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Research Paper

Density-independent algorithm for sensing moisture content of sawdust based on reflection measurements

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A density-independent algorithm for moisture content determination in sawdust, based on a one-port reflection measurement technique is proposed for the first time. Performance of this algorithm is demonstrated through measurement of the dielectric properties of sawdust with an open-ended half-mode substrate integrated waveguide (HMSIW) sensor. For accurate measurement of the dielectric properties of sawdust, the HMSIW sensor was calibrated by using a three-material calibration technique, with air, water and 25% ethanol aqueous solution. For moisture determination, a density-independent calibration function expressed in terms of the dielectric properties was used. Both moist and dry bulk densities were considered for the complex-plane representation of the dielectric properties. Results of moisture prediction, relative to each complex-plane representation were found to be similar at 5 GHz and 23 °C with the standard errors of performance of 0.955% and 0.957%, respectively.

1. Introduction

Sawdust is a common raw material in bioenergy production (Jensen et al., 2006; Kaliyan & Morey, 2009; Nyström & Dahlquist, 2004). The advantage of sawdust biomaterial is the cost per power unit, which is lower than that of other energy sources. Typically, higher efficiency in converting sawdust into heat is obtained for pelletised sawdust with moisture content ranging from 6% to 8% (wet basis). The process of converting sawdust into pellets involves both drying and densification. Normally, the moisture content of the raw sawdust is around 15–45% (wet basis) and it is dried to about 10% (wet basis) before densification. During the densification (pelleting) process, moisture is added to bring the sawdust to 14–15% moisture content. After that, pellets are dried to a moisture content of about 6–8% (wet basis). Therefore, moisture content is a critical parameter as it relates to the quality of the pellets and energy consumption for pelleting and drying.

Physically, sawdust is a heterogeneous material with porous structure similar to that of wood. The main constituents of sawdust material are wood, water and air. In this paper, moisture content is the parameter of interest. Recently, a broadband microwave technique (Paz, Trabelsi, Nelson, & Thorin, 2011) was used for measuring the dielectric

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Nomenclature

a_f	Slope of regression line of complex-plane representation of the dielectric properties each divided by moist bulk density
a'_f	Slope of regression line of complex-plane representation of the dielectric properties each divided by dry bulk density
Δe_i	Difference between predicted value and that determined by a standard oven method for ith sample
e_A	Average value of Δe_i
ε	Dielectric properties of sawdust
ε_A	Dielectric properties of air
ε_B	Dielectric properties of water
ε_C	Dielectric properties of 25% ethanol aqueous solution
ε'	Dielectric constant
ε''	Dielectric loss factor
HMSIW	Half-mode substrate integrated waveguide
M	Moisture content, wet basis (%)
$m_{sawdust}$	Mass of sawdust (g)
m_{water}	Mass of water (g)
m_{wood}	Mass of wood (g)
N	Number of samples
ψ	Density-independent function
ψ_{dry}	Density-independent function of dry bulk density
ψ_{moist}	Density-independent function of moist bulk density
ρ_{dry}	Dry bulk density (g cm^{-3})
ρ_{moist}	Moist bulk density (g cm^{-3})
R^2	Coefficient of determination
Γ	Reflection coefficient of sawdust
Γ_A	Reflection coefficient of air
Γ_B	Reflection coefficient of water
Γ_C	Reflection coefficient of 25% ethanol aqueous solution
SEP	Standard error of performance
SD	Standard deviation
v_{air}	Volume of air (cm^3)
$v_{sawdust}$	Volume of sawdust (cm^3)
v_{water}	Volume of water (cm^3)
v_{wood}	Volume of wood (cm^3)

properties of sawdust samples of different moisture contents. The measured dielectric properties of sawdust were found to increase linearly with the volumetric moisture content of the sawdust. This provides the basis for developing a microwave technique for determining moisture content in sawdust. Typically, the dielectric properties of the particular materials are dependent on bulk density (Nelson, 1994; Trabelsi, Krazszewski, & Nelson, 1998a; Trabelsi, Kraszewski, & Nelson, 2001; Trabelsi & Nelson, 2003). It would be advantageous to have a density-independent algorithm for moisture content determination in sawdust.

In this paper, a density-independent algorithm for moisture content determination in sawdust, based on reflection measurements, is proposed for the first time. In Section 2, a low-cost open-ended half-mode substrate integrated waveguide (HMSIW) sensor with grounded flange is described, and details of its use for measuring the dielectric properties of sawdust are given. The density-independent calibration function was developed, based on complex-plane representations of the dielectric properties, each divided by either moist or dry bulk density (McKeown, Trabelsi, Nelson, & Tollner, 2017; McKeown, Trabelsi, & Tollner, 2016; Trabelsi et al., 1998a; Trabelsi, Krazsewski, & Nelson, 1998b; Trabelsi & Nelson 1998; Trabelsi, Paz, & Nelson, 2013). Results of moisture prediction by using both approaches (moist and dry bulk density) are presented and the performance of each algorithm is given in Section 3.

2. Materials and methods

2.1. *Open-ended half-mode substrate integrated waveguide (HMSIW) sensor*

The open-ended HMSIW sensor (Fig. 1), fed by a microstrip line (Lai, Fumeaux, Hong, & Vahldieck, 2009), was used as the open-ended waveguide sensor with a grounded flange (Kempin, Ghasr, Case, & Zoughi, 2014) for measuring the dielectric properties of sawdust. To avoid the ionic conduction effect (Paz et al., 2011), the operating frequency of the sensor was selected to be above 4 GHz. Therefore, the dimensions of the sensor are as shown in Fig. 1. The aperture waveguide of the HMSIW was inserted into an opening in the grounded flange and soldered to both sides of the HMSIW. An acrylic conformal coating was applied to the waveguide aperture to protect from the material being measured. The dielectric properties of the sawdust (ε) were determined by measuring the reflection coefficient (Γ) of three materials of known dielectric properties and that of sawdust by using the following expression (Wei & Sridhar, 1991):

$$\frac{(\varepsilon-\varepsilon_A)(\varepsilon_B-\varepsilon_C)}{(\varepsilon-\varepsilon_B)(\varepsilon_C-\varepsilon_A)}=\frac{(\Gamma-\Gamma_A)(\Gamma_B-\Gamma_C)}{(\Gamma-\Gamma_B)(\Gamma_B-\Gamma_A)} \quad (1)$$

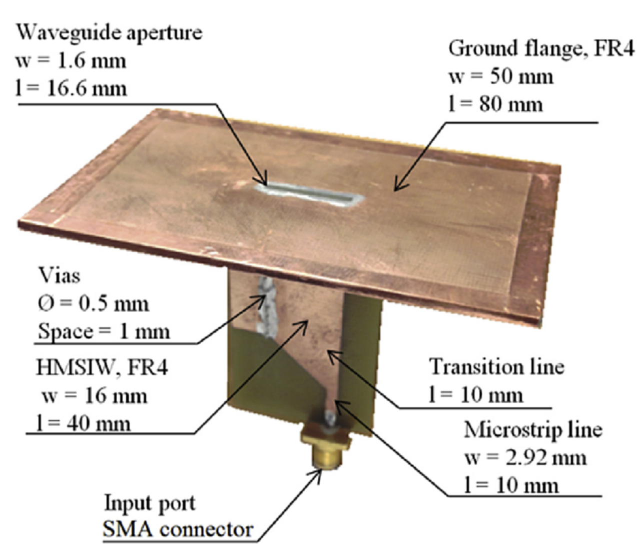

Fig. 1 – Half-mode substrate integrated waveguide (HMSIW) sensor with grounded flange.