Development of an impedance method to measure the moisture content of a wet paper web

ZIQI WU*, WARREN J. BATCHELOR† AND ROBERT E. JOHNSTON‡

As part of a project on paper drying, an impedance method has been developed to measure the moisture content profile through paper (z-direction) for the purpose of understanding the mechanisms of internal heat and mass transfer within a thick handsheet during drying. The impedance of a wet paper sample between a pair of electrodes was measured at 100 kHz. The results demonstrated that the measured impedance was strongly related to the moisture content of the handsheet, independent of thickness within the tested moisture content range (7 to 60%) and dry thickness range (120 to 260 µm). The repeatability of the tests was satisfactory. The effects of temperature and frequency on the impedance were also studied and some of the results are illustrated in this paper.

Keywords

Impedance method, measurement, moisture content, paper

As part of a project on paper drying, we were interested in developing methods to continuously and simultaneously measure moisture content, temperature and layer shrinkage as a profile through the z-direction (thickness) of a paper sheet. In this paper, we report on the method that we have adapted and developed for the measurement of moisture content.

There are several possible methods to measure the moisture content profile of paper in the thickness direction. A common method is to measure the local moisture contents of the layers in a multi-ply sheet by interrupting the drying process, then quickly delaminating the sheet and gravimetrically measuring the average instantaneous moisture content of each ply (*1*). Obviously, this can only be done once and it is not suitable to monitor the moisture content continuously during the drying of paper. For the purpose of measuring the moisture content continuously, the impedance/capacitance method (*2,3*) is one of the most promising in view of its simplicity and low cost. The principle of the method is that the measured impedance indirectly indicates the change in moisture content due to change of the electrical properties of the sample. Baum has given a good introduction to the theory of the electrical properties of paper (*4*).

In the literature, there are comparatively few studies on the influence of moisture on the electrical properties of paper. Most studies have been done in the context of the use of paper as an electrical insulator and have only considered dry paper, or dry paper impregnated with oil.

Wet paper consists of fibres in the form of a porous network structure. Water is contained between fibres and within fibre lumens and walls. Depending on the moisture content, the pores can be filled with water and/or air. The main principle of the impedance method is that the paper web between two electrodes can be treated as an AC circuit of capacitors and resistors, the values of which depend on the moisture content.

To illustrate the relationships between the various electrical quantities we consider an AC circuit consisting of a resistance and a capacitance in series. For such a circuit, the impedance, Z, is equal to $\sqrt{R^2+1/\omega^2C^2}$ where R is the resistance, ω is the frequency and $1/\omega C$ the capacitive reactance.

The capacitance, *C*, is given by $C=k\varepsilon_o A/d$ where *k* is the dielectric constant, ε_o is the permittivity of free space, *A* is the area of the capacitor electrodes and *d* is the separation between the plates. The product $k\varepsilon_o$ is termed the permittivity, ε. The inductive reactance is generally negligible for a paper sheet.

The resistance of paper depends on the moisture content (*4,5*) as well as the concentration of electrolytes in the paper (*4*). For a cellulosic material like cotton, it was found the effect of changing moisture content on conductivity (σ) could be expressed in terms of moisture content [M (%)] by the power law relationship (*6*).

$$\sigma = \sigma_{sm}\left(\frac{M}{M_{sm}}\right)^n \qquad [1]$$

where M_{sm} is the moisture content at saturation and σ_{sm} is the conductivity at saturation. The experimentally determined value of *n* was 9.3.

The capacitive reactance, $1/\omega C$, is determined by the sample's dielectric constant, *k*, its geometry and the test frequency employed. The dielectric constant of paper is partly a measure of the polarizability of its constituents. The polarizability is a molecular property, whereas the dielectric constant also depends on the concentration and spatial distribution of the constituents. Paper is a cellulosic material and has molecular groups having permanent dipole moments,

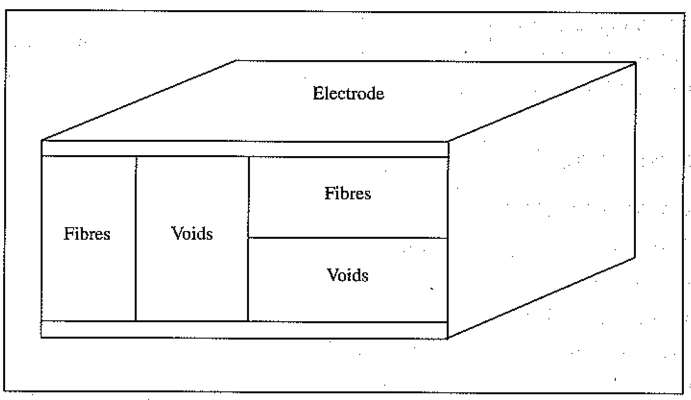

Fig. 1 A model of paper structure.

* Student
† Lecturer, Member Appita
‡ Professor, Member Appita
CRC for Hardwood Fibre and Paper Science, Pulp and Paper Institute, Department of Chemical Engineering, Monash University, Clayton, VIC 3168.

such as water itself or the hydroxyl and carboxyl groups of lignin or cellulose. At low frequencies (<1 MHz), all of these parts contribute to the dielectric constant. If water is present, however, even in relatively small amounts, it is apt to make the major contribution due to its polar nature. This is because the dielectric constant of water is around 80 (*7*), a value significantly higher than the dielectric constant of completely dry paper, which ranges from 1.3 to 1.8 (*5*). Hence the dielectric constant of paper depends heavily on the moisture content (*8*).

Sakamoto et al. (*9*) presented a model to evaluate the dielectric constant of dry or mineral oil-impregnated paper (see Fig. 1 for the paper structure model). In Sakamoto's model, the paper was simulated as three parallel elements, each with their own dielectric properties: fibres only; voids only; fibres and voids in series.

Apart from the moisture content, other factors that affect the dielectric properties include sheet density, frequency and temperature.

The relationship between paper density (ρ) and the permittivity was reported by Delevanti et al. (*10*) as:

$$K\rho = \frac{\varepsilon - 1}{\varepsilon + 2} \qquad [2]$$

where K is a constant for a particular species of fibre.

The frequency employed in testing, and the sample temperature, also has some effect on the dielectric constant. It was found (*11,12*) that increasing the frequency tended to decrease the dielectric constant and hence to decrease the impedance.

In summary, many factors influence the resistance and capacitance of wet and dry paper and no single model has been developed that adequately accounts for all of the variables. Therefore the relationship between impedance and moisture content must be experimentally determined, taking all relevant variables into account.

EXPERIMENTAL

Hand sheet preparation

An unrefined, never dried *E. globulus* kraft pulp was used in this study to prepare handsheets for experiments. The pulp was obtained from Australian Paper's, Maryvale mill. The pulp had a Kappa number of 17.9, a freeness of 587 CSF and was stored at 4°C at a solids content of 26.2%.

Handsheets for tests were prepared generally according to AS/NZS 1301.-203s:1993 except that no pressing stage was used and that sheets with a range of different grammages were made. After the handsheets had been formed they were dried to a moisture content of around 65% using blotting paper.

The finished handsheets ranged in thickness from 120 to 260 micrometres (after being completely air-dried), with grammages from 37 to 55 g/m^2, respectively.

Equipment

A test unit was specially built to measure the impedance of a wet paper sheet at different temperatures. The test unit has a round chamber and an airtight matching lid with a release hole. Both lid and chamber were made from clear perspex. The inner diameter of the chamber is 8.0 cm. Two thin brass plates of 2 by 2 cm^2 are embedded in the centre of the chamber and lid as the electrodes of a parallel capacitor. Two thin K-type thermocouples were mounted in the lid and the bottom chamber to measure the temperature of the sample under test. A schematic of the test rig is shown in Fig. 2. A metal weight on top of the unit was used to simulate the effect of felt tension by keeping a constant pressure of 25 g/cm^2 (approx. 2.45 kPa) on the sample during testing. A fan forced convection oven was used to carry out the tests on the effects of temperature. A Hewlett Packard 4263A LCR meter was employed to measure the impedance.

Procedures

A paper sample to be tested was cut to closely fit the test chamber and the electrodes were connected to the LCR meter. The time to reach a steady measurement was different for different moisture contents, ranging from a couple of minutes for a very wet sample (>60%) to a few seconds for a relatively dry sample (<15%). The impedance and temperature readings were measured after the steady state was reached. Then the sample was removed to measure its weight by an analytical balance (Mettler Toledo AB204).

For temperatures higher than 20°C, the whole test unit was put into an oven and preheated to the desired temperature. The cut sample, which was in a sealed plastic bag to prevent moisture escaping, was also put into the oven to be preheated. After about 15 to 20 minutes the sample was taken out from the bag, put into the test chamber and quickly covered with the lid. After the impedance reading was taken, the whole test unit was taken out and cooled down. The sample was then quickly transferred into a pre-weighed sealed plastic bag and the actual moisture of the handsheet was determined by the gravimetric method. Samples with moisture contents in the range 7 to 60% were tested. Measurements were made at temperatures of 20°C, 40°C and 55°C. The dry handsheet thicknesses were measured using a Messmer Digi-Cal thickness tester at room temperature.

The effect of frequency was tested by measuring the impedance of the same sample at frequencies of 100, 1,000, 10,000 and 100,000 Hz at 20°C.

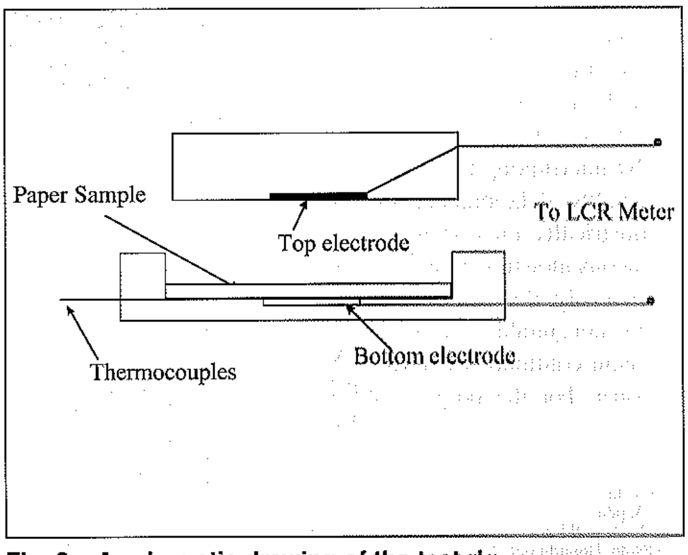

Fig. 2 A schematic drawing of the test rig.

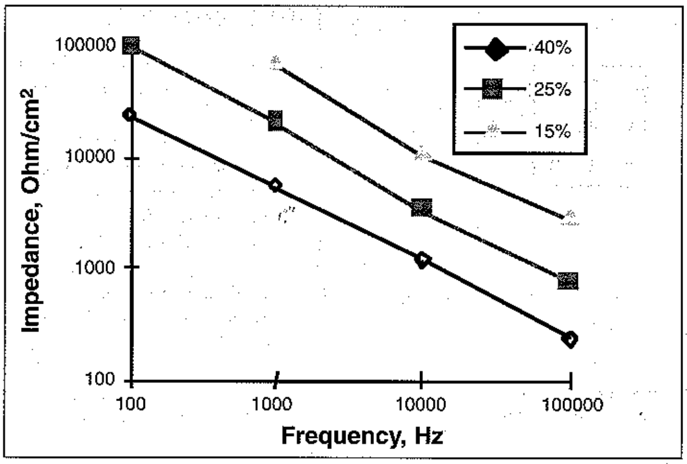

Fig. 3 Effect of test frequency on impedance. Tests were conducted at 20°C for a sample of 42 g/m² at 25% and 40% moisture content.

RESULTS

Effect of frequency

Frequency has a significant effect on the impedance measured at a range of different moisture levels. As Figure 3 shows, impedance steadily decreases with increasing frequency. It was very difficult to obtain stable impedance readings at high values of impedance. At 15% moisture, a stable reading could not be obtained at 100 Hz at all and there were some difficulties in obtaining a reading at 1 kHz. Since we wanted to measure impedance at moisture contents as low as 7%, where the impedance is approximately an order of magnitude higher than at a moisture content of 15%, the highest frequency of 100 kHz was selected for all measurements. This allowed measurements of impedance to be made across the whole range of moisture contents without having to switch frequencies.

Effect of sample thickness

A typical plot for five handsheet samples of different thickness, at 20°C is shown in Figure 4. The repeatability of all the tests was considered to be satisfactory. The tested samples were from 120 to 260 µm in thickness when dry or 210 to 460 µm when at 60% moisture content. These values corresponded to making sheets in the grammage range of 37 to 55 g/m². According to all the experiments conducted, the thickness of tested samples was found to have little effect on the impedance under the conditions of the test. This result was somewhat surprising as it was initially expected that the sample thickness would have some effect on the measured impedance. Efforts are continuing to understand this unexpected result.

To obtain an equation for calibration, the data from the five samples was combined into a single set and fitted using a power law equation. The result of the fit is shown as the line in Fig. 5, with the best-fit equation given by equation (*3*).

$$Moisture = \left(\frac{3.60\times10^{6}}{Z}\right)^{\frac{1}{2.674}} \qquad [3]$$

The R^2 value for the fit of 0.99 indicated that the power law equation provided a very accurate representation of the data giving a simple but relatively accurate method to measure the moisture content. Using this method, measurement of handsheet moisture content with an accuracy of ±3% moisture content now becomes feasible.

It should be emphasised that the calibration equation given here applies only for the measurements at 20°C and for the particular furnish (unbleached *E. globulus* kraft pulp) that was measured here. While we could find no information in the literature on the effect of furnish type on impedance, a number of other electrical properties are known to be affected by the chemical composition of the fibres (*13*).

Effect of temperature

Besides the tests at 20°C, tests were conducted at 40°C and 55°C to study the effect of temperature on impedance. The results are summarized in Fig. 5. It was found that the impedance generally decreases when the temperature increases, although the effect of temperature on the measured impedance is not nearly as strong as the effect of moisture. The measured decrease in impedance is likely to be due to a fall in both the resistance and the capacitance of the sample. This is because both the resistance and capacitance are largely determined by the mobility of the water molecules and the ions within the sample and the mobility will increase with temperature.

It should be noted that special care needs to be taken to successfully obtain the correct data at 40°C or higher temperatures because the high evaporation rate at high temperatures can cause significant moisture loss during transfer from test rig to weighing bag. This was minimized by taking the whole unit out from the oven and cooling it to room temperature. Then the sample was taken out quickly and put in a pre-weighed bag.

Finally, work continues on this impedance method to refine the techniques and improve the measurement accuracy. In particular, more data still needs to be

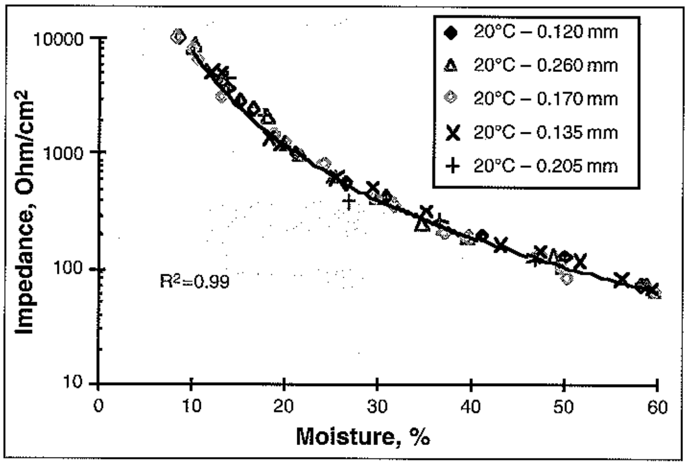

Fig. 4 Impedence vs moisture content for a test at 20°C, 100,000 Hz frequency on *E. globulus* kraft.

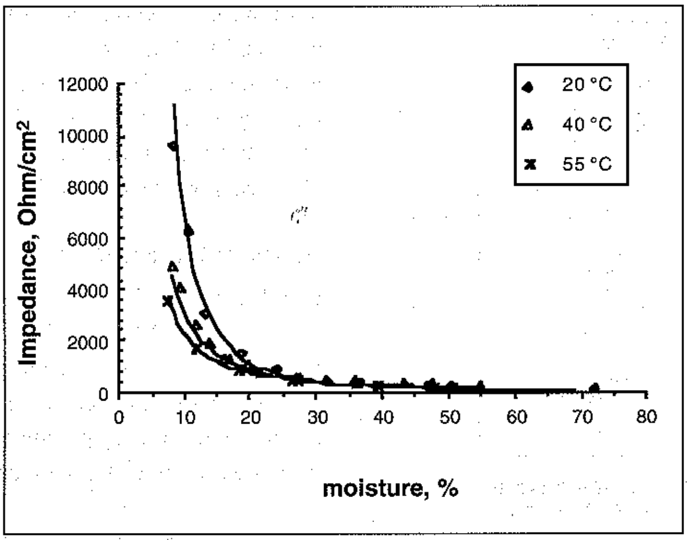

Fig. 5 **Plot of measured impedance versus moisture content at 20, 40 and 55°C. All measurements were made at 100 kHz frequency. The thickness of the sheet was approximately 260 μm for all measurements.**

obtained at higher temperatures where the drying studies will be conducted. Once the method is fully developed, it will be applied to continuously measure the moisture content profile of a handsheet during drying by inserting very thin electrodes in between multiple plies of a handsheet.

CONCLUSIONS

Impedance measurements on an unbleached eucalypt kraft pulp were successfully used to develop a method for continuously and non-destructively determining the moisture content of a sample in the range of 7% to 60%. For the samples tested here, the impedance was found to have a power law relationship to the moisture content. Unexpectedly, the thickness of the sample did not significantly affect the measured impedance. It was determined that 100,000 Hz is a suitable frequency for this method. The effect of temperature on the impedance was also investigated. It was found that the impedance generally decreases when the temperature increases.

ACKNOWLEDGEMENTS

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