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Research Paper

Microwave sensing of moisture in flowing biomass pellets

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Production of pelleted biomass for fuel is an emerging industry in the United States. Moisture content is a primary quality attribute of pelleted biomass materials because it is critical in binding, storage, combustion, and the pricing of pelleted biomass. To produce pellets of high quality, moisture content must be tightly controlled. A microwave system was designed for moisture sensing in flowing bulk material and used to determine feasibility of sensing moisture content in pelleted biomass from measurement of the dielectric properties at microwave frequencies. Samples of pelleted biomass derived from peanut hulls and pine sawdust were used for moisture content determination. Moisture contents of pine sawdust pellets ranged from 5.4%–9.9% (wet basis), and the range for peanut hull pellets was 8.9%–14.5%. At each moisture content, three different material flow rates were tested, and moisture content predictions were compared to those obtained with static measurement. Moisture content of flowing material was predicted by using a permittivity-based density-independent moisture calibration function. Root-mean-square deviations were computed for comparisons between reference moisture content, and predicted moisture contents for both static and flowing materials. Results showed that predicted moisture contents under static and flowing conditions were comparable.

1. Introduction

Pelleted biomass is a feedstock that is combusted for energy generation, alone or sometimes co-fired with fossil-fuel-burning power plants (Granada et al., 2006). Pelletised biomass offers advantages over raw biomass because of its increased bulk density and uniformity. In the United States, primary sources of pelleted biomass consist of residues from sawmills and plywood mills; timber logging residues; pulpwood originating from forests; urban wood waste residues from tree-trimming, building, construction, and demolition; as well as hardwood and softwood from short-rotation woody crops. From 2002 to 2013, energy derived from densified or pelleted biomass grew nearly 60% (Joyce, 2014). The United

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Nomenclature

a_f	Slope of regression line formed when plotting complex plane
A	Attenuation (dB)
A_{cs}	Cross-sectional area (m^2)
b	y-axis intercept
c	Velocity of light in vacuum, ($m\ s^{-1}$)
d	Material thickness (m)
Δe_i	Difference between predicted value and that determined by another method for ith sample
ε'	Dielectric constant
ε''	Dielectric loss factor
f	Frequency (Hz)
$M_{\%}$	Moisture content, wet basis (%)
$M_{\%flow}$	Average of predicted moisture content during flow (%)
$M_{\%ref}$	Moisture content determined by a standard method (%)
$M_{\%static}$	Average predicted moisture content of static samples (%)
m_d	Mass of dry matter (g)
m_w	Mass of water in the sample (g)
n	Integer used in phase ambiguity calculation
ψ	Density-independent function
p	Number of observations
ϕ	Phase shift
Q	Flow rate ($kg\ s^{-1}$)
ρ	Bulk density ($kg\ m^{-1}$)
ρ_f	Flowing material bulk density ($kg\ m^{-1}$)
R^2	Coefficient of determination
RMSD	Root mean square deviation
$\|S21\|$	Modulus of scattering parameters
θ	Argument of scattering parameter
v_h	Flow velocity ($m\ s^{-1}$)

States production capacity for pellets has increased from 3 million tonnes in 2008 to 12 million tonnes in 2014 (US International Trade Commission, 2015). Furthermore, policies in the European Union (EU) are driving demand for exported pellet production in the United States. The Renewable Energy Directive of the EU requires a certain percentage of each member state's energy to be generated from renewable fuels by 2020; this includes biomass-derived energy (EU Directive 2009/28/EC, 2009). These trends demonstrate that biomass is a growing renewable energy resource and export product in the USA.

Moisture content is a primary quality attribute of pelleted biomass, because it affects binding, density, storage, and combustion of the pellets (Nyström & Dahlquist, 2004). Water acts as a binding agent, and the amount is critical to the integrity of biomass pellets through strengthening bonds by facilitating van der Waals' forces and/or hydrogen bonding between particles (Kaliyan & Morey, 2009, 2010). However, in excessive amounts, moisture that is unable to be absorbed by particles attaches itself to the biomass surface and hinders particle compaction, thus reducing pellet quality (Nielsen, Felby, Poulsen, & Gardner, 2009; Zhang, Cai, Chen, Zhang, & Zhang, 2015). If moisture content of the feedstock is too low, then during extrusion through the pellet mill the material may plug die holes if the resistance exceeds the force of the roller (Lehtikangas, 2001). Moisture content may also affect pellet density since there is generally a trend of decreasing density with increasing moisture content (Mani, Tabil, & Sokhansanj, 2006). In storage, low moisture content inhibits the growth of fungi (mould) in pellets. Pellets, made of tree bark and stored for 3 months at 21% moisture content were found to have microbial contamination, whereas those with lower moisture contents were largely free of microbial growth (Lehtikangas, 2000). During the combustion of pellets, their moisture content directly affects the process by reducing the energy output as the mass of the water in the sample absorbs energy as it evaporates (Gil et al., 2010). Moisture content also influences the combustion efficiency and the temperature of combustion (Obernberger & Thek, 2004). Knowledge of the moisture content permits better control of the combustion process.

Opinion on the optimum moisture content of pellets varies and usually depends on material type and pelletising temperatures. A study with a single pellet press determined that the optimal moisture content for triticale-, willow-, alfalfa-, fescue-, sorghum-, and miscanthus-based pellets was approximately 10% moisture content (Puig-Arnavat, Shang, Sárossy, Ahrenfeldt, & Henriksen, 2016). Optimal moisture content for pellet density and diametric compression strength was 12.2% and 11.5%, respectively for water hyacinth pellets (Zhang et al., 2015). Densification of oak into “logs”, with roughly triple the diameter of traditional pellets, had both high-density and good long-term durability performance at 8% moisture content (Li & Liu, 2000). A study on compression force, particle size, and moisture content showed that pellets produced from corn stover had the highest pellet density at 12% moisture content and that the density was greater than that of wheat straw, barley straw, and switchgrass that were also pelletised at 12% (Mani et al., 2006). In production of peanut-hull pellets, maximum durability was achieved at 9.1% moisture content (Fasina, 2008). Furthermore, in the same study, it was demonstrated that the pellets absorbed up to 4.8% moisture when exposed to humid air over 48 h. Pine pellets had an optimal moisture content for densification in the range 6%–8%.

Moisture contents of the feedstocks also vary throughout the pelleting process. Input materials can have widely different initial moisture contents depending on the material. While sawdust and cutter shavings are preferred materials for pellet feedstock, increasing demand for pellets in European markets has led pellet producers pursuing other raw materials such as wood bark, branches, and logging residue (Selkimäki, Mola-Yudego, Röser, Prinz, & Sikanen, 2010). In their natural state, sawdust, logging residues, and bark have moisture contents that depend on prevailing climate conditions and storage-time and are in the range 35.5%–61.6% (Lehtikangas, 2001). Other materials such as alfalfa and switchgrass have lower moisture contents between 12% and 20% (Jannasch, Quan, & Samson, 2001). After sawdust and other woody residues that are high in moisture content are received at the