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Full Length Article

The performance of resistance, inductance, and capacitance handheld meters for determining moisture content of low-carbon fuels

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HIGHLIGHTS

- The performance of 9 handheld moisture meters on 7 low-carbon fuels was determined.
- The moisture content was increased by 5% intervals from a range of 0–60% (wet-basis).
- Performance varied by each meter, irrespective of the measurement technology.
- Performance improved if the sample was similar to the meters intended sample material.

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ABSTRACT

The moisture content (MC) of a fuel is generally determined through gravimetric analysis where a sample is dehydrated in an oven over a period of approximately 24 h; the MC is then calculated by dividing the difference between the initial and final mass, by the initial mass. Handheld moisture meters offer the benefit of near-instantaneous measurements and should provide accurate and dependable results. The performance of nine moisture meters applied to seven low-carbon fuels (LCFs) was determined. The nine meters employed three measurement technologies: electrical conductance/resistance, electrical capacitance and electromagnetic inductance. The seven LCF samples considered were: shredded switchgrass, two batches of shredded wood, two batches of ragger tails and two batches of sanitary products. A moisture meter applicable for LCF should have a clear relationship between the actual MC and the measured MC, low variability, and be accurate within an absolute difference of 2%. Results indicated that none of the meters were suitable for use on LCF in general. It was not possible to identify a specific measurement technology that performed better for a certain LCF type from the results.

1. Introduction

As carbon emission limits become stricter and carbon cap-and-trade policy is implemented [1,2], industrial facilities are considering various methods to decrease their emissions. One method is to combust fuels that have lower life-cycle carbon emissions than traditional fossil fuels such as coal, petroleum coke (petcoke) or natural gas. These low-carbon fuels (LCF) include solid end-of-life materials, virgin and non-virgin biomass.

The Lafarge Bath, Ontario, cement plant produces Portland cement. To manufacture cement, reactants require a temperature of approximately 1450 °C [3]. To meet these conditions, the energy required is produced by combustion of a significant amount of raw fuels, traditionally coal and petcoke; however, since 2014 this facility has started a pilot program (referred to as Cement 2020) to test the co-firing of LCFs alongside fossil fuels. The LCFs that have been or are under consideration include wooden railway ties, utility poles, ragger tails (non-recyclable waste from paper and cardboard recycling such as strands of plastic tape, binding thread, non-pulped cardboard and other plastic implements), asphalt shingles, construction & demolition (C&D) waste, single-use coffee pods and sanitary products. To have appropriate quantities of alternative fuels on hand, LCFs are acquired from multiple sources. An issue that has been identified with the delivered LCF is that the moisture content (MC) of the fuel has been found to exceed the expected maximum on multiple occasions. High MC is not only a source of energy waste (since part of the fuel energy will be used to evaporate water), it also poses handling problems in cold weather (freezing), on a conveyer system (clumping, clogging) and can be a source of excessive biodegradation and toxic dust generation due to molds in warm weather.

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Various standards for determining MC are available. The ASTM family includes ASTM E790 [4] and ASTM E871 [5]. The methodology of these standards follow a gravimetric analysis that requires the sample to be dehydrated in an oven, and the MC is determined from the mass before and after dehydration:

$$MC\ (\%) = \frac{m_w - m_d}{m_w} \times 100 \tag{1}$$

where MC is the percent moisture content on a wet basis, m_w is the mass of the wet sample, and m_d is the mass of the dry sample. Similar standards are stipulated by the ISO and DIN, among others.

The main concern with these methods is the extensive time required to dry the sample, which can take up to 24 h. It is not realistic to expect a delivery of LCF to wait 24 h to determine if the fuel meets specification, and therefore a fast method of moisture measurement is necessary. Another issue with the gravimetric approach is that it is difficult to obtain a representative sample of the fuel delivery. Some LCFs, such as wood fuels, can be heterogeneous and therefore can have significant variations in the MC throughout the delivery [6].

One option that is both quick and easy to implement is the use of handheld moisture meters. These meters use various methods to rapidly determine the MC of a sample. However, the handheld meters are typically manufactured for specific materials, such as hay, wood chips, solid wood, paper, plaster, and soil. Given the unusual type and wide diversity of LCFs, none of the off-the-shelf meters designed for a specific material can be blindly used to newly identified materials. Therefore, to identify if a measurement technology may be suitable for use on LCFs, this work considers:

(a) The accuracy of existing meters when applied to different LCF types.
(b) How precise these instruments can be, even if their absolute accuracy is poor, *i.e.* to what extent can these readily available instruments be used to measure novel materials, once calibrated for the material.

The existing hand-held moisture meters used in this study were based on electrical capacitance, electromagnetic inductance (EMI), or electrical resistance (or its inverse, conductance; $\sigma = \frac{1}{\rho}$ where σ is conductivity and ρ is resistivity). Other technologies that were not considered include near-infrared reflectance (NIR) and microwave radiation, for reasons that are explained in Appendix A.

There are two styles of meters, pin and pin-less. Pin style probes require a pin to be inserted into the medium to be measured, while pin-less are considered non-invasive since they do not require the insertion of a probe into the medium.

The electrical resistance (or conductance) method is a pin-style, which determines the MC of the analyzed medium from the relationship between the resistance (or conductance) and the MC. Due to the high conductivity of water and much lower conductivity of other components of the measured medium (for example, cellulose, hemi-cellulose and lignin for biomass samples), the electrical resistance of the medium will decrease as the MC increases. The pins of the meter are inserted into the medium and an electrical current is passed between them to determine the resistance. The MC of the medium is then determined from the resistance curve, which is the relationship between the resistance and MC [7,8]. Existing studies have found mixed results from the use of electrical resistance probes. In a study by Byler et al. [9], four resistance meters were used to measure the MC of cotton bales. Results indicated that due to low precision, the meters could not be relied upon for crucial measurements. Instead, the meters should only be used for a general indicator of the MC. In a study by Chesser Jr. et al., [10] two resistance meters were found to report MC below the actual MC of switchgrass at multiple moisture levels.

Electrical capacitance probes can be either pin or pin-less. The capacitance of a material is influenced by the relationship between the high relative permittivity, ε_r, of water (80.1 at 20 °C and at frequencies below 1 GHz) and that of the analyzed medium (approximately 3–5 for soil and 1.0006 for air) [11,12], where the relative permittivity, ε_r, is the ratio of the absolute permittivity (ε) of the material to that of vacuum, ε_0 [3]. The absolute permittivity is a complex scalar that can be defined by $\varepsilon = \varepsilon' - j\varepsilon''$, where ε′ is the real part and referred to as the dielectric constant, ε″ is the imaginary part referred to as the loss-factor, and $j = \sqrt{-1}$, [13–15]. This technique uses the empirical relationship between the MC and the change in the probe electrical signal to estimate the MC. The permittivity of the analyzed medium is determined from the charge time of a capacitor when placed either in or on the surface of the medium [12]. In a study [16] where a multi-electrode capacitive sensor was used to predict the moisture content of chipped pine, it was found that the accuracy of the sensor was much greater for bulk samples, as opposed to single chips, which may make the capacitive technology suitable for LCF. Wilson [17] found the accuracy of a capacitance meter to be greater than that of three resistance meters when used to measure the MC of wood samples.

Electromagnetic induction (EMI) meters, also known as radiofrequency (RF) meters, are a pin-less technology that use electromagnetic radiation to measure the apparent conductivity of the analyzed medium [18,19]. EMI meters comprise of two electrical coils: a transmitter coil and a receiver coil. The transmitter coil emits a time-varying magnetic field, which induces eddy currents in the analyzed medium from the high dielectric properties of the water molecules. The eddy currents are proportional to the medium electrical conductivity and produce a secondary magnetic field, which is 90° out of phase from the primary magnetic field. The receiver coil measures the intensity of the out-of-phase secondary magnetic field and converts this signal into an output voltage. This voltage is used to determine the MC of the analyzed medium [20]. The measured permittivity is highly influenced by the meter's frequency and the moisture content of the sample [15,21].

1.1. Measurement considerations

Moisture meters are generally designed for a specific material. Provided that a good repeatability (precision) is demonstrated, the meter may be calibrated to a different material. Properties that can affect the moisture measurement include particle shape, grain orientation (in wood), temperature, chemical composition, and density. In order to extend their applicability, many meters have a menu of materials, e.g. wood species, or hay origin, and apply an appropriate set of calibration constants to the sample at hand. The manufacturer advice is sometimes to select the "closest" choice if a particular material is not listed in the menu.

Wood orientation is specific to meters that are designed for measuring moisture in solid wood. The meter must be oriented along the grain in a specific manner as explained by the owner's manual; incorrect placement of the meter can result in inaccurate measurements. Wood orientation is not a concern for LCF measurements as any wood content is ground to particle sizes below 2.5 cm in length.

The temperature of an LCF sample is important for resistance/conductance meters since its operation depends on the correlation between the temperature and the materials electrical resistance. As the temperature of the sample increases, the electrical resistance of the sample decreases thereby affecting the meter reading