

PAPER SURFACE MAKEUP PROCESS OBSERVED BY ULTRASOUND

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ABSTRACT

Quality assurance demands constant control and timely corrective action. This paper reports on an automated, nondestructive, ultrasonic measurement system for monitoring deployment of water–alcohol solutions onto paper. The monitoring is done using a set of characteristic values derived from mathematical transformations of the transmitted ultrasonic signal. The measurement system can also monitor the paper drying process. Being able to follow both wetting and drying of a paper sample is one step toward a system that performs online surface makeup of high-quality paper. The ability to monitor and adjust variations in the moisture content of a paper web offers the possibility of improving the competitive advantage in the production of high-quality magazine paper.

INTRODUCTION

Paper properties and production methods have been widely investigated (1, 2), but there are still many unknown factors that tend to turn paper manufacture into an art more than a science. This is not consistent with the stringent quality demands that papermakers face from converters, printers, and end users. The demands stem from the fact that quality is one of the primary drivers of profitability in manufacturing industries. End users want competitively priced high-quality papers tailored for specific applications. In order to satisfy the customers' expectations, the papermaker should have the ability to continuously measure and control paper quality parameters such as thickness, strength, surface smoothness, color, and moisture. Many current quality control procedures rely on point-by-point measurements. However, the measurement times are usually too long to facilitate online correction of surface errors during the run in the paper machine (3).

Prior to calendering, an optimal moisture content of the paper web can be achieved if the amount of water in the paper can be controlled. Sheet moisture content is altered by spraying water onto the paper or by evaporating water out of the paper. A proper moisture content of the paper lets a

certain surface smoothness be achieved with lower nip pressures in the supercalender than would otherwise be required. A low nip pressure reduces the risk of the paper darkening that can occur at high nip pressures. Successful control of moisture content in the paper web requires a fast-sensing actuating system. Usually, no more than two seconds are available for conditioning and amending the paper web. However, the ability to monitor and manipulate paper quality online would have far-reaching influences in the paper industry.

The temporal development of wetting processes in paper can be studied by means of airborne ultrasound transmission through paper. The instruments designed for this purpose are called liquid-penetration dynamics meters (4–6). The readout from the acoustic transmission meter—the dynamic wetting curve—is the resultant curve of several subprocesses of the paper-wetting event. As by different samples, the overall shape of the wetting curve is typical of each wetting agent.

The following study reports on a development of the wetting/liquid-penetration meter, described by Stor-Pellinen (7), using truly noncontact airborne ultrasound. The received ultrasonic signal was transformed in several ways, and characteristic features of each transform were recorded. Transformation parameters were sought that correlated well with the measurement parameters, since such parameters could be used to monitor treatment of the paper web. The ultrasonic system was tested to indicate the possibility of using ultrasound for online control of moisture content within the paper web.

THEORY

Ultrasound transmission through thin paper sheet during wetting

As sound encounters a border between two acoustically different media, part of the wave is reflected and part of the wave is transmitted. The transmitted wave undergoes amplitude and phase changes. If the wavelength of the probing sound is longer than the thickness of the paper, the pressure oscillations on both sides of the sample make the sample oscillate. The amplitude transmission factor T for sound orthogonally incident on the sample is described by Eq. 1,

$$T = \sqrt{\frac{Z_0^2}{Z_0^2 + (\pi f M)^2}} \quad (1)$$

where Z_0 is the acoustic impedance of the surrounding air, f is the probing frequency, and M is the grammage of the sample (3). When paper is wetted, the wetting liquid is first adsorbed to the surface of the paper sheet, changing both its smoothness and the impedance ratio of air and sample. Thereafter, the liquid is absorbed into the paper structure, increasing sheet density while decreasing its effective stiffness (7).

When probing sound impacts obliquely onto a paper sheet, a plate wave might be excited at which the transmitted pressure amplitude is given by Eq. 2 (8),

$$T = \left(\frac{P_{in} - P_{out}}{\hat{i}} \right) = i \omega M \left(1 - \left(\frac{c_b \sin \hat{i}}{c_0} \right)^4 \right) \quad (2)$$

where $P_{in} - P_{out}$ is the amplitude difference between the incident and transmitted sound, v is the Poisson number for the sheet, ω is the angular frequency of the sound, and c_0 and c_b are the phase velocity in air and in the sample, respectively. The variable ξ is the complement of the incidence angle. The phase velocity in the sheet depends on the mechanical parameters as given in Eq. 3,

$$c_b^4 = \frac{E \omega^2 d^3}{12M(1 - \hat{i})} \quad (3)$$

where E is the Young's modulus of the sheet and d is sheet thickness. One can see that both the bulk and the plate wave modes changes when the sample is wetted (8).

Ultrasound transmission through thin paper sheet during drying

The infrared (IR) absorption coefficients of water and air are 0.97 and 0.01, respectively (9). Nevertheless, the temperature of air near the sheet surface can be higher than in the sheet itself because of the markedly higher heat capacity of water than that of air, and because water also has a much higher thermal conductivity (0.2 W/mK) than air (0.03 W/mK) (9). This temperature gradient near the sheet surface drives water out of the paper in the form of saturated steam until the sum of partial pressures reaches the stationary state (6).

Under the measurement conditions, the high IR exposure keeps the temperature rising during the entire heating cycle. The reduction of moisture near the sheet surface sustains the diffusion of water from the interior of the sheet to its surface. Until the stage of exhaustion, the reduction rate alters continuously, since both the temperature gradient and the thermal conductance change with time. Drying alters the strength, density, and surface roughness of the paper sheet (1). Because all of these material properties affect the transmission of ultrasound through the sample, the drying effects can be distinguished as changes in the ultrasonic signal.

MEASUREMENT SYSTEM

The measurement system was a laboratory prototype intended to simulate in-plant testing. It consisted of a spraying unit, a drying unit, a sample-holding unit, and an ultrasound probing unit. The mechanical spraying unit could be operated over a wide range of translational velocities and spray pressures, and the ratio of liquid/air in the mixture could be selected. The power of the drying unit operating in the IR spectrum also could be controlled. The sample-holding unit enabled controlled stretching of the samples. The ultrasound unit was operated over a range of probing frequencies and angles. Measurements were performed in a climate-controlled room with constant relative humidity and temperature.

The sample was clamped by its upper and lower rim in an Alwetron TCT5 sample holder with a maximum pulling force of 200 N. The holding jaws had integrated 160-W thermal resistors, which enabled drying of the grip area.

The samples were wetted with isopropyl alcohol solutions of different concentration (0%, 10%, 50%, 100%) that were sprayed on the paper surface at rates of 0–4000 mL/min from two spray nozzles. The nozzles were positioned 15 cm below the sample surface.

The samples were dried using two IR sources with selectable output power of 100–4000 W. The IR sources were positioned 22 cm above the sample surface. The measurement system is depicted in **Figure 1**.

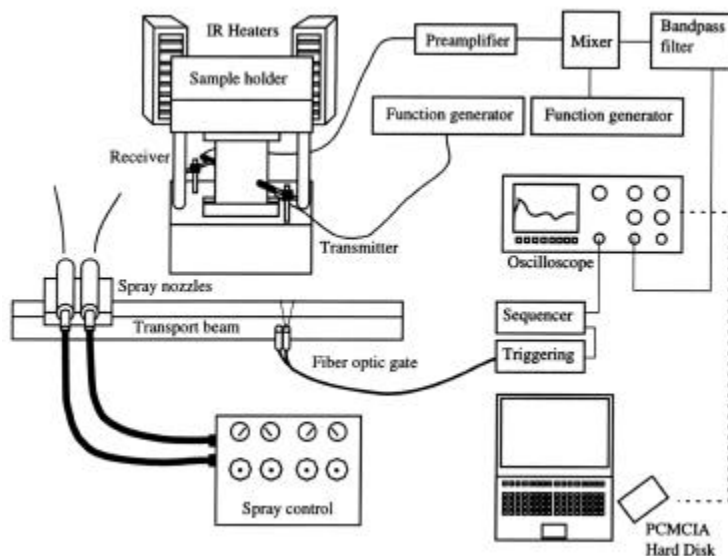


Figure 1. Principal components of the laboratory measurement system.

The transducers used in the 40-kHz frequency band were Project unlimited SQ-40TE2-18 (transmitter) and SQ-40RE2-18 (receiver) with 38–42-kHz bandwidth. The higher frequency bands were measured with laboratory-made PZT-transducers resonating at 224 kHz and 1600 kHz. The bandwidths of the modes were 148–257 kHz and 1480–1640 kHz. The transducers were positioned obliquely relative to the sample so that they would not hinder the spray from reaching the probing area. **Table I** shows transducer positions and incidence angles of the probing beam in the different setups. Reflected waves and spurious echoes, which modulated the measurement signal, were reduced by suspending plastic sheets in an irregular pattern around the sample holder.

The signals were mixed to 40 kHz before being digitized with a digital oscilloscope at a 1-MHz sampling rate. During the wetting measurements, the oscilloscope was triggered when the spray unit passed by the fiber-optic gate. This event determined the origin of the time axis. The initiation of the dryers triggered the probing sequence. The measurement data were stored on a PCMCIA card plugged into the oscilloscope and later transferred to the lab for offline analysis.

Wetting measurements

The samples in the wetting measurements were ordinary A4 copying paper (100 mm, 80 g/m²). Prior to measurement, the samples were stretched 0.02% by length in the reference measurements and 0.5% or 0.9% by length in the wetting measurements. After initial stretch, the sprayers were activated and the transporter powered up. With every sample, a reference measurement was first performed that was similar to the real measurement in all aspects but for opening the water valve to the nozzles. After this, the valve was opened and the actual measurement was performed. The sampling of the received signal started only when the spray unit reached the sample rim and continued for 1.7 seconds intermittently for 50 ms every 110 ms, giving 16 sequences of continuous signal. Five parallel samples were measured.

Frequency, kHz	Transmitter	Receiver	Incidence
40	(75, 75, 40)	(125, 135, -30)	34.2°
	(144, 39, 37)	(83, 144, -33)	35.7°
224	(110, 103, 15)	(104, 107, -17)	77.3°
	(126, 78, 20)	(112, 88, -21)	67.2°
1600	(110, 103, 15)	(104, 107, -17)	77.3°
	(126, 78, 20)	(112, 88, -21)	67.2°

Table I. Transducer coordinates in the experiments and corresponding angles of incidence of the acoustical probe beam.

Drying measurements

The samples in the drying measurements were supercalendered base paper of A5 size. Samples were prepared prior to the measurements by immersing them in wetting liquid for one hour, after which the surfaces of the samples were dried between two cellulose sheets. The prepared samples were then stored in a plastic bag for 24 hours to facilitate uniform liquid distribution in every sample.

The drying measurements began by attaching a wet sample to the sample holder. The rims of the sample were dried for one minute, after which the sample was stretched by 0.01%, 0.1%, or 0.2% by length. The IR dryers were switched on 120 seconds after removal of a sample from the storage bag. The startup of the dryers initiated the automated measurement procedure.

With every sample, a reference measurement was performed first. The conditions for the reference measurement were similar to that of the actual measurement in all aspects but for the IR power, which was shut off. After this, the IR power was increased and the actual measurement was performed. The sampling of the received signal commenced when the IR source was turned on and continued for either 61 seconds at high drying power (2800 W) or 159 seconds at low drying power (1600 W). Overall, 20 sequences of the continuous acoustic signal

were obtained. Probing was conducted intermittently, with 50% sampling time and 50% waiting time. The period was 1.5 seconds with the higher drying power and 3.9 seconds with the lower drying power. Five parallel samples were measured.

METHODS

Data analysis

In the explorative data analysis effort, the recorded ultrasonic signals were analyzed to see if there was any correlation with the measured parameters (applied amount of liquid, drying power, applied stretch, and isopropanol concentration). The strategy was to mathematically transform the signal vector in order to reveal characteristics of the sample treatment process. Those characteristic values of the transforms that worked well on a test sample were chosen for the main investigation.

The analysis was performed in six steps:

1. Filtering and averaging the parallel reference and measurement signals
2. Forming difference signals by subtracting the measurement signal from the reference signal
3. Windowing the filtered difference signals
4. Transforming the difference signals in several ways and calculating characteristic values (CVs) of the transforms
5. Monitoring the chosen CVs
6. Identifying the CVs showing high linear correlation with the measurement parameters.

Figure 2 is a schematic depiction of the analysis process.

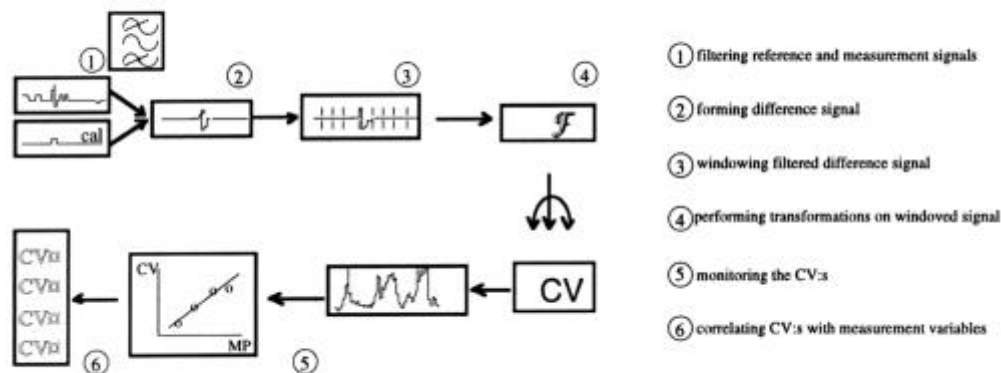


Figure 2. Schematic outline of the analysis of the measured signal.

Detailed description of data analysis

The following section briefly outlines the details of the data analysis.

Filtering. The measured signal was downsampled by removing every second data point. This was done two or three times, leaving six data points per cycle in the raw data. The downsampled

signals from five parallel measurements were averaged after alignment of their initial phases. The averaged signal was filtered with a software eight-order Butterworth 39–41-kHz bandpass filter.

Difference signal. A difference signal was formed by subtracting the filtered reference signal from the filtered measurement signal.

Windowing. The difference signal was divided into 20 time frames that were analyzed separately.

Transformation to CVs. Eighteen transformations of the signal were performed and analyzed. Characteristic values (CVs) were obtained from

- Filtered signal
- Signal power spectrum
- Signal coherence (between reference and measurement signals), as defined in Eq. 4,

$$C_{xy} = \frac{|P_{xy}|^2}{C_{xx} C_{yy}} \quad (4)$$

where P_{xy} is the cross-power spectrum between the signals $x(t)$ and $y(t)$, C_{xx} is the autocorrelation of $x(t)$, and C_{yy} is the autocorrelation of $y(t)$.

- Cepstrum of the signal
- Tenth-order median filter filtered signal
- Signal envelope
- Signal spectrogram
- Autocorrelation of the signal and cross-correlation between the signal and its reference
- Continuous wavelet transform, discrete wavelet transform, and wavelet packet transform of the difference signal. The Daubechies "db4" wavelet (10) was used, and 50 levels were analyzed.

Higher-order spectral analysis was used to investigate the temporal development of the signal's nonlinearity. The following items were analyzed:

- Bicoherence spectrum of the signal, as defined in Eq. 5

$$\text{bic}(f_1, f_2) = \frac{B(f_1, f_2)}{P(f_1) P(f_2) P(f_1 + f_2)} \quad (5)$$

where $B(f_1, f_2)$ is the estimated bispectrum, i.e., the Fourier transform of the third-order autocumulant of the measured sequence, and $P(f)$ is the power spectrum of the difference signal.

- Fourier transform of the second-, third-, and fourth-order cross-cumulants. The cross-cumulant took the reference signal and the actual measurement signal as arguments.
- Wigner spectra (Wigner mono-, bi-, and tri-spectra), which describe temporal development of the signal's higher-order moment spectra.

Monitoring CVs. For each time frame of the monitored signal, the 200 characteristic values of that frame were recorded in a profile vector. The profiles were plotted to enable visual inspection of outliers, as seen in **Figure 3**.

Identifying significant CVs. For each measurement parameter (MP), the highest linear correlations between CVs and MPs were identified. This was done by comparing CV profiles obtained at different test levels of the MPs. All CVs that showed a linear correlation coefficient within the range 0.95–0.999 were considered highly correlated with the measurement parameter and further analyzed.

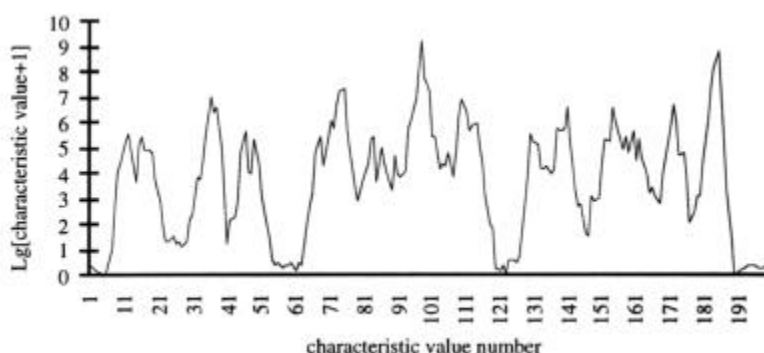


Figure 3. Characteristic value profile from the fourth time frame of a test sample.

RESULTS AND DISCUSSION

Results showed that there were 61 characteristic values that correlated linearly with the measurement parameters at $r^2 \geq 0.95$. The investigation showed that it was possible to deduce the applied amount of water and the selected amount of drying power. It was also possible to determine the concentration of isopropanol in the applied liquid. The largest numbers of highly correlating CVs were obtained with the 40-kHz transducers both in the wetting test and in the drying test.

The highest linear correlation between the applied amount of water and a characteristic value was found for CV 31 (the maximum value of the autocorrelation function of the difference signal) and CV 40 (the sum of the logarithm of the elements of the coherence vector between the reference and measurement). The largest numbers of highly correlated characteristic values were obtained at 800–1000 ms after initiation of spraying.

The highest linear correlation between the amount of drying energy and a characteristic value was found for CV 4 (when pure water was applied) and for CV 96 (when isopropanol solutions were applied). The CV 4 is the maximum value of the “db4” wavelet approximation at level four from the difference signal, while CV 96 is the maximum value of the Fourier transform of the difference signal. The greatest number of highly correlated characteristic values was also in the drying measurements obtained at 800–1000 ms after initiation of drying. **Figure 4a** shows the relationship between CV 31 and the amount of wetting liquid measured at 1600 kHz. **Figure 4b** shows the relation between CV 4 and drying power measured at 40 kHz.

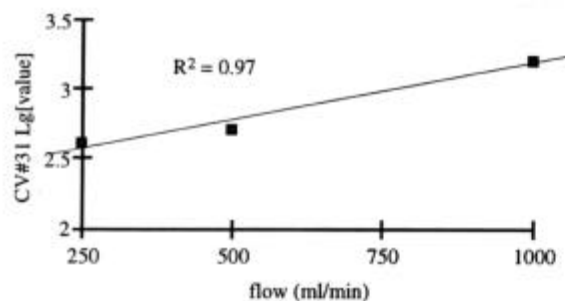


Figure 4a. Correlations between the amount of applied water and CV 31.

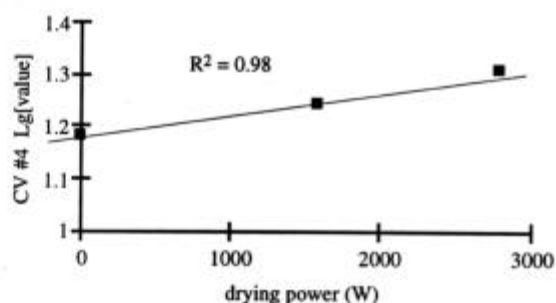


Figure 4b. Correlations between the amount of applied drying energy and CV 4.

In the wetting tests—at all probing frequencies—the number of highly correlated characteristic values was found to be a monotonically decreasing function of isopropanol concentration of the wetting liquid. This trend was most clearly seen with 40-kHz probing frequency. The number of highly correlated CVs was found to be a monotonically decreasing function of wetting liquid isopropanol concentration in the drying tests also. The decrease was most clearly seen with 1600-kHz probing frequency.

The degree of stretch could be estimated in the drying tests using 1600-kHz probing frequency, but it could not be estimated in the wetting tests. **Figures 5a and 5b** show the dependence between the number of highly correlating CVs and the isopropanol concentration of the wetting liquid between 800 ms and 1000 ms after the initiation of the measurement. Figure 5a shows the results from the wetting measurement employing 40-kHz ultrasound, and Fig. 5b shows the results from the drying measurement employing 1600-kHz ultrasound.

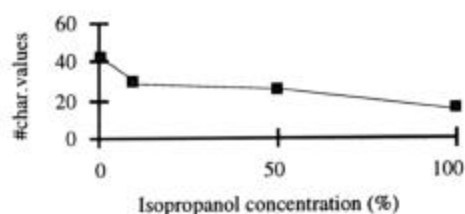


Figure 5a. Relation between isopropanol concentration of applied water and the number of highly correlating CVs in the wetting measurements.

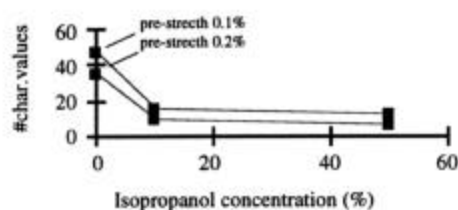


Figure 5b. Relation between isopropanol concentration of applied water and the number of highly correlating CVs in the drying measurements.

Following the wetting of the sample with different frequencies gave an indication that it might be possible to follow the wetting process on different spatial scales. This is in line with earlier experiments on the wetting process (7).

Errors

The biggest source of error in the wetting measurements was the powerful broadband noise generated by the nozzles during spraying. This noise was reduced with a bandpass filter. Another significant source of error was the uneven distribution of spray on the sample surface. The distribution of the liquid on the sample surface was investigated with an amaranth dye solution. The results of the deployment tests are shown in **Figures 6 and 7**. The hit pattern was analyzed with an image-processing routine. Deviations in distribution were ascribed to variations in water droplet size, turbulence in the air–water moisture ratio, and variations in nozzle exit velocity.

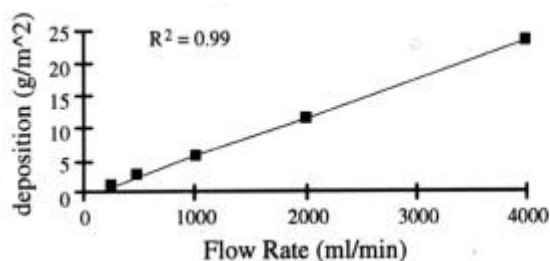


Figure 6. Test graph showing liquid coverage; deposition is the amount of water deposited onto the acoustically probed area of the sample.

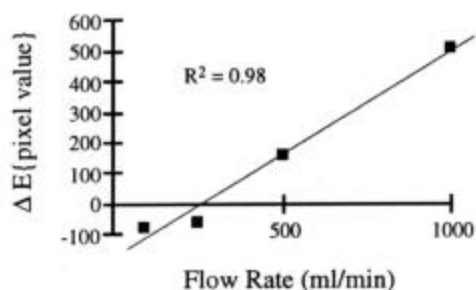


Figure 7a. Deployment test, 40-kHz setup.

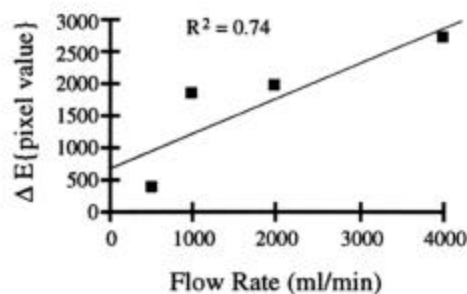


Figure 7b. Deployment test, 224/1600-kHz setup.

The biggest source of error in the drying measurements was the transducers. **Figure 8** shows the recorded temperature rise of the transducers during the drying measurements. Another possible source of error was the alteration in the humidity of the surrounding air. A change in ambient relative humidity does not induce significant changes in air density ($\delta\rho/\delta H_{\text{rel}} = 0.01\%$) nor in the phase velocity of sound in air ($\delta c/\delta H_{\text{rel}} = 0.005\%$). However, a change in ambient relative humidity does induce some increase in sound attenuation ($\delta\alpha/\delta H_{\text{rel}} = 0.08\%$) (3). Water from the sample diffuses more readily to the side of the transmitter than to the side of the receiver due to a greater temperature gradient in that direction, as seen in **Figure 9**. The evaporated water might protect the paper surface from temperature increase.

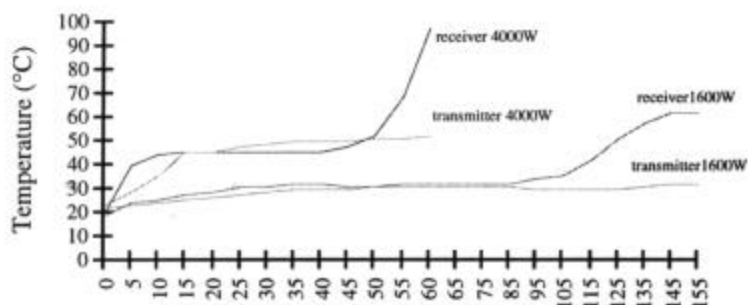


Figure 8. Recorded temperature rise of the transducers during the drying measurements.

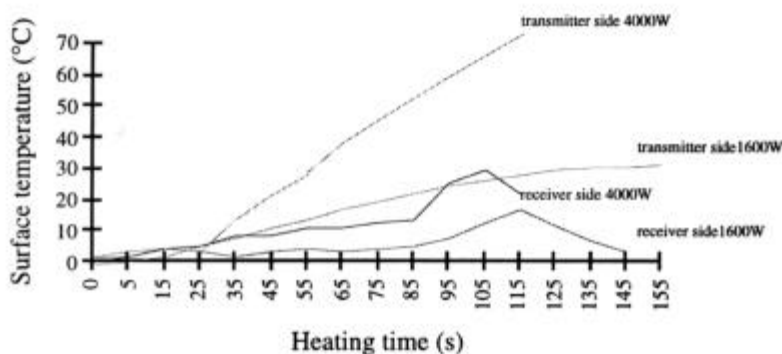


Figure 9. Temperature gradients between paper surface and ambient air during the heating period.

CONCLUSIONS

The tests performed on uncoated paper revealed linear correlations between measurement variables (i.e., amount of sprayed water or amount of drying energy) and characteristic values of the ultrasonic transmission signal. In some cases, the correlations were higher than 0.95. In the wetting tests, the amount of applied liquid and the isopropanol concentration of the liquid could be deduced. In the drying tests, the selected drying power and the isopropanol concentration of the wetting liquid could be deduced. The ability to track sheet moisture content with an ultrasound system indicates the potential of using ultrasound as a tool for controlling an online surface makeup system on a paper machine.

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