood [9] and plant physiologists stop observations of stem diameter changes and AE rates long before most of the tracheids reach the fiber saturation point [2]. The aim of this study was to relate AEs of dehydrating Norway spruce (*Picea abies* (L.) Karst.) sapwood to radial wood shrinkage processes from the totally saturated “green” state till the cessation of all shrinkage processes.

### AE Testing Procedure and Data Analysis

AEs were monitored with the μDiSP™ Digital AE system from Physical Acoustics Corporation (PAC, Princeton Jct, NJ, USA). Preamplifiers (40 dB) were used in connection with 150-kHz R15 resonant transducers, 60-kHz R6 and WD broadband transducers (operating frequency range 50-200 kHz, 35-100 kHz and 100-1000 kHz, respectively). AEs were recorded with a detection threshold of 35 dB (0 dB = 1 μV input). The detection threshold was chosen as the peak amplitude of signals produced by waving the AE transducer in air, plus 15 dB. Extraction of features such as the number of counts, the peak amplitude (dB), the AE duration (μs), the relative AE energy (pVs) and the average frequency (kHz) of each AE signal was carried out with AE Win® software (PAC). AE energy (also referred to as “PAC-Energy”) is defined as the area of the rectified voltage signal over the duration of the AE signal.

AE transducers were positioned on the tangential face of fully saturated Norway spruce standard beams (cambial age = 20 - 25) using an acrylic resin clamp [9]. Preparation of fully saturated sapwood beams (0.6 cm tangential, 0.6 cm radial, and 5.0 cm or 10.0 cm longitudinal) is described in [10]. Silicone paste (Wacker, Burghausen, Germany) served as a coupling agent. The samples were positioned on an acrylic resin sample holder fixed upon a compression spring. Coupling pressure during the dehydration process was recorded with a DMS load cell (Type 8416-5500, range 0 - 500 N; amplification with an inline amplifier for DMS, Type 9235; Burster, Gernsbach, Germany) between the AE transducer and the screw of the acrylic resin clamp. The coupling pressure was set to 30 N. The acrylic resin clamp was then kept so deep in water that the wood sample was totally covered till the applied pressure reached a constant value. After quickly removing superficial water from the clamp and the wood, recording of AEs and coupling pressure was started. AE testing was done at ambient temperatures (25°C, 30% r.h.) until coupling pressure reached a constant value, which was the case after about 20 h. The coupling pressure decrease during dehydration induced by shrinkage (about 3 N in total) was related to the total radial shrinkage (digital gauge, accuracy 1 μm). AE data filtering and presentation was done with Vallen VisualAE™ software (Vallen Systeme GMbH, Munich, Germany).

Values are given as mean values ± standard error. Differences between mean values were tested for significance with One-Way ANOVA and subsequent Scheffe-test or by t-test. Associations between two variables were examined using linear regression analysis.
Results and Discussion

Shrinkage processes and total AE-rate

Two different radial shrinkage processes were observed (Figs. 1-3). First, a shrinkage period at moderate water losses, which was termed “tension shrinkage” (TS), and second, the final shrinkage (FS) period, leading to $3.86 \pm 0.11\%$ ($n = 71$) shrinkage. The onset of the rapid rise in tension shrinkage coincided with the decrease of the rapid rise of the total AE rate ($r = 0.99, n = 22$). Tension shrinkage is caused by a decrease in diameter of tracheids, which still contain “free” water. Hydrostatic tension forces acting perpendicular to the cell walls try to draw the walls inwards. When the stress becomes too high cavitation occurs [8]. Accordingly, tension shrinkage was to some extent a reversible process, because the tension was released after cavitation. After this relaxation period, the final shrinkage process started when most of the cell lumina contained no free water, but cell walls were still fully saturated with liquid. The beginning of the final shrinkage process coincided with a rapid rise in the AE rate. Towards the end of AE detection, two peaks in the AE rate could be found in most of the samples. The first peak occurred after $72.76 \pm 0.72\%$ ($n = 42$), the second after $85.38 \pm 0.45\%$ ($n = 42$) of the AE detection time, which was defined as the time between the start of AE testing and when the last AEs were detected. No AEs were detected after no more than $25\%$ of the total radial shrinkage had taken place (Figs. 1-3). Whereas WD transducers detected a quite similar total AE number in 5 and 10 cm samples, R6 and R15 transducers detected significant higher numbers of AEs in 10 cm samples (Table 1).

Fig. 1 AE activity (rate/min) and radial wood shrinkage during dehydration detected by WD transducer and load cell, respectively. AE rates were clustered in peak amplitude steps (left side) and average frequency steps (right side). Mean AE energy (1 eu = 1 pVs) was calculated for 1 sec steps (below, red line, right y-axis).
AE activity (rate/min) and radial wood shrinkage during dehydration detected by R6 transducer and load cell, respectively. AE-rates were clustered in peak amplitude steps (left side) and average frequency steps (right side). Mean AE energy (1 eu = 1 pVs) was calculated for 1 sec steps (below, red line, right y-axis).

Fig. 3 AE activity (rate/min) and radial wood shrinkage during dehydration detected by R15 transducer and load cell, respectively. AE-rates were clustered in peak amplitude steps (left side). Mean AE energy (1 eu = 1 pVs) was calculated for 1 sec steps (right side, red line, right y-axis).

**AE characteristics during shrinkage processes**

Highest mean peak amplitudes and energies were measured during the tension shrinkage period at moderate water losses (Figs. 1-3). The relative time occurrence of the maximum mean peak amplitudes/min showed no significant differences between the transducer types (WD, R6, R15). Highest mean amplitude values were reached after 27.77 ± 0.90% of the AE detection time (n = 42). The cumulated AE energy rate can be used to characterize the hydraulic vulnerability of
sapwood. Norway spruce wood consists of 90% of tracheids, which vary in diameter. It is supposed that mean high energy AEs represent cavitations of more vulnerable, larger tracheids, because more elastic energy is stored in larger conduits under tension [10]. Tension shrinkage processes can be observed in living trees and are used to pinpoint periods of drought stress in the field [2, 3]. In accordance, the maximum AE rate of signals >60 dB and the maximum AE energy rate/min were detected in the middle of the tension shrinkage period (R6, R15, r = 0.88, n = 14). At the time of maximum AE rates of signals >60 dB, lower AE rates/min were measured by WD transducers than by R6 or R15 transducers (P < 0.05, Fig. 4). The lower number of AEs recorded by WD transducers might be explained both by the lower sensitivity of WD than R6 and R15 transducers and the frequency operating range (100-1000 kHz). In highly attenuating materials, such as wood, the usable upper frequency level is supposed to be 100-200 kHz [6].

Table 1 Frequency characteristics of AEs measured by transducer types WD, R6 and R15 at different shrinkage stages of wood samples varying in length (L). Frequency factors were calculated from AE rates/min clustered by average frequency steps. Stage TS gives results for the middle of the tension shrinkage period, when the maximum AE energy/min was detected, FS1 for the first AE peak at the onset of the final shrinkage period, and FS2 for the second AE peak during the final shrinkage period. Different letters indicate significant differences (P < 0.001) in the Frequency Factors between 5-cm and 10-cm samples.

<table>
<thead>
<tr>
<th>L (cm)</th>
<th>AEs total</th>
<th>Frequency Factor</th>
<th>n</th>
<th>Stage TS Mean (SE)</th>
<th>Stage FS1 Mean (SE)</th>
<th>Stage FS2 Mean (SE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WD 5</td>
<td>359099.5  (23420.8)</td>
<td>&lt; 175 kHz / &gt; 175 kHz</td>
<td>7</td>
<td>1.73 (0.21)a</td>
<td>0.95 (0.08)a</td>
<td>0.20 (0.02)a</td>
</tr>
<tr>
<td>WD 10</td>
<td>410353.5  (37057.6)</td>
<td>&lt; 175 kHz / &gt; 175 kHz</td>
<td>7</td>
<td>1.44 (0.06)a</td>
<td>0.97 (0.08)a</td>
<td>0.17 (0.02)a</td>
</tr>
<tr>
<td>R6 5</td>
<td>393935.3  (29590.1)</td>
<td>&lt; 50 kHz / &gt; 50 kHz</td>
<td>7</td>
<td>1.43 (0.16)a</td>
<td>0.31 (0.06)a</td>
<td>0.05 (0.01)a</td>
</tr>
<tr>
<td>R6 10</td>
<td>620891.8  (26459.2)</td>
<td>&lt; 50 kHz / &gt; 50 kHz</td>
<td>7</td>
<td>0.77 (0.05)b</td>
<td>0.47 (0.04)b</td>
<td>0.04 (0.02)a</td>
</tr>
<tr>
<td>R15 5</td>
<td>370243.3  (18305.9)</td>
<td>&lt; 155 kHz / &gt; 155 kHz</td>
<td>7</td>
<td>2.83 (0.19)a</td>
<td>2.92 (0.41)a</td>
<td>0.99 (0.15)a</td>
</tr>
<tr>
<td>R15 10</td>
<td>575638.7  (28961.2)</td>
<td>&lt; 155 kHz / &gt; 155 kHz</td>
<td>7</td>
<td>2.51 (0.12)a</td>
<td>3.89 (0.35)a</td>
<td>1.07 (0.11)a</td>
</tr>
</tbody>
</table>

Analysis of average frequencies showed that the number of signals <175 kHz was 1.4 - 1.7 times higher than those of signals >175 kHz when the mean AE energy rate/min reached maximum values (Table 1). At the same time the R6 transducer recorded 1.4 times the number of AEs <50 kHz than of AEs >50 kHz in 5-cm samples, but only 0.8 times the number in 10-cm samples (R6, Table 1). The rate/min of signals <50 kHz, related to the corresponding total AE rate/min, reached maximum values during the tension shrinkage period (R6, 58.57 ± 2.61% (5 cm), 43.36 ± 1.52% (10 cm), P < 0.001). Sample length-dependent differences were also present in the maximum mean energy/min values. In 10-cm samples, much lower maximum energies/min were detected than in 5-cm samples. Maximum mean energies/min during the tension shrinkage period were positively related to the relative amount of signals <50 KHz (related to the total AE rate at the same time, Fig. 5).

AEs within the frequency range from 30 to 50 kHz reached highest absolute rates shortly before the final shrinkage process started (Fig. 2). The relative rates (related to the corresponding total AE rate) of AEs <50 kHz were, however, lower than during the tension shrinkage period, when maximum mean energies/min were measured (R6, 22.56 ± 3.52% (5 cm), 31.82 ± 1.84% (10 cm), P < 0.05). The number of signals with average frequencies <50 kHz was less than half.
the number of signals >50 kHz at the next to the last AE rate/min peak (R6, Table 1). Shortly before the final shrinkage took place, WD transducers detected a quite similar number of signals <175 kHz and >175 kHz (WD, Table 1). The AE rate/min measured by WD transducers was significantly lower than measured by R15 or by R6 transducers ($P < 0.001$, Fig. 4).

![Box- and whiskers plots of the AE rate/min at different shrinkage stages detected by different transducer types (WD, R6, R15) for 5-cm sample length (left side) and 10-cm sample length (right side). Stage TS gives results for the middle of the tension shrinkage period, when the maximum AE energy/min was detected, FS1 for the first AE peak, located around the fiber saturation point, at the onset of the final shrinkage period, and FS2 for the second AE peak during the final shrinkage period.](image)

Fig. 4 Box- and whiskers plots of the AE rate/min at different shrinkage stages detected by different transducer types (WD, R6, R15) for 5-cm sample length (left side) and 10-cm sample length (right side). Stage TS gives results for the middle of the tension shrinkage period, when the maximum AE energy/min was detected, FS1 for the first AE peak, located around the fiber saturation point, at the onset of the final shrinkage period, and FS2 for the second AE peak during the final shrinkage period.

The final shrinkage process was characterized by a very high proportion of signals with high average frequencies (>250 kHz (WD), >100 kHz (R6)), low amplitudes and energies (Figs. 1-3). These signals may come from cavitation events in tracheids, which contribute less to axial water transport than to other wood functions such as radial water transport, mechanical support and storage of water, or from cavitations in ray tracheids [10]. At the last AE peak, the number of signals <175 kHz was less than 25% the number of AEs >175 kHz (WD, Table 1). R6 transducers measured a much more lower number of AEs with average frequencies <50 kHz in relation to signals >50 kHz (Table 1). The relative amount of signals <50 kHz made up only 5.05 ± 1.00% (5 cm) and 4.25 ± 0.80% (10 cm) of the total AE rate. R15 transducer detected a lower relative amount of signals <155 kHz than during the tension shrinkage period or at the onset of the final shrinkage period (R15, Table 1). The AE rate/min measured by WD, R6 and R15 transducers showed no significant differences (Fig. 4).

The bulk of AEs during lumber drying resembles cavitation events of water conducting elements [7]. Extremely high energy AEs, which were detected during the tension shrinkage period as well as at the onset of the final shrinkage process may have been induced by mechanical failure [11]. References [12, 13] could distinguish two phases during Norway spruce lumber drying by analyzing AE burst rates. The first peak in the AE rate was interpreted as checking caused by surface tension stress, and the second peak (at high water loss) as checking caused by tensile stresses inside the samples. Reference [8] supposed that sapwood within-ring internal checking is caused by water tension and not by differential shrinkage, because checking occurred long before
most of the cells reached the fiber saturation point. Internal checks caused by high tensions may also occur in low density earlywood of living trees during periods of summer drought, and are a severe problem of short rotation forests [4].

The method presented might help to understand the mechanisms that cause internal checking in living trees. Knowledge about the relationship between shrinkage processes, AE rates and AE features, such as the average frequency, the peak amplitude and energy (especially single high energy events), could also be helpful for analyzing checking processes during lumber drying stages. It is recommended to use standardized sample sizes, because sample length had a significant impact on frequency and energy composition. Both WD and R6 transducers were suitable to characterize the different stages of shrinkage by analyzing the average frequency composition of the AEs. R6 transducers reacted, however, very sensitively to background noise.

![Graph showing relationship between relative amount of signals <50 kHz and maximum mean AE Energy/min](image)

Fig. 5 Relationship between the relative amount of signals <50 kHz related to the total AE rate and the maximum mean AE Energy/min during the tension shrinkage period detected at the same time by R6 transducers.

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References


