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Research Paper

Predicting moisture content of chipped pine samples with a multi-electrode capacitance sensor

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ABSTRACT

Woody biomass is currently sold on a weight basis, practical moisture sensors are essential for fair sales, especially in energy markets. To address this need, an 8-electrode electrical capacitance tomography (ECT) sensor was built and tested for predicting moisture content of wood chips and compared with the near infrared spectroscopy (NIR) method. The goal was to find an optimal means of measuring moisture content of woody biomass in the form of chips in two situations: individual chips and bulk samples. Tests were made on chips ranging in moisture content from 4% to 140% (d.b.). Results indicated that NIR had better performance in measuring moisture of single wood chips, while ECT was more accurate and rapid in bulk moisture determination. Knowledge of the mass of wood chips under test was required in the ECT moisture prediction model, unlike in the case of NIR. Both methods had the capability to measure moisture content of biomass while in motion. From a practical standpoint, however, only a portion of the material flowing past a near-infrared sensor could be practically scanned and the sub-sampled biomass would have to be representative of the entire population to be accurate. The ECT sensor, on the other hand, could likely be designed to scan the entirety of a large quantity of moving material and provide an accurate bulk average moisture content. Compared to a single paired-plate capacitance sensor, the ECT system also provided images, through its tomography function, that displayed permittivity distribution variability throughout bulk biomass samples.

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Nomenclature

α, β, and k	Model coefficients (constants)
ε	Random error
C	Sensor output (V)
G	Permittivity distribution matrix
S	Sensitivity matrix
M	Mass (g)
ECT	Electrical capacitance tomography
MC	Moisture content
NIR	Near infrared
SPP	Single paired parallel-plate
RMSE	Root mean square error

1. Introduction

In the southern USA and elsewhere woody biomass is most often sold as pulpwood and sawn logs on a wet mass basis, a system that works because the moisture content (MC) of harvested trees normally fluctuates within a narrow range and wood from multiple sources can be considered a uniform product. However, when MC varies outside its typical range, the use of wet mass as a basis for selling timber products becomes untenable. This is particularly true in energy markets, where moisture is often considered a contaminant and there are methods of altering MC of feedstocks before shipment. A moisture sensor that could be widely accepted and could work reliably and accurately across a broad range of product forms and MC would help in promoting robust and stable biomass for energy markets. Ideally, such a sensor would be useful not only in laboratory settings when evaluating relatively small samples of material, but also in applications where the material to be assessed was flowing and when the quantity to be evaluated was very large.

Multiple methods and technologies have been investigated to evaluate MC of biomass, including dielectric property measurements (James, 1988; Kandala & Sundaram, 2010; Kandala & Puppala, 2012), X-ray (Roels & Carmeliet, 2006), microwave (Hansson, Lundgren, Antti, & Hagman, 2005; Johansson, 2001; Trabelsi, Paz, & Nelson, 2013; Vallejos & Grote, 2009), acoustic sensing (Amoodeh, Khoshtaghaza, & Minaei, 2006; Minamisawa, Ozawa, Sakai, & Takagi, 1990), radio-frequency scanning (Barale et al., 2002; Hanson & Kelly, 1998) and near infrared spectroscopy (NIR) (Adedipe & Dawson-Andoh, 2008; Defo, Taylor, & Bond, 2007; Mesic, Corluka, & Valter, 2005; Jensen et al., 2006; Tormanen & Makynen, 2011). Of the available technologies, the most likely to be successful for both bulk static and flowing materials are NIR and dielectric sensing (Nyström & Dahlquist, 2004). Both these technologies have been shown effective in measuring MC of diverse biological materials. NIR systems have been developed, for example, for analysing wood chips (Axrup, Markides, & Nilsson, 2000), forage (Digman & Shinners, 2008) and other biomass (such as Mesic et al., 2005).

Dielectric methods are used to measure permittivity of woody biomass, which is known to correlate with MC (Nelson, 1991). One of the most common dielectric transducers used in assessing permittivity is a capacitance sensor (Kandala & Sundaram, 2010). It is a simple and robust system that can independently measure mass and MC of biomass (Kandala & Puppala, 2012; Kandala & Sundaram, 2010). However, when the distribution of MC within the sample is not uniform, the single capacitance sensor cannot provide any information about the sample's variability. The use of multiple electrodes provides the opportunity to probe the distribution of MC in a bulk sample using a tomographic approach (Jazayeri & Ahmet, 2000). This technology is referred to as electrical capacitance tomography (ECT). Sensors having eight (Huang, Plaskowski, Xie, & Beck, 1988), twelve (Olmos, Primicia, & Marron, 2007) or sixteen (Wang, Huang, & Li, 2009) electrodes have been developed. ECT has been widely applied in, for example, (1) evaluating distributions of multiple-phased flow in pipes (two phase flow: Xie, Atkinson, & Lenn, 2007; Li, Huang, Wang, & Li, 2008; Johana, Yunus, Rahim, & Seong, 2011; three phase flow: Li et al., 2012), (2) measuring mass flow rate of solid materials (Sun, Liu, Lei, & Li, 2008; Young et al., 1996), and (3) sensing the distribution and volume of water inside mixtures of sand and clay (Karim & Ismail, 2011).

The research reported here was aimed at evaluating the application of ECT for the accurate, rapid, non-contact measurement of MC in biomass (specifically, pine chip) flows. However, preceding that aim it was necessary to determine how well the system functioned in a static bulk measurement mode. This paper, therefore, presents details of the ECT sensor development and described its accuracy relative to a widely accepted method in bulk biomass MC measurements, NIR. The experiments conducted were designed to evaluate both sensing technologies under the best possible conditions for each. Because it is essentially a surface measurement, it was hypothesised that NIR would be best applied in predicting MC for situations where the dry density and moisture distribution of the material under test could be considered uniform. The first objective in this study was, therefore, to compare NIR and ECT MC measurements on the smallest,

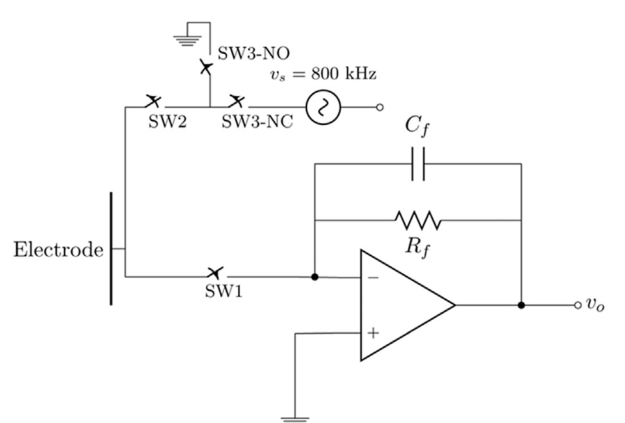

Fig. 1 – Schematic diagram of the capacitance-to-voltage circuit and the switch network used to operate it in its two modes. The electrode was connected to the RF source signal (mode 1) when switches 2 and 3 were closed, 1 open. The electrode was connected to the capacitance-to-voltage circuit with switch 1 closed and switches 2 and 3 open. Values of R_f and C_f used were: R_f = 680 kΩ, C_f = 10 pf.