NEW DENSITY-INDEPENDENT MOISTURE MEASUREMENT METHODS USING FREQUENCY-SWEPT MICROWAVE TRANSMISSION

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Abstract

This paper presents density independent moisture measurement procedures using frequency-swept microwaves. By proper processing changes of attenuation and phase of a transmitted signal versus frequency, calibration curves can be easily generated on-site, without any need of varying density or layer thickness of moist material under test. It is shown, that the new measurement methods are usable up to very high moisture contents of more then 40%, in contrast to previous methods, which are only usable below approximately 25%.

1 Introduction

The moisture content of organic materials has significant influence on their processing technology. Being defined as

$$\psi = \frac{m_w}{m_w + m_d} \cdot 100\% \quad , \tag{1}$$

with m_w, m_d the masses of water and dry material, respectively, the moisture content is usually determined by the dry-weighing method, which is tedious and time consuming. However, application of microwaves for that purpose shows many advantages compared to other non-contacting measurement approaches such as radiometric or infrared equipment.

Microwaves can penetrate a significant volume, thus having the capability of delivering the average moisture content of a bulk of material. Both, attenuation (in Np)

$$A = \frac{\omega}{c} L \cdot R(\rho) \cdot g_1(\epsilon_r(\psi)) \tag{2}$$

and phase shift (in rad)

$$\Phi = \frac{\omega}{c} L \cdot R(\rho) \cdot g_2(\epsilon_r(\psi)) \tag{3}$$

through a layer of material relative to free space are correlated with moisture content via the dielectric properties, given by the complex permittivity $\epsilon_r = \epsilon' - j\epsilon''$, but also depend on density ρ (ω angular frequency, c velocity of light in vacuum). It is empirically found, that A and Φ show virtually the same functional dependence $R(\rho)$ on density, whereas g_1 and g_2 are different functions of complex permittivity and hence moisture.

2 Density independent moisture measurement

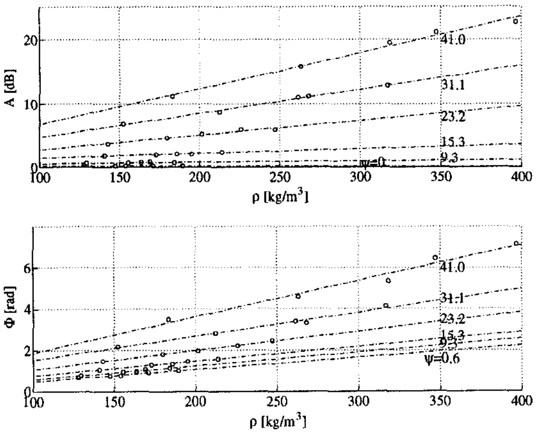

Figure 1: Attenuation and phase versus density for various ψ-values of tobacco (10GHz)

Density independent microwave moisture measurement using microwaves alone in a two parameter measurement has been introduced first by [1] in 1977 and later by [2] in 1980. Further refinements of [1] are given in [3, 4]. According to [1], the density dependence is assumed to be given by $R(\rho) = \rho$, which results in

$$\frac{A}{\rho L} = M_1(\psi) \quad \text{and} \quad \frac{\Phi}{\rho L} = M_2(\psi) \quad . \tag{4}$$

M_1 and M_2 are moisture-functions and not dependent on density. The linear dependence on ρ is often fulfilled,

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as can be seen in Fig. 1 for tobacco, however, this is not always the case. By combining equations (4), the relation

$$X_1 = \frac{A}{\Phi} = M(\psi) \tag{5}$$

is a function of moisture only. In the practical implementation, calibration measurements of A and Φ have to be made on material with varying moisture content ψ. Also, the (ρL)-product has to be determined experimentally. Then M_1 and M_2 are fitted numerically to suitably chosen functions. Finally $M(\psi)$ can be calculated, and in some cases inverted analytically to deliver

$$\psi = M^{-1}\left(\frac{A}{\Phi}\right) \quad . \tag{6}$$

Following the procedure of [3], density independence of

$$X_2 = \frac{\epsilon'(\psi,\rho) - 1}{\epsilon''(\psi,\rho)} \tag{7}$$

is claimed and substantiated by laboratory measurements. However, ϵ_r can only be determined in a transmission measurement, if L is known, which is seldom the case. Therefore it is shown in [3], that for low values of ϵ' and ϵ'', X_2 can be approximated by

$$X_2(\psi) \propto \frac{\Phi(\psi,\rho)}{A(\psi,\rho)} \quad , \tag{8}$$

a function being independent of L and ρ. In practise, for a given material, moisture ψ is varied. For a fixed moisture content and a given density, the measurement values of A and Φ are mapped in a Φ-over A-diagram. As a second point in this diagram, the origin is taken, and a straight line is defined through both points. The moisture content is assumed to be proportional to the slope of that curve.

A further refinement of the procedure can be deduced from [5], who plots the Φ-A-diagram by varying density or layer thickness L for a given ψ, thus determining the slope of the straight line from a set of measured points instead of using only one measured point and the origin.

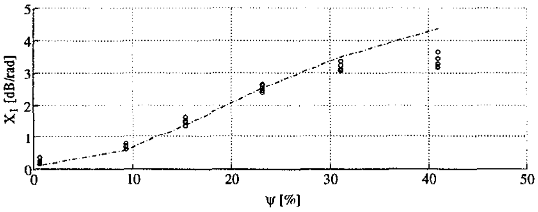

Figure 2: Calibration curve and measured values X_1 versus moisture content for tobacco (10GHz)

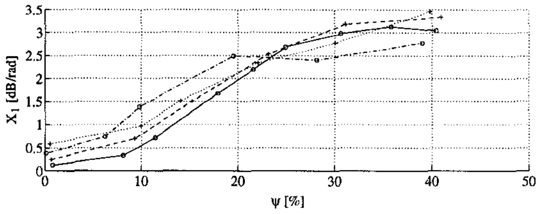

Figure 3: Measured X_1 versus moisture content for rape-seed(- ·), oats(· · ·), tobacco(- -) and marjoram(–) (10GHz)

In order to further illustrate the described methods of density independent moisture determination, some experimental results are given based on measurements of tobacco. According to [1], by interpolating the measurement points of A and Φ in Fig. 1 by straight lines, curves can be plotted for ρ =const. as functions of ψ. The generated points are fitted by parabolic functions

$$\frac{A}{\rho L} = a \cdot \psi^2 + b\psi + c \tag{9}$$

and

$$\frac{\Phi}{\rho L} = d \cdot \psi^2 + e\psi + f \quad , \tag{10}$$

leading to a calibration curve

$$X_1 = \frac{a\psi^2 + b\psi + c}{d\psi^2 + e\psi + f} \quad , \tag{11}$$

which can be inverted to deliver $\psi(X_1)$.

This dependence is depicted in Fig. 2, together with measurement points after [3]. It can be seen, that both approaches work very well between moisture contents of $\psi \approx$8-25%. An S-shaped calibration curve is found. Similar results can be observed for many other organic materials like for example rape-seed, oats and marjoram as shown in Fig. 3.

For low ψ-values, water is bound closely to the material. Attenuation and phase-shift increases slowly with ψ. Above approximately 10% and up to 25% attenuation rises faster than phase and measurement procedures work well. For higher moisture contents, only free water increases and A and Φ behave similar. That means, that the calibration curve flattens and may even loose its uniqueness. Small measurement errors in A and Φ result in big deviations in the associated ψ-value, making the entire measurement approach impractical.

Summarizing the features of the established density independent moisture measurement procedures, the following statements can be made:

- the various approaches work equally well, because they are based on the ratio $\frac{A}{\Phi}$,
- a significant effort is required for calibration, because layer thickness and/or density has to be varied for constant moisture content ψ,
- the methods work only satisfactory over a limited range of moisture content.

It is the purpose of this paper to introduce new density independent measurement approaches, which greatly simplify the calibration procedure and are also capable of proper operation at moisture contents of up to 40% and more. By suitable choice of the operating parameters no flattening of the calibration curve at high moisture values takes place. As a result, due to the steeper slope, measurement accuracy is greatly improved. With respect to calibration no laboratory reference measurements are needed and no layer thickness or density variations are required, thus enabling on-site calibration by the user employing test materials.

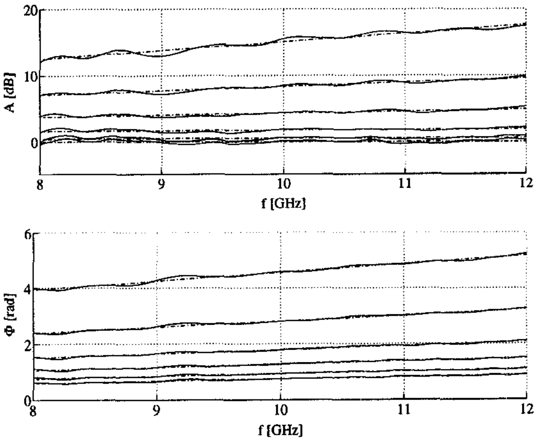

Figure 4: Attenuation and phase-shift versus frequency for various moisture contents of tobacco

3 New approach

The new measurement approach is based on attenuation and phase measurements over a broad frequency range. Using frequency swept data is not new, however, it was used earlier only for interpolation in order to improve accuracy at a given frequency, which was then employed in further calculations. In the new approach, changes of A and Φ versus frequency are recorded and evaluated.

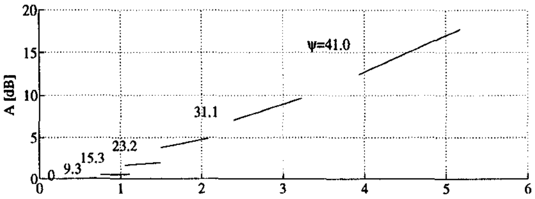

Figure 5: Attenuation versus phase-shift for various moisture contents for tobacco

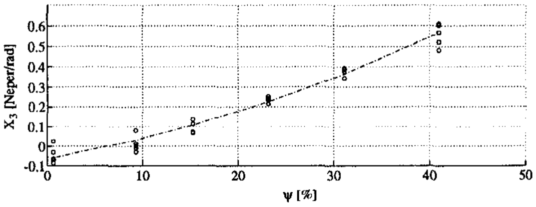

Figure 6: Gradient of A-Φ plots versus moisture content with various densities for tobacco

By doing this, as a first new feature, an online calibration procedure is facilitated. Inspection of (2) and (3) shows, that frequency changes alter amplitude and phase in the same manner as layer thickness and density would do, as long as ϵ_r is approximately constant. This is the case for low microwave frequencies below 3 GHz, where $\epsilon^{'}$ of water is virtually constant and the transition from a ionic conductivity to losses from dipole relaxation keeps $\epsilon^{''}$ also frequency independent to a high degree. Plotting A over Φ then facilitates to retrieve the slope of the straight line, which is a density independent measure for moisture content. Increasing frequency results in growing dispersion of ϵ_r and hence a frequency dependence of g_1 and g_2. However, the ratio A over Φ still remains density independent and a function of moisture content. The slope of this function, although in general different from the previous solutions (5) or (8) is still usable as a measurement value for moisture content.

The new measurement procedure is illustrated by measurements on tobacco in X-band (8-12 GHz). As can be seen in Fig. 5, attenuation A and phase Φ still depend virtually linearly on frequency, although permittivity of free water shows significant dispersion in the used frequency range [6]. The slope of the straight lines versus frequency increases with growing moisture content ψ. Plotting the A-Φ-diagram therefore leads again to straight lines, as it was the case for earlier

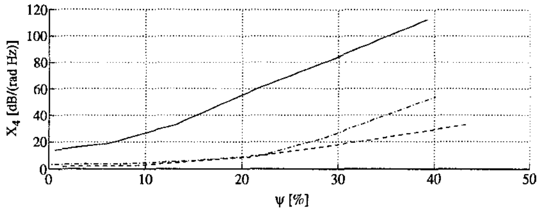

Figure 7: X_4 versus moisture contents for tobacco (- -), marjoram(- ·) and rape-seed(–)

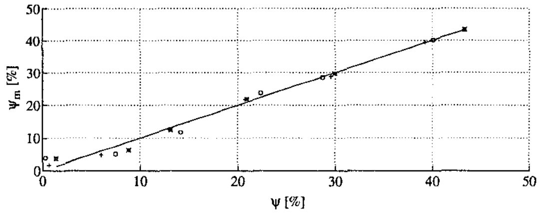

Figure 8: Measured moisture content (X_4) versus moisture contents for tobacco(o), marjoram($*$) and rape-seed($+$)

procedures. Fig. 6 shows a calibration curve

$$X_3 = \frac{\frac{\Delta A(\omega)}{\Delta\omega}}{\frac{\Delta\Phi(\omega)}{\Delta\omega}} \propto \frac{\Delta g_1(\epsilon_r(\omega))}{\Delta g_2(\epsilon_r(\omega))} \quad . \qquad (12)$$

Comparing with earlier curves (Fig. 2 and 3), a favourable improvement can be seen. The slope of this function is smoothed and the flattening at high moisture values is completely missing. This is a result of the choice of frequency range, i.e. dispersion of ϵ_r. Other functional dependence can be obtained by adjusting frequency range with respect to dispersion of $\epsilon^{'}$ and $\epsilon^{''}$, depending on the measured material. In a practical implementation the calibration curve can be fitted by a suitable function (polynomial or exponential curve), and the correlation between measurement and moisture value can be obtained by direct inversion:

$$\psi = f(X_3) \xrightarrow{e.g.} \psi = k_1 X_3^2 + k_2 X_3 + k_3 \quad . \qquad (13)$$

An evaluation according to (12) is not the only possibility, but another function can be used also. Calculating the ratio

$$X_4 = \frac{d}{d\omega}\left(\frac{A}{\Phi}\right) = \frac{A}{\Phi}\left(\frac{1}{A}\frac{dA}{d\omega} - \frac{1}{\Phi}\frac{d\Phi}{d\omega}\right) \qquad (14)$$

fulfills all the requirements with respect to density independence, but is also capable of covering high moisture values and suitable for online calibration. Related measurement results are shown in Fig. 7, and the accuracy of the procedure is further substantiated in Fig. 8, where oven values and those gained by microwaves are compared.

4 Conclusion

The presented new density independent moisture measurement procedures, which are based on collecting data versus broad frequency ranges, show various favorable features, which are important in practise:

- they are suitable for on-site calibration by the user, who only has to change moisture of the material under investigation and supply reference moisture values (for example from oven-measurements),
- measurement accuracy is improved, especially at high moisture content,
- phase measurement is greatly simplified, because of phase tracking versus frequency in contrast to estimating integral phase through a layer of material, which only can be measured in the range ±π.

5 Acknowledgement

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