MEYER AND SCHILZ FUNCTION TO ESTIMATE COMMON BEAN SEED WATER CONTENT EVALUATED BY RADIOFREQUENCY

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ABSTRACT: Derivation of density-independent dielectric functions for moisture determination in grains is important for the implementation of on-line sensors in automated driers. The object of this study was to investigate the Meyer and Schilz function [(ε'–1)/ε"] for indirect and non-destructive water content measurement of seeds of common bean by radiofrequency, where ε' and ε" are the relative permittivity and the dielectric loss factor, respectively. Samples consisted of common bean seeds variety Campeão-3 at moisture contents ranging from 11.5 to 20.6% w.b., and bulk densities from 756 to 854 kg m^{-3}, performing dielectric measurements in a room at 20 ± 1ºC and 66 ± 2% relative humidity. The model could estimate common bean seed moisture content with a standard error of the estimate, and maximum error of 0.5 and 1.0 percentage point in moisture, w.b., respectively.
Key words: dielectric properties, grain drying, bulk density, automatic control

FUNÇÃO DE MEYER E SCHILZ PARA ESTIMAR O TEOR DE ÁGUA DE SEMENTES DE FEIJÃO AVALIADO POR RADIOFREQUÊNCIA

RESUMO: A obtenção de funções dielétricas que sejam independentes da massa específica aparente para estimar o teor de água dos grãos é importante para o desenvolvimento de sensores para utilização em secadores automáticos. O objetivo do presente trabalho foi avaliar a adequabilidade da função de Meyer e Schilz, [(ε'–1)/ε"], para determinação indireta, não destrutiva e em linha do teor de água de sementes de feijão em radiofreqüências, em que ε' e ε" representam a permissividade elétrica relativa e o fator de perda dielétrica, respectivamente. Foram utilizadas amostras da variedade Campeão-3 com teor de água entre 11,5 e 20,6% b.u. e massa específica aparente no intervalo entre 756 e 854 kg m^{-3}. Todas as medições das propriedades dielétricas foram feitas em ambiente a 20 ± 1ºC e umidade relativa de 66 ± 2%. O modelo permitiu estimar o teor de água das sementes de feijão com erro padrão da estimativa e erro máximo de 0,5 e 1,0 ponto percentual, respectivamente.
Palavras-chave: propriedades dielétricas, secagem de grãos, massa específica, controle automático

INTRODUCTION

The interest in dielectric properties of grains and pulses has been increasing over the years due to the potential utilization of these properties by new technologies, such as the density-independent on-line estimation of moisture content in automatic control processes in grain harvest and drying operations. The most convenient method of reducing errors in moisture content measurement caused by fluctuations in grain mass flow rate is the derivation of density-independent dielectric models. In a previous study (Berbert et al., 2004) three methods based on the works of McFarlane (1987), Kraszewski & Kulinski (1976) and Lawrence & Nelson (1993) have been analyzed for their ability to produce dielectric models capable of estimating common bean seed moisture content continuously, and in real time. However, none of the models could estimate it with the degree of accuracy needed in automatic control operations of high-capacity drying equipments.

The method described here is an adaptation of the Meyer & Schilz (1980) microwave method for density independent determination of moisture content of granular material and involves the measurement of two dielectric parameters at a single frequency. The measuring principle was developed from considerations of the interaction of electromagnetic waves with a sample of moist material. This interaction was described using the equation defining the complex permittivity ε = ε' – jε", where j = √-1; ε' and ε" are the relative permittivity and the dielectric loss factor, respectively

The object of this research work was to investigate the Meyer and Schilz function, [(ε'–1)/ε"], for indirect and non-destructive on-line moisture content measurement of common bean seeds at radiofrequencies.

MATERIAL AND METHODS

This research work was carried out in Campos dos Goytacazes, RJ, Brazil. All dielectric property measurements have been performed using samples of common bean (*Phaseolus vulgaris* L.) seeds, variety *Campeão-3*. The moisture content of the seeds from the original lot (harvested at 24% w.b. moisture) was initially reduced to 20.6% w.b. using a fixed-bed drier operating at 28ºC. The lot was then divided into 2 kg samples, which were subsequently stored in polyethylene bags in a chamber kept at 4ºC in order to maintain the original characteristics of the seeds. To obtain samples with moisture content levels from 20.6 to 11.5% w.b., with progressive reductions of one percentage point moisture, samples were dried for different periods of time at 28ºC in an experimental thin-layer drier. After the drying treatment samples were stored in Kilner jars inside a chamber at 4ºC for at least 15 days. During the storage period the samples were revolved three times a day to allow the moisture to distribute evenly within and amongst the seeds. All electric measurements were taken in a room at 20 ± 1ºC and 66 ± 2% relative humidity.

Dielectric property measurements were taken with a 4285A HP Meter which estimates complex impedance $|Z|e^{j\theta}$ and derived parameters of inductance L, capacitance C, and resistance R components in frequencies ranging from 75 kHz to 30 MHz. The values of the two parameters that describe the complex relative permittivity of common bean seeds ε = ε' – jε'' were indirectly obtained through capacitance and conductance measurements of the capacitive sensor both empty and filled with the seed sample. All electrical measurements used the meter equivalent parallel circuit, which interprets the capacitor as part of a parallel capacitor-resistor assembly. The method employed to calculate the values of ε' and ε'' of seed samples, as well as the details of the capacitor built to hold the sample beans are described in Berbert & Stenning (1999). Moisture content determination was made on a wet basis, drying 10 g sub-samples in a forced air oven at 105ºC for 24 h.

Adaptation of the microwave method for density independent determination of moisture content described by Meyer & Schilz (1980)

The method described by Meyer & Schilz (1980) involves the measurement of two dielectric parameters at a single frequency in which a simple way of preventing the influence of the density effect on the measurements has been proposed.

A moist material generally consists of a two-phase mixture: dry matter and water. The dry matter can also be considered as an example of heterogeneous media, but in this context, it will be considered a homogeneous material, one which has a smaller effect on the electric field as compared to that of water. If temperature and frequency are kept at constant levels, the complex permittivity of a moist material is a function of its bulk density, ρ, and moisture content, M.

$$\varepsilon = \varepsilon(\rho, M) = \varepsilon'(\rho, M) - j\varepsilon''(\rho, M) \quad (1)$$

Experimental data on tobacco, instant coffee, fishmeal, wheat and barley revealed that the dependence of the complex dielectric parameters on bulk density and moisture content could be approximated by two separate functions, provided the quantity (ε' – 1) was used instead of ε'. It followed that

$$(\varepsilon' - 1) = F_1(M)\, F_2(\rho) \quad (2)$$

$$\varepsilon'' = F_3(M)\, F_4(\rho) \quad (3)$$

According to Meyer & Schilz (1980), the bulk density functions F_2 and F_4 can often be expressed by linear functions or linearly related power series, and their ratio can be approximated by a constant.

$$\frac{\varepsilon' - 1}{\varepsilon''} = \frac{F_1(M)}{F_3(M)} \frac{F_2(\rho_d)}{F_4(\rho_d)} \approx \frac{F_1(M)}{F_3(M)} \text{constant} = F_5(M) \quad (4)$$

If the assumptions for the development of F_4 are correct, $F_5(M)$ and hence the ratio [(ε' – 1)/ε"] is a material specific function, which only depends on moisture content, temperature and frequency of the applied field.

RESULTS AND DISCUSSION

The dielectric function proposed by Meyer & Schilz (1980) [(ε' – 1)/ε"] is density independent for seeds of common bean variety *Campeão-3* at moisture contents ranging from 11.5 to 20.6% w.b. and bulk densities in the range 756 to 854 kg m^{-3}. Figure 1 shows the complex plane, ε = ε' – jε", for 4 MHz, for samples of common bean seeds at 11.5, 14.2 and

20.6% w.b. moisture, and six levels of bulk density, at 20 ± 1ºC and 66 ± 2% relative humidity. Least squares best fit to experimental observations, ε” = F(ε’), resulted in straight lines with correlation coefficients close to unity. The locus of the relative permittivity e’ as a function of bulk density ρ can be represented in the complex plane by a straight line which originates at the point (1.0) for ρ = 0. Theoretically, this point represents the dielectric parameters of vacuum, i.e., ε’ = 1 and ε” = 0 (Kraus & Carver, 1973). The angle θ formed by the x-axis and any straight line representing the function ε” = F(ε’) is independent of ρ (Figure 1). Consequently the value of tanθ is also bulk density independent. However, since tanθ = [ε”/(ε’ – 1)], the function or its reciprocal are also bulk density independent for specific values of moisture content and temperature.

Curves representing the variation of [(ε’ – 1)/ε”] as a function of moisture content for seeds of common bean may be classified in three categories (Figure 2). For frequencies between 75 and 100 kHz, the curve is concave to the x-axis and may be represented by a quartic function with a correlation coefficient of 0.96. In this interval values of the Mayer and Schilz function increases from 9.1 to 10.6 when moisture increased from 11.5 to 14.2% w.b.; then they progressively decrease until a value of 6.4 is reached at 19.5% w.b. From this point on the curve becomes asyntotic with progressive increases in moisture contents.

For values of frequency between 2 and 5 MHz, the behavior of the curves is somewhat different from those observed in lower frequencies although they may still be represented by quartic functions with correlation coefficients close to unity. The curve at 5 MHz is concave upward and has its maximum value of 12.1 at 11.5% w.b. When moisture is increased to 14.2% w.b. the value of [(ε’ – 1)/ε”] falls abruptly to 8.0; if moisture is further increased from 14.2 to 20.6% w.b. the value of the function increases gradually up to 8.6.

Meyer & Schilz (1980) reported that the uniqueness of the ratio [(ε’–1)/ε”] as a function of moisture of granular materials was only attained for values of frequency above approximately 10 GHz. Nonetheless, Berbert & Stenning (1998) studying the dielectric properties of wheat seeds at radiofrequencies observed that an uniqueness of the function [(ε’ – 1)/ε”] was achieved over much lower frequencies. In the present work, analysis of the experimental results revealed that the function is not unique at any frequency from 75 kHz to 5 MHz (Figure 2). As a consequence for common bean seeds with moisture contents within the whole studied range, i.e., from 11.5 to 20.6% w.b., it is not possible to derive a unique bulk density-independent model for moisture estimation based on the Meyer and Schilz function. Thus, the most adequate way to address the problem was to investigate if there would be unique functions for smaller ranges of moisture content. At 85 kHz and 5 MHz the values of [(ε’–1)/ε”] were unique for the following moisture content (M) ranges 16.0% ≤ M ≤ 20.6% and 11.5% ≤ M < 16.0%, respectively.

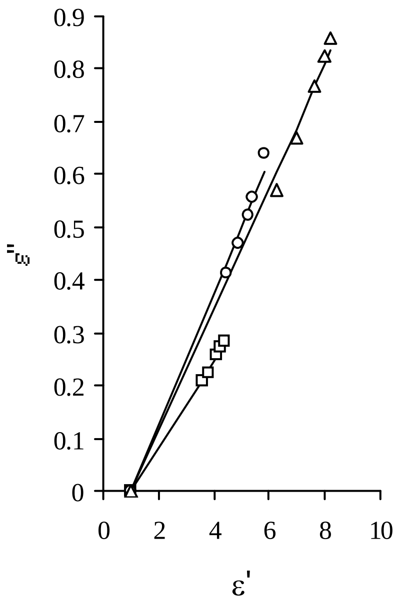

Figure 1 - Plane plot of complex permittivity of seeds of common bean variety *Campeão-3* at 4 MHz, 20 ± 1ºC and 66 ± 2% relative humidity and indicated values of moisture content. □, 11.5%; ○, 14.2%; Δ, 20.6%.

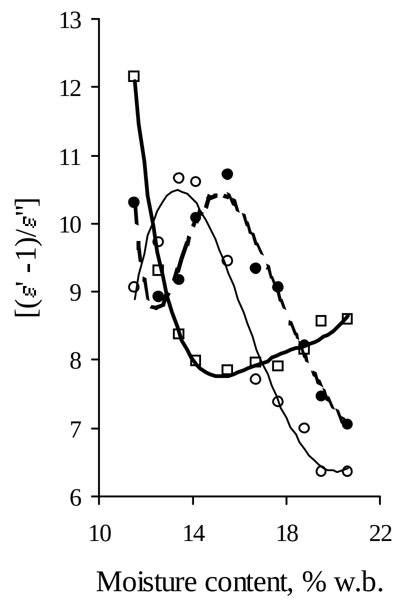

Figure 2 - Variation of [(ε’-1)/ε”] as a function of moisture content for seeds of common bean variety *Campeão-3* at 20 ± 1ºC and 66 ± 2% relative humidity and indicated values of frequency. □, 85 kHz; ●, 300 kHz; □, 5 MHz.

Although the Meyer and Schilz function at 5 MHz is unique for the moisture interval 11.5% ≤ M < 16.0% (Figure 2), it is not fully density-independent (Figure 3). Similar behavior was observed for all frequency values between 2 and 4 MHz. The straight lines presented in Figure 3 also indicate that the sensitivity of the function to moisture is greatly reduced at high moisture contents. As noted previously by Lawrence & Nelson (1993), regression lines with small negative slopes (0.003) were obtained at all moisture content levels.

The variation of [(ε'-1)/ε"] measured at 85 kHz as a function of bulk density is presented graphically in Figure 4 for samples of common bean with moisture contents in the range 11.5% to 16.0%. The Meyer and Schilz function is not density-independent, and it shows no sensitivity for variation for moistures above 19.5% w.b.

Multiple regression analysis was performed to relate moisture content (11.5% ≤ M ≤ 15.5%) to the Meyer and Schilz function measured at 5 MHz and equation (5) was obtained, with a coefficient of determination r^2 = 0.83, which was then used to estimate moisture content of samples of common bean and a standard error of estimate and a worst-case error of 0.6 and 1.2 percentage points in moisture were obtained, respectively.

$$M = 0.215\left(\frac{\varepsilon'-1}{\varepsilon''}\right)^2_{5MHZ} - 5.051\left(\frac{\varepsilon'-1}{\varepsilon''}\right)_{5MHz} + 41.044 \quad (5)$$

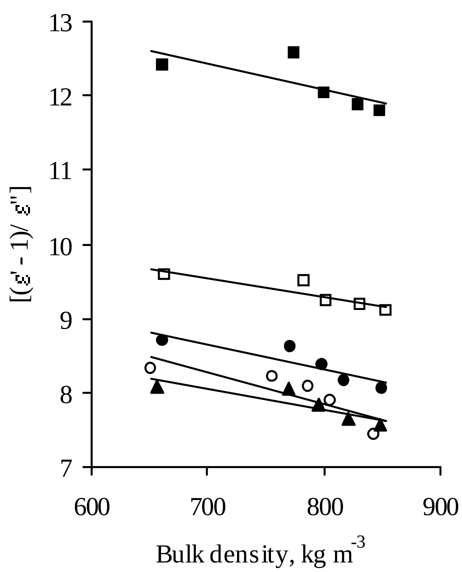

Figure 3 - Relationship between the Meyer and Schilz function, [(ε'-1)/ε"], measured at 5 MHz, and bulk density in common bean variety *Campeão-3*, at 20 ± 1ºC and 66 ± 2% relative humidity and indicated values of moisture content (% w.b.). ■, 11.5; □, 12.6; ●, 13.4; ○, 14.2; ▲, 15.5.

For moisture content values in the range 16.7% ≤ M ≤ 20.6% and values of [(ε' – 1)/ε"] measured at 85 kHz, equation (6) was obtained, with a coefficient of determination r^2 = 0.78, which is capable of estimating moisture content with a standard error of estimate and a worst-case error of 0.7 and 1.3 percentage points in moisture, respectively.

$$M = -0.336\left(\frac{\varepsilon'-1}{\varepsilon''}\right)^2_{85kHz} + 2.648\left(\frac{\varepsilon'-1}{\varepsilon''}\right)_{85kHz} + 16.635 \quad (6)$$

Equations (5) and (6) were then used to estimate the moisture content of samples of common bean seeds and the results are presented in Figure 5. The continuous line indicates ideal agreement between measured and calculated values. Although producing a worst case error of 1.3 percentage points in moisture, which is slightly above the value considered as acceptable for engineering purposes (1.0 percentage point in moisture), the resulting standard errors of estimate, 0.6 and 0.7 percentage point, indicate that the use of the method developed by Meyer & Schilz (1980) results in better estimates of the moisture content of samples of common bean seeds than the methods examined in a previous paper (Berbert et al., 2004), which produced models that could estimate common bean moisture

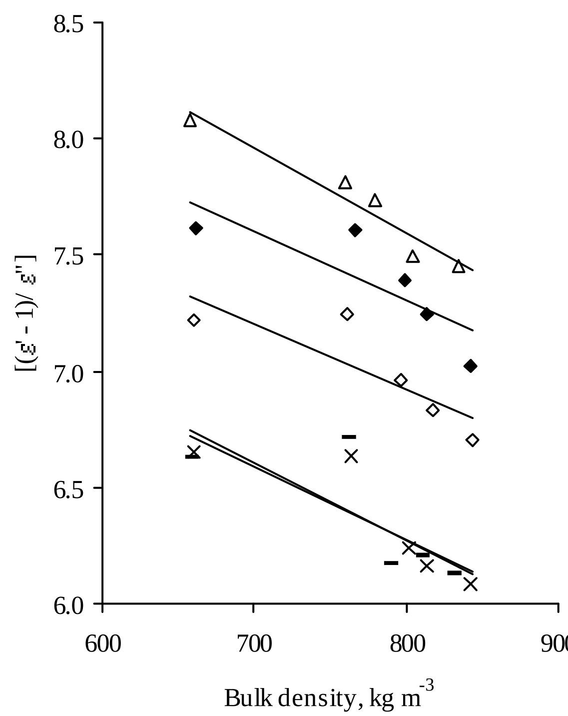

Figure 4 - Relationship between the Meyer and Schilz function, [(ε'-1)/ε"], measured at 85 kHz, and bulk density in common bean variety *Campeão-3*, at 20 ± 1ºC and 66 ± 2% relative humidity and indicated values of moisture content (% w.b.). Δ, 16.7; ◆, 17.7; ◇, 18.8; ×, 19.5; —, 20.6.

content with standard errors of estimate varying from 1.0 to 1.3 percentage points, and maximum errors ranging from 1.9 to 3.5 percentage points in moisture.

Lawrence & Nelson (1993) attempted to improve the performance of the Meyer and Schilz technique for density independent estimation of wheat moisture content using the square of the difference of the ratios [(ε' – 1)/ε"] at 1.0 and 10 MHz in combination with the natural logarithm of the loss factor at 1 MHz, which was previously shown to be a good indicator of wheat seed moisture content. Using a similar approach, multiple regression analyses were performed in the present study to relate moisture content (11.5% ≤ M ≤ 15.5%) of common bean seeds to the dielectric parameters of interest at 2 and 5 MHz, yielding equation (7) with a coefficient of determination (r^2) of 0.90. The standard error of estimate and the worst-case error were 0.5 and 1.0 percentage point in moisture, respectively.

$$M = 19.444 - 0.724\varepsilon'_{5MHz} + 3.787\ln(\varepsilon'')_{2MHz} + 3.284\Psi \quad (7)$$

where

$$\Psi = \left[\left(\frac{\varepsilon'-1}{\varepsilon''}\right)_{2MHz} - \left(\frac{\varepsilon'-1}{\varepsilon''}\right)_{5MHz}\right]^2$$

Regression analysis using dielectric data measured at 85 and 100 kHz yielded the density independent equation (8) for moistures ranging from 16.7 to 20.6% w.b., with a coefficient of determination r^2 = 0.90 and that produced a standard error of estimate and maximum error of 0.5 and 0.9 percentage point in moisture, respectively.

$$M = 26.980 - 0.923\varepsilon'_{100kHz} + 6.553\ln(\varepsilon'')_{85kHz} - 63.813\Psi' \quad (8)$$

where

$$\Psi' = \left[\left(\frac{\varepsilon'-1}{\varepsilon''}\right)_{100kHz} - \left(\frac{\varepsilon'-1}{\varepsilon''}\right)_{85kHz}\right]^2$$

The introduction of the hypothesis proposed by Lawrence & Nelson (1993) in the Meyer and Schilz function is effective in producing a dielectric model with slightly better performance in the estimation of the moisture content of common bean seeds (Figure 6).

Comparison of the results obtained in the present work with those reported by Berbert & Stenning (1998) revealed that the Meyer and Schilz function performs slightly better in terms of the indirect estimation of moisture content of wheat seeds than that of common bean seeds. The use of the function $[(\varepsilon'-1)/\varepsilon'']_{1MHz}$ allowed density-independent estimation of the moisture content of wheat seeds with a standard error of estimate and maximum error of 0.3 and 0.7, respectively. For wheat seeds the standard error of estimate is within the uncertainty related to the standard oven method itself, which could be as high as 0.3 percentage point in moisture (Kraszewski et al., 1977).

Berbert et al. (2004) analyzed the suitability of the methods proposed by Kraszewski & Kulinski (1976), McFarlane (1987) and Lawrence & Nelson (1993) for on-line estimation of common bean moisture contents, and obtained standard errors of estimate

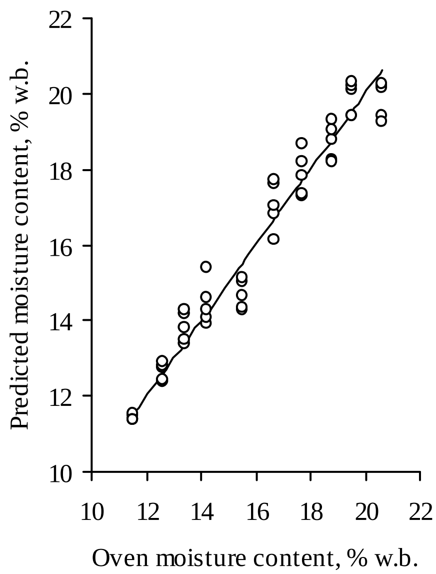

Figure 5 - Relationship between oven moisture content and moisture content predicted by Equations (5) and (6) for seeds of common bean variety *Campeão-3.*

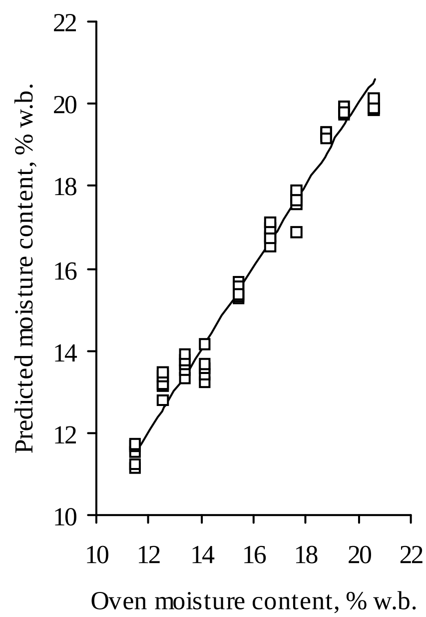

Figure 6 - Relationship between oven moisture content and moisture content predicted by Equations (7) and (8) for seeds of common bean variety *Campeão-3.*

from 1.0 to 1.3 percentage points in moisture and worst-case errors from 1.9 to 3.5 percentage points. Therefore, the errors in moisture estimation obtained with the Meyer and Schilz technique are smaller. The former methods covered a wider range of moisture content employing the same set of frequencies throughout the measurement process, while with the latter method the frequency of operation depends on the moisture interval. For samples in the range 11.5% $\leq$ M < 16.0% the dielectric parameters ε' and ε" have to be measured at 5 MHz, whereas in the range 16.0% $\leq$ M $\leq$ 20.6% the values of the function [(ε' – 1)/ε"] have to be measured at 85 kHz. There is a clear limitation in the applicability of the Meyer and Schilz function to the automatic control of the drying of common bean seeds in continuous flow driers, a situation that requires continuous assessment of the control variable being measured, i.e., moisture content.

CONCLUSIONS

The usefulness of the dielectric function [(ε'–1)/ε"] for the density-independent estimation of the moisture content of common bean seeds has been demonstrated. However, complex impedance measurements of this function at radiofrequencies in the range from 75 kHz to 5 MHz cannot be used as the basis for the development of an on-line sensor of common bean moisture content for use in the automatic control of continuous flow driers.

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