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Development of an integrated corn dryer with an indirect moisture measuring system

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Abstract. Moisture sensors are used for real-time measurement of the moisture content of seeds in modern grain dryers. The electrical properties of grains are dependent on moisture content, density, temperature and structure of materials and also on the frequency of the applied electric field. In the study, a laboratory scale dryer integrated with capacitive sensor has been developed and modeled for shelled corn. The dielectric properties of shelled corn with different moisture content have been measured to find optimal working frequency. Modeling based on the relationship between the moisture content and electrical properties of corn have been done. Changes of moisture content affect the dielectric constant of the grain, which in turn makes variation in capacitance. The dielectric properties of corn have been measured at 1 MHz frequency value. The dielectric properties of corn have been characterized using the curve fitting technique. Corn drying experiments have been carried out in the laboratory scale test installation. Model accuracy has been verified by comparison with the results of drying tests.

Keywords. Corn drying; dielectric constant; capacitive sensor; mathematical model.

1. Introduction

Corn is one of the most important food crops in the world and moisture content is the fundamental factor of affecting on safe transportation and storage. Based on the FAO data, the annual production of cereal in all over the world and Turkey is 6.000.000 and 1.148.487.291 million tons in 2018, respectively [1]. The corn plant is a tall annual grass with a stout, erect, solid stem. The kernel of corn is divided into three main parts: embryo, endosperm and carpel wall. The newly harvested corn contain between 20 and 30% moisture. Moisture content is an important parameter for determining the quality of cereal grains. Standard methods for determining grain moisture are time consuming, and fast, reliable and simultaneous test devices are still under investigation. There are many methods for moisture determination of cereal grains such as drying method, resistance method, capacitance method, microwave method and neutron method [2]. Drying industry include challenging areas for interdisciplinary research related to basic and applied natural sciences. Modern practical grain moisture devices are working according to the method of detecting the electrical features of the grain [3]. Early 20th-century research showed that grain's electrical resistance is linked to its moisture content. The first quantitative data on the permittivity of grain were reported in the 1–50 MHz frequency range [4]. The dielectric properties can be indicated by the complicated permittivity relative to free space, or complicated dielectric constant [5]. The dielectric properties are symbolized here by the relative complex permittivity $\varepsilon = \varepsilon' - j\varepsilon''$. The real part, which refers to a material's ability to store electric field energy, is expressed as the dielectric constant ε'. The imaginary part ε'', or dielectric loss factor, indicates the ability of a material to dissipate electrical energy in the form of heat [5]. In the open literature, studies have been published on grain models based on dielectric properties. It is known that the dielectric features of agricultural crop and food produce are related to the frequency, moisture content, volume density and chemical composition [6–9]. Non-destructive moisture meters have come to the fore in the control of drying systems. The electrical properties of the materials are needed for moisture meters that can be integrated into the control systems of the dryers. Sensors that associate dielectric properties with moisture can be developed and many researchers have conducted studies on different materials. Studies on macaroni and cheese by Nelson and Bartley [10]; on avocados by Wang *et al* [11]; on cherries by Wang *et al* [12]; on chicken breast by Zhuang *et al* [13]; on egg whites by Wang *et al* [14]; on various vegetables by Ozturk

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et al [15, 16]; on milk powders by Dag *et al* [17]; on banana leaves by Basyigit [18]; on cherry leaves by Dogan *et al* [19], have been reported in the open literature.

Sacılık and Colak [20] showed dielectric property of agricultural materials is an important parameter that determines the interaction of material with the electric fields. They examined the dielectric properties of corn kernels at frequencies in a range between of 1 and 100 MHz for moisture content in between 9.71 and 21.51% (dry basis) with bulk density variable between 772.5 and 902.2 kg/m^3 and concluded that the dielectric constant, loss factor and loss tangent increased by the increasing moisture content and bulk density. Zhang *et al* [21] designed a prototype sensor with a non-destructive measurement method based on correlations of dielectric properties to determine the moisture content of corn grain. They observed reliable measurements in a wide range of 12.59–36.5% moisture with detection in less than 1 second with the proposed method. It is recommended to use different sizes of electrodes to provide the wide application requirement of the study. Kumhala *et al* [22], tested the applicability of the pre-designed parallel plate capacitive sensor for determining moisture in maize. They determined that changes in maize volume density and moisture content were an important factor to be considered for capacitive sensor calibration. Independent measurement of grain moisture content can be recommended for grain with moisture content in the range from 65 to 15%. On the other hand, Trabelsi and Nelson [23], discussed principles of dielectric measurement by microwave free-space transmission measurements and the important sources of errors in such measurements. The resulting values of dielectric constant and loss factor were found to be linearly dependent on the bulk density of the granular material. Transmission, reflection, or any other measurement technique was suggested to use the permeation components. Similarly, Xu *et al* [24] designed capacitance measurement method using dielectric properties of the grain to measure the grain moisture based on differential frequency method. Results showed that the data fusion mixture of multiple parameters can develop the measuring sensitive. To remove the errors, usually the measurements must be carried out continuously. In addition, the capacitive technique has been stated by many researchers to be a basic, fast and low-cost the way that can be used to determine the moisture content of seeds and grains [25–30]. According to their results, dielectric properties differ in product type, shape, temperature, frequency, moisture content and electrical conductivity and moisture meters need to be calibrated. In the present study, a laboratory scale dryer integrated with capacitive sensor has been developed and modeled for shelled corn. The dielectric properties of shelled corn with different moisture content have been measured. Modeling according to connection between the capacitance and dielectric constant of corn have been done.

2. Material and method

2.1 *Experiments*

It is planted as a main crop in the Aegean, Mediterranean and Marmara. In the present study, the corn variety (*Zea mays indentata Sturt*. FAO 650–700) was used for experimental measurements. The initial moisture value of the corn used in the experiments was 20% (± 1%). By taking random corn kernels from the product volume, width, length and thickness measurements were made with the help of a caliper, and the averages were taken. The moisture content of the corn was determined both automatically with the digital moisture meter integrated in the dryer and manually at certain time intervals by sampling from the drying cabinet. Manually taken corn samples were placed in plastic bags for both moisture and electrical properties measurements. Three different measurements have been made, and the averages of the measurements have been taken. Then, the dielectric properties of corn samples were measured with Instek LCR-8110G brand device. Electrical properties changed with the moisture content of the corn. Five different moisture contents from 8 to 20% were targeted and samples were taken at certain time intervals during drying. Then measurements of moisture of corn samples have been carried out with Sartorius MA30 type device. Moisture content on a wet basis can be calculated by following equations;

$$MC_{wb} = \frac{M_t - M_d}{M_t} \tag{1}$$

where M_t and M_d denote total and dry mass, respectively. Three different measurements have been made, and the averages of the measurements have been taken. In the table 1, moisture content values and sizes of seeds used in dielectric measurements are presented.

2.2 *Dielectric measurements*

Granular materials are widely used both in nature and in various industries [31]. For this reason, it is particularly important in terms of both academic and industrial. Knowing the dielectric properties makes it possible to develop indirect detection methods for non-destructive determination of the water content and other physical properties of a material [32, 33]. For the methods to be effective, the dielectric properties should be measured correctly, and clear relationships must be identified between the dielectric properties and any given inner properties. This can be done theoretically or empirically experimental [5, 32, 34]. The dielectric properties of grains are the dielectric constant (ε'), dielectric loss factor (ε''), loss tangent (tan δ) and the conductivity (σ). Two of these four parameters must be measured to determine the dielectric properties of any agricultural product [35, 36].

Table 1. Corn characteristics.

Grain type	Initial moisture content % (w.b.)	Length (mm) (Average)	Width (mm) (Average)	Thickness (mm) (Average)
Corn (*Zea mays indent ata Sturt.*)	20.9	3.6	9.0	5.5
	18.1	3.7	9.4	5.9
	14.3	4.6	9.4	6.0
	11.0	4.7	10.0	6.3
	8.8	5.4	9.2	6.5

The dielectric properties are shown by the complex permittivity connected to empty space, or complex dielectric constant, $\varepsilon = \varepsilon' - j''$, where ε' is the dielectric constant, and ε'' is the dielectric loss factor [37]. Capacitance of a capacitor as C between two plates [38].

$$C = \frac{\varepsilon_0 \varepsilon' \boldsymbol{A}}{d} \tag{2}$$

where A is the area of the plate, and d is the distance between the plates [39].

The variation of dielectric coefficients at two different frequencies can be used to predict corn moisture. Using Eq. (2), the change of dielectric constants is expressed by the following equation [40].

$$\left(\varepsilon_1' - \varepsilon_2'\right) = (C_1 - C_2)\frac{d}{(\varepsilon_0 A)} \tag{3}$$

where ε_1' and ε_2' are the dielectric constants of the material at two frequencies. The capacitance difference (C_1-C_2) in Eq. (3) is an indicator of moisture in the product. The two frequencies have two parameters, the dissipation factor D and the phase angle θ. When these parameters are included, the moisture content of the product can be expressed with the help of the function below [40]:

$$MC = A_0 + A_1(C_1 - C_2) + A_2(C_1 - C_2)^2 + A_3 \left[\frac{(\theta_1 - \theta_2)}{(C_1 - C_2) + 2(D_1 - D_2)} - (C_1 - C_2)(D_1 - D_2)\right] \tag{4}$$

The air gaps in the capacitor walls are formed differently depending on the shape of the material. The radiated power represents the term in two frequencies (D_1 - D_2) depending on the change in the impedance values of the system. Considering a single frequency, the change in phase angle is negligible. In addition, the dissipation factor has a small value under low frequency conditions. Because the dielectric constant changes slightly in the low frequency range. Moisture content (w.b.) in grain products such as harvested corn is usually below 30%. There is a non-linear relationship between capacitance and moisture. At low moisture content (below 30%), the capacitance value is also low. If the capacitance has a small value in pF units, the square root term can be neglected and the MC equation has a linear equality that can be written as a logarithmic or exponential equation due to the property of a capacitor. Hence, Eq. (4) can be rewritten as follows.

$$MC = A_0 + A_1 C + A_2 C^2 \tag{5}$$

The dielectric measurements of corn samples were carried out at Sakarya University Physics Laboratory. First, corn samples were prepared to determine the electrical properties. To obtain samples with different moisture content, corn samples were dried in a laboratory oven at 105°C for different times. Then, moisture values were measured with the Sartorius moisture analyzer. Corn samples were stored in plastic containers. Then the dielectric measurements of maize shown in figure 1(a) were done with Instek LCR-8110G brand device. The corn sample was put in the medium cavity between the two plate sensors. Images precision LCR meter are shown in figures 1(b) and (c). This instrument is a device with 0.1% basic accuracy and it can operate in wide test frequency between 20 Hz ~ 10/5/1 MHz. As a result of the measurements, the change in the dielectric constant of the corn according to the moisture is shown in table 2. For a given frequency, the dielectric constant was increased with increasing moisture content, and the values matched well with preceding research results [20, 41].

These results confirmed the frequency dependence of the permeability of corn and the comparative values were reasonably consistent with previous data.

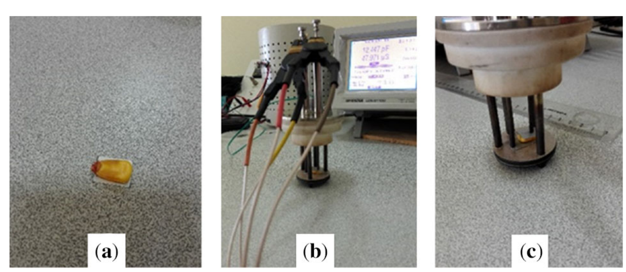

Figure 1. (**a**) Corn seed, (**b**) Instrument and (**c**) Dielectric measurement.

Table 2. The change of corn dielectric constant with moisture content (w.b.).

Current study (1 MHz, 22°C)		Ref. [20] (1 MHz, 22°C)		Ref. [41] (1 MHz, 24°C)	
$\%M_{w.b}$	ε'	$\%M_{w.b}$	ε'	$\%M_{w.b}$	ε'
20.96	9.7	21.51	9.5	20.3	7.1
18.11	5.7	18.53	5.5	16.9	5.9
14.31	4.6	15.57	4.2	14.9	5.0
11.01	4.2	12.56	3.9	13.4	4.9
8.8	3.9	9.71	3.8	11.2	4.1
				8.1	3.9

2.3 *An indirect moisture measuring system*

During drying, the most important problem is to control the parameters of the dryer such as temperature, air velocity, and discharge speed to achieve the desired drying performance. Within the scope of this work, a laboratory scale model of a tower type grain dryer was manufactured. A Silosense brand capacitive grain moisture meter was integrated into the dryer to control the dryer. Dielectric properties depend on variables such as grain type, moisture, frequency, temperature and moisture meters need to be calibrated.

During the drying experiments, the drying air flowing in a single direction is moistened and passes between the grains. Its temperature is decreasing from inlet temperature (≅ 105°C) to outlet temperature (≅ 45°C). The ambient temperature, at which the capacitive grain moisture meter measures, varies between 60 and 80°C during the drying period.

Measurements were taken with the voltage level set to 3.3 V. An E-server interface converter was used to provide a direct interface connection from TCP-IP to an Ethernet computer port. Data collected automatically using the e-server interface. The Silosense capacitive moisture sensor is shown in figures 2(a) and (b) and block diagram of the hardware of the corn moisture measurement system is demonstrated in figure 3.

The capacitance value measured in analog form is converted into digital data by ADC (Analog to digital converter). Digital data pre-filtering is done with the CPU (Central Processing Unit). After filtering, data is sent via RS485 (Modbus communication) and displayed on the DOP (Operator touchscreen panel). Data is sent to the PC for recording via the Ethernet tool. In addition, automation control is used by sending it to PLC (Programmable logic controller).

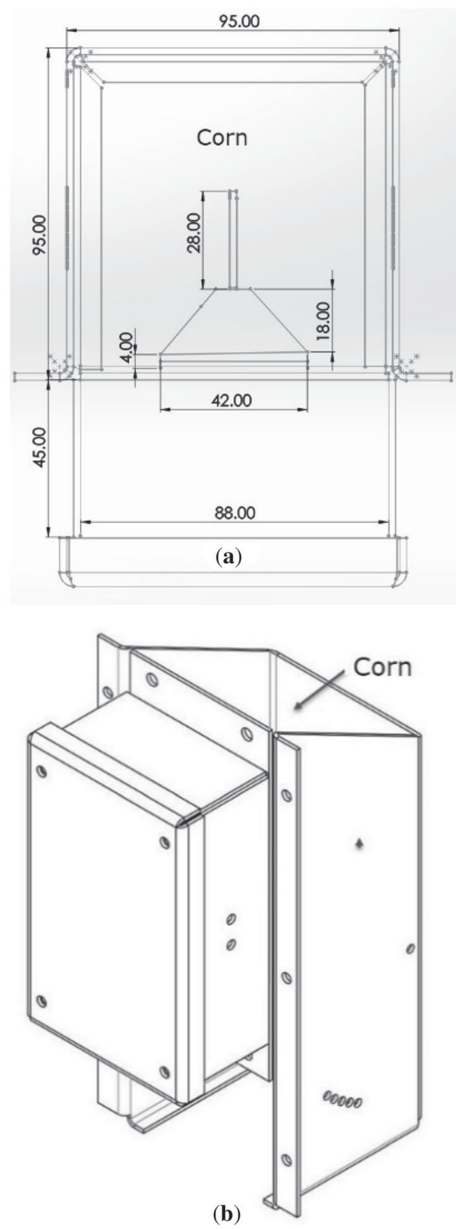

Figure 2. (**a**) Sectional and (**b**) Perspective view of the capacitive sensor for dielectric measurements on corn (Distance measurements are made in mm).

2.4 *Drying experiments*

A laboratory scale grain dryer is shown in figure 4. Drying experiments are carried out at 101°C inlet gas temperature. The laboratory scale dryer is consisted of following main

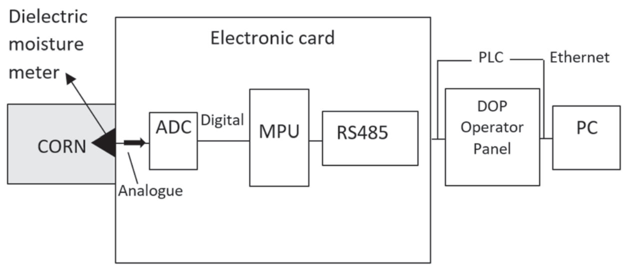

Figure 3. Measurement system structure diagram.

Table 3. Test conditions and measurement results average value.

Test conditions	Values
Capacity/kg	90
Initial moisture content (wet basis)%	26.7
Unprocessed grain temperature/°C	17.3
Ambient temperature/°C	17.1
Relative humidity of ambient/%	65
Fan flow/$m^3 min^{-1}$	1–3
Hot air temperature/°C	90–110
Fuel	LPG

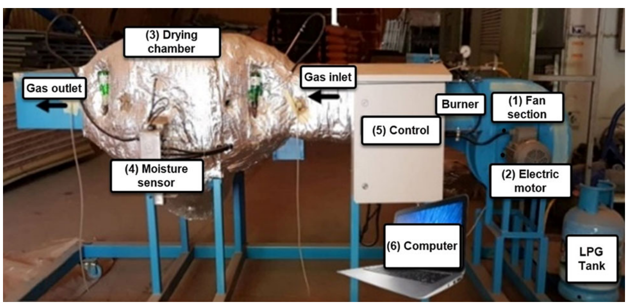

Figure 4. Laboratory scale grain dryer.

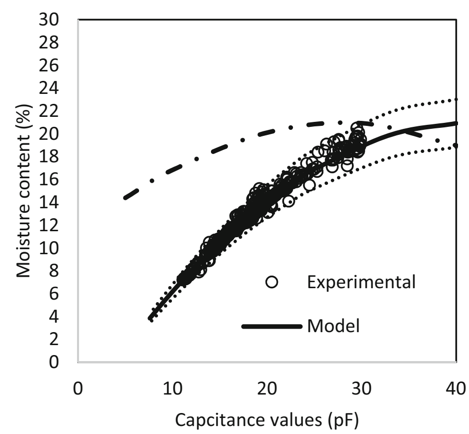

Figure 5. Plot of corn moisture content versus capacitance (The continuous line (-) is the model curve from the current study; dotted lines (…) are lower and upper error bounds; dash-dot line (-.-) is the model curve proposed by *Zhang et a*l [42]).

components; (1) fan section, (2) electric motor, (3) drying chamber, (4) capacitance sensor (dielectric moisture meter), (5) control panel and (6) computer. The capacitance sensor consisted of two metal plates 2 mm thick and 800 mm long and 300 mm wide.

The capacitive throughput sensor and the whole oscillating circuit ran at 1 MHz corn sample is placed inside the container. This frequency was chosen based on our previous experimentation on capacitive measurements with the purpose to minimize reduce the impact of surrounding effects. The laboratory setup consisted of a cabinet with a sensor equipped with an electronic measuring device to move the measured amount of material through a capacitance. The capacitance of circuit elements was calculated according to Eqs. (2) -(5). Microsoft Excel was used for data analyses and to characterize the regression models between capacitance and moisture content values. Test conditions in the drying process are given in table 3.

3. Results and discussion

Corn was dried from 21% (w.b.) moisture content to 7% (w.b.) in the grain dryer. Capacitance of samples were measured to determine moisture contents. The variation of moisture content with the measured capacitance values is given in figure 5. It was observed that there was an exponential relationship between moisture content and capacitance values. The dashed lines in the figure indicate the lower and upper bounds (±10%). The mathematical model (Eq. 6) that gives the relationship between moisture content (MC) and capacitance (C) was found as a quadratic function as follows:

$$\boldsymbol{MC} = -0.015C^2 + 1.2408C - 4.7063 \quad (6)$$

Here, the values of A_0, A_1 and A_2 were equal in − 4.7063, 1.2408 and − 0.015, respectively.

As seen in figure 5, capacitance values decreased with decreasing corn moisture content. As the moisture content of corn increased, the dielectric constants increased too. Similar results supporting this behavior are reported in the open literature. Zhang *et al* [42] conducted a moisture content measurement study of corn based on the cylindrical capacitive sensor principle. They examined the relationship between capacitance and moisture content. They calculated the capacitance measurement of the sensor by measuring the voltage. Based on experimental data, they obtained the binary cubic equation by using the least squares method for the relationship between capacitances and moisture. Capacitance values increased as humidity values increased.

They found an equation y=−0.000054149x^3−0.0089798x^2+0.63413x+11.4539. With the help of this equation, the expected moisture content values were calculated using the capacitance values and shown in figure 5. As seen in figure, there was no similarity between the data. Also, Firouz and Alimardani [43] designed sensor based on cylindrical capacitive method. They used five frequencies (1 kHz, 10 kHz, 100 kHz, 500 kHz and 1 MHz) for selected moisture contents. They investigated the relationship between the frequency-dependent dielectric constant and moisture content. Also they reported that as the frequency increased, the dielectric constant and moisture content graph were regular. They derived the homographic function equation for the dielectric constant depending on the moisture content of corn. They expressed the relationship between dielectric constants and moisture content with a quadratic equation y = − 0.005x2+ 0.202x + 4.447. It was observed that the data obtained from this equation did not match the data obtained in the current study (table 2). However, the relationships between reported capacitance, product moisture changes, and dielectric coefficients data were similar. The reasons are: the differences in product amount, material type, material moisture, gap between two capacitors, are applied frequency, temperature and voltage.

The comparison of the experimental data obtained from the corn dryer with the model results was made in figure 6. It can be seen that the predicted data agreed well with the experimental data. In this study, we found that the data obtained with the digital moisture meter have a similar distribution and scatter in a certain range as reported in previous studies. Deviations in moisture data are expected when drying granular products such as cereals. Since the grains are not exactly the same, the moisture content of each is close to each other, but not equal.

The drying air flowing in a single direction is moistened and passes between the grains, and therefore the drying environment to which the grain is exposed can be variable.

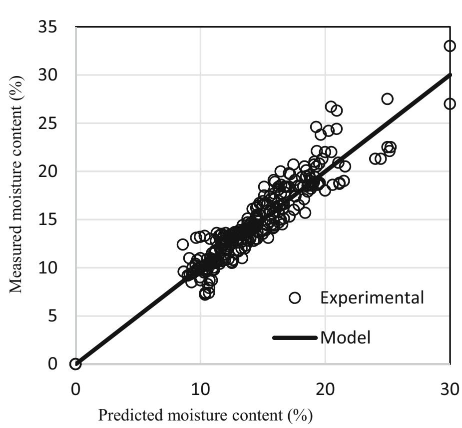

Figure 6. The comparison of the experimental data with the model results.

This causes values to scatter, but does not affect the moisture content estimate. Drying tests were repeated approximately fifteen times under the same conditions. The standard deviations of the data obtained for each test were calculated. It was seen that the data were clustered around the arithmetic mean. When the moisture content values of corn exceeds 19%, the digital moisture meter measures with an error value of ∓ 3.2. At lower moisture content, the error values gradually decrease, with an error value of ∓ 1.8 between 10% and 19% (w.b). The accuracy of the device has been proven with the measurement data corresponding to different moisture content in the drying experiments. These data are shown in figures 5 and 6.

4. Conclusion

A laboratory scale dryer integrated with capacitive moisture sensor has been developed for shelled corn. The dielectric properties of shelled corn with different moisture content have been measured by precision LCR meter at different frequency values. The measured values agreed with the data reported in the open literature. Drying experiments were conducted in a laboratory scale dryer. Time-dependent corn moisture values were measured separately with the capacitive moisture meter integrated in the dryer, as well as the laboratory type moisture analyzer. The measurement data obtained were analyzed comparatively. The mathematical model that gives the relationship between moisture content (MC) and capacitance (C) was found as a quadratic equation $\boldsymbol{C} = -0.015C^2 + 1.2408C - 4.7063$. It was desired to investigate the change in capacitance of corn as a function of moisture content. The relationship between capacitance and moisture content was inferred. The third-degree polynomial equations defining the relationship between capacitance and moisture content were found to be correct sufficiently for predicting the dielectric constant of corn. The results were obtained as expected. When the moisture content changed, the capacitance changed as a homographic function. With this method, the moisture content of grains can be reliably estimated. The electrical properties of the cereal grain vary according to the frequency of the applied electric field, the moisture content of the product, their temperature, and their bulk density. The link between frequency and humidity has been used for many years in research. Capacitance values measured at these frequencies show promise for detecting moisture content. The commercial development of grain capacitance moisture meters can be expected to increase their reliability and utility in the grain industries. In this study, data that can be useful to researchers working on product capacitive moisture meters was obtained. In our future studies, it is proposed to reveal the capacitance relationship of moisture meters integrated on the dryer at different operating temperatures.

List of symbols

A Area of the plate, m^2
C Capacitance of the capacitor filled with sample, pF
C0 Capacitance of the empty capacitor, pF
d Distances between the plates, m
f Frequency, Hz
θ Phase angle, °
δ Loss tangent, $\varepsilon''/\varepsilon'$
ε' The real part of the complex dielectric constant, pF/m
ε'' Imaginary part of the complex dielectric constant, pF/m
ε^* Complex dielectric constant, $\varepsilon' - j\,\varepsilon''$
ε0 Permeability of free space, 8854×10^{-12}
σ Conductivity, S/Ohm^{-1}
MC Moisture content, % w.b

Subscript

t Total
w.b. Wet base
d Dry

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