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Capacitive Online Corn Moisture Content Sensor Considering Porosity Distributions: Modeling, Design, and Experiments

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Abstract: An online corn moisture content measurement device would be a key technology for providing accurate feedback information for industrial drying processes to enable the dynamic tracking and closed-loop control of the process. To overcome the problem of large measurement error caused by the characteristics of the corn flow state and the pore distribution when a parallel plate capacitor is applied to the online moisture content measurement process, in this study, we summarized the constraint conditions of the sensor's structure parameters by mathematical modeling and calculated the optimal sensor design size. Moreover, the influence of porosity variation on moisture content measurement was studied by using the designed sensor. In addition, a mathematical model for calculating corn moisture content was obtained for the moisture content range of 14.7% to 26.4% w.b., temperature of 5 °C to 35 °C, and porosity of 38.4% to 44.6%. The results indicated that the fluctuation in the online moisture content measurement value was obviously reduced after the porosity compensation. The absolute error of the measured moisture content value was −0.62 to 0.67% w.b., and the average of absolute values of error was 0.32% w.b. The main results provide a theoretical basis and technical support for the development of intelligent industrial grain–drying equipment.

Keywords: corn; moisture sensor; online measurement; industrial drying; porosity

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1. Introduction

Industrial corn drying plays an important role in improving grain storage, inhibiting the growth of pests and microorganisms, increasing product storage period, and reducing transportation costs [1,2]. In recent years, the method used to control industrial corn dryers have entered the stage of intelligent control with the development of computer control technology and artificial intelligence [3,4]. To realize the intelligent control of the grain drying process, modeling the complex drying system with an artificial intelligence algorithm in combination with modern control technology might help to effectively construct an intelligent predictive controller [5]. However, an online corn moisture content measurement device is necessary to provide accurate data samples for establishing a data-driven model of the drying process and for providing accurate feedback information for the dryer controller. Therefore, an in-depth study of online corn moisture content sensor is vital to improving the intelligent control theory of grain drying and to developing intelligent control technology.

In recent years, for the moisture content measurement of agricultural products, researchers have developed a variety of static measurement instruments with high measurement accuracy based on optical [6,7], nuclear [8], hygrometric [9], and dielectric methods [10–12]. However, due to the difference in drying parameters, environmental conditions, material properties, and development costs, the most practical method is an electronic online measurement device based on the resistance and capacitance properties of materials [13,14]. Due to the shape of a corn kernel being flat or nearly spherical, the moisture content of different parts in a single kernel varies widely, and water diffusion occurs from the endosperm to the embryo during the drying process [15]. Thus, it is difficult to develop a high-precision online measurement device based on the resistance characteristics of a single grain given the difference in the texture and the dynamic change in the moisture distribution in a single kernel.

Since Nelson's research in 1977, [16] showed that a strong correlation exists between grain's dielectric properties and moisture content, various practical applications of moisture content measurement of agricultural products based on their dielectric properties have emerged, such as for flaxseed [17], safflower seeds [18], meat [19], date [20], and hazelnut [21]. The capacitive sensor is a low-cost and easy-to-use method to detect some features of agricultural products according to their dielectric properties. The parallel plate capacitor, designed based on the capacitance method, is a classic and mature application of the capacitance method. For decades, this type of sensor was widely used in quality measurement (especially moisture content measurement) of some agricultural products, having acceptable accuracy. In the grain drying process, a moisture sensor based on the parallel plate structure can accurately and quickly reflect the average moisture content in the drying layer.

Porosity is an essential physical parameter that is related to the shape, filling method, size, and distribution of the material; moisture content; storage time; motion state; and many other factors [22]. Considering the porosity change caused by the objective conditions of the drying process, such as the mechanical properties of the grain and the flow characteristics caused by the filling method, the online moisture content measurement devices based on capacitance method still have some defects, such as low precision and poor stability. In the industrial corn drying process, some complex factors, such as the flow of corn [23], harsh external environment [24], and impurities [25], lead to changes in the porosity in the measurement cavity. Given the complex process of corn drying, a researcher should not only consider the traditional sensor design index, such as range, resolution, and measure precision, but also the factors causing interference due to the objective conditions of the drying process such as the mechanical properties of the corn and the flow characteristics caused by the filling method. In addition, applications in actual drying sites are still unreliable. Therefore, it is necessary to consider the influence of porosity when designing a capacitive online moisture content sensor to be applied in the drying process.

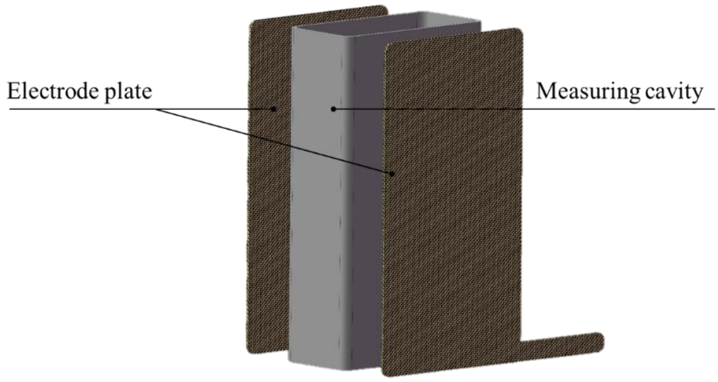
Based on the above considerations, the objectives of this study were: (1) to summarize the constraint conditions of a sensor's structure parameters by mathematical modeling and to calculate the optimal size of a sensor; (2) to reveal the effects of porosity on the capacitance characteristics of the filling layer through designing a multiple–factor experiment and to obtain the mathematical model calculating corn moisture content. The novelty aspect of this study is that the porosity, which is a basic physical parameter of agricultural materials, was unified and quantified to establish the characteristic function to fully characterize the proportion relations of all phase system components (i.e., air and corn) of the filling layer to identify the path optimizing moisture content measurement technology in the industrial corn drying process.

2. Materials and Methods

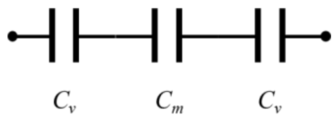
2.1. Modeling

2.1.1. Theory Consideration

The relatively mature corn online moisture content sensor is generally a parallel plate capacitor designed based on the dielectric properties of materials, and its structure is modeled in Figure 1a. The measuring cavity is composed of insulating material, the metal plate placed on the outer wall of the cavity is an electrode plate, and the cavity is filled with corn to be measured. The structure shown in Figure 1a is equivalent to a series capacitance model when the edge effect of the capacitance sensor is ignored, as shown in Figure 1b.



(a)



(b)

Figure 1. Model of a parallel plate capacitor sensor: (**a**) the original model and (**b**) the equivalent model.

When the corn reaches the state to be measured in the measurement cavity, the output capacitance (C) of sensor is:

$$C = \frac{S\varepsilon_0\varepsilon_m}{d}, \tag{1}$$

where ε_0 is the vacuum dielectric constant, which is 8.85 pF/m [22]; ε_m is the relative dielectric constant of the corn; d is the distance between the two parallel plates; and S is the area of plate. The medium between two plates included dry matter, water, and air. The total volume (V) and the total relative dielectric constant (ε_m) of above three can be expressed, respectively, as:

$$V = V_1 + V_2 + V_3, \tag{2}$$

$$\varepsilon_m = \frac{V_1}{V}\varepsilon_1 + \frac{V_2}{V}\varepsilon_2 + \frac{V_3}{V}\varepsilon_3, \tag{3}$$

where V_1, V_2, and V_3 are the volume of dry matter, water, and air, respectively; ε_1, ε_2, and ε_3 the relative dielectric constant of these three, respectively. Substituting Equation (3) into Equation (1), the Equation (4) can be obtained:

$$C = \frac{S\varepsilon_0}{d}\left(\frac{V_1}{V}\varepsilon_1 + \frac{V_2}{V}\varepsilon_2 + \frac{V_3}{V}\varepsilon_3\right) \tag{4}$$

The porosity of the filling layer in the measurement cavity is calculated using Equation (5):

$$p = \frac{V_3}{V} \tag{5}$$

The moisture content of corn feeding into the measurement cavity is calculated as:

$$M_d = \frac{\rho_2 V_2}{\rho_1 V_2}, \tag{6}$$

where M_d is the moisture content, dry basis, and ρ_1 and ρ_2 are the density of water and dry matter, respectively.

Defining K_1, and K_2 as follows, and substituting Equations (5) and (6) into Equation (4), the Equation (9) can be obtained:

$$K_1 = \frac{\rho_1}{\rho_2}, \tag{7}$$

$$K_2 = \frac{V\rho_1}{G}, \tag{8}$$

$$C = \frac{\varepsilon_1 + K_1 M_d \varepsilon_2}{1 + K_1 M_d + (1 + Md) K_2 p} + \varepsilon\varepsilon_3, \tag{9}$$

where G is the total mass of corn filled into the measurement cavity, which generally changed little and can be regarded as a constant value under the constraint of the determined installation position of the level sensor. According to Equation (9), the output capacitance of sensor is mainly related to M_d, p, ε_1, ε_2, ε_3, ρ_1, ρ_2, V, and G. Among the above parameters, V, ρ_2, and G were the determined constants; ρ_1 is a function depending on M_d [22]; and ε_1, ε_2, and ε_3 are also related to temperature T. Therefore, the feedback capacitance value of the sensor in practical application is a function depending on Md, p, and t. However, the porosity in Equation (9), which is not only affected by the air volume among grains but also by the air volume inside grains [23], is one of the important factors affecting the dielectric properties of materials, especially in online moisture content measurement devices installed to monitor the extremely complex process of industrial corn drying.

2.1.2. Mathematical Modeling

Based on the series capacitance calculation method, Equations (10) and (11) were obtained for calculating the corn capacitance and the capacitance of the cavity outer wall, respectively:

$$C_m = \frac{\varepsilon_0 \varepsilon_m S}{y_m}, \tag{10}$$

$$C_c = \frac{\varepsilon_0 \varepsilon_c S}{y_c}, \tag{11}$$

where C_m and C_c are the capacitance of the corn and outer wall, respectively; ε_m and ε_c are the dielectric constant of the corn and outer wall, respectively; and y_m and y_c are the thickness of corn and outer wall, respectively. Therefore, the total capacitance to be measured is the sum of the series capacitance, which can be calculated using Equation (12):

$$C_{tot} = \frac{\varepsilon_0 \varepsilon_m \varepsilon_c S}{2\varepsilon_m y_c + \varepsilon_c y_m}, \tag{12}$$

where C_{tot} is the total capacitance value of the series capacitance to be measured.

Equation (12) shows that the measured capacitance is only related to the relative dielectric constant, which corresponds to the moisture content one-by-one under the determined electric field frequency, corn porosity, and temperature. Thus, Equation (13) can be obtained:

$$C_{tot} = f(M), \tag{13}$$

where M is the moisture content of the corn to be measured, in wet basis. Equation (14) can be obtained by differentiating Equation (13):

$$\frac{dC_{tot}}{dM} = \frac{\varepsilon_0 \varepsilon_c^2 S y_m}{(2\varepsilon_m y_c + \varepsilon_c y_m)^2} \cdot \frac{d\varepsilon_m}{dM} \tag{14}$$

A relationship exists between the resolution of the capacitance measurement circuit and the resolution of the moisture sensor, as shown in Equation (15):

$$\frac{R_c}{R_m} = \frac{dC}{d\varepsilon_m} \cdot \frac{d\varepsilon_m}{dM} = \frac{dC}{dM}, \tag{15}$$

where R_C and R_m are the resolution of the capacitance measurement circuit and moisture sensor, respectively. Assuming the change rate of the corn dielectric constant with moisture content was K, the full-range resolution of the moisture sensor, as shown in Equation (16), can be obtained from Equation (14):

$$R_m = \frac{R_c}{K} \cdot \frac{(2\varepsilon_m y_c + \varepsilon_c y_m)^2}{\varepsilon_0 \varepsilon_c^2 S y_m} \tag{16}$$

From Equation (16), when the corn dielectric constant changes little with the moisture content, the resolution of moisture sensor decreases with decreasing moisture content. Therefore, in the process of designing a sensor, it is necessary to ensure that the measurement near the safe moisture content meets the minimum resolution requirements.

On the other side, due to the internal friction of corn, the corn gradually forms a cone in the process of flowing into measurement cavity. Thus, the chamber will not be filled with corn with an unreasonable sensor structure design, as shown in Figure 2a.

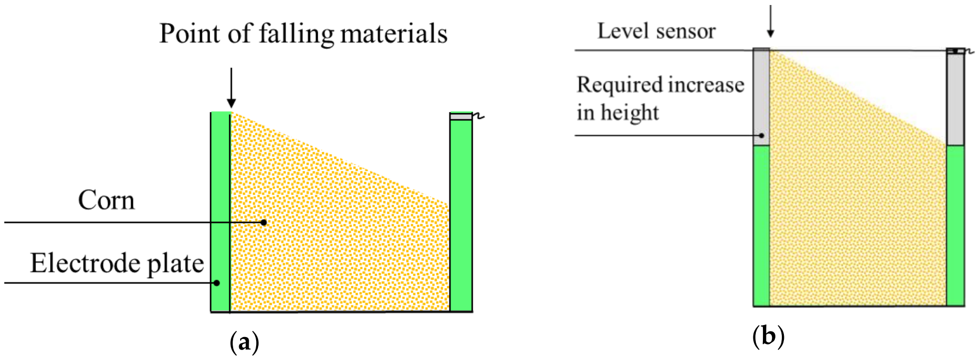


Figure 2. Improvement in moisture sensor: (**a**) underfilling of corn and (**b**) scheme for increasing chamber height.

However, the level sensor still judges that the chamber is full of corn at this time, which causes measurement error. Increasing the height of the cavity can cover the measurement area with corn. When the grain filling method is determined, grain with same moisture content has the same repose angle. Therefore, when the material's falling point is at the top of measurement cavity, as shown in Figure 2b, the required increase in height has the largest value, which should satisfy Equation (17):

$$\Delta z \geq \Delta z_{\max} = \sqrt{x_m^2 + y_m^2} \cdot \tan(\alpha_{\max}), \tag{17}$$

where Δz is the required increase in height, x_m is the width of parallel plate, and α is the repose angle. Based on the mathematical relationship, when x_m is equal to y_m, the minimum value of Δz is obtained, and the structure of the designed sensor is the most compact. Thus, the height and the required increase in height of cavity can be calculated using Equations (18) and (19), respectively:

$$z_m = \frac{V - \sqrt{2} y_m^3 \cdot \tan(\alpha_{\max})}{y^2}, \tag{18}$$

$$\Delta z = \sqrt{2} y_m \cdot \tan(\alpha_{\max}) \tag{19}$$

To summarize, the constraint conditions of the moisture sensor's structural parameters are as follows:

$$\begin{cases} \frac{\varepsilon_0(\varepsilon_m)_{\max}\varepsilon_c S}{2(\varepsilon_m)_{\max}y_c+\varepsilon_c y_m} - \frac{\varepsilon_0(\varepsilon_m)_{\min}\varepsilon_c S}{2(\varepsilon_m)_{\min}y_c+\varepsilon_c y_m} < C_{dy} \\ \frac{\varepsilon_0(\varepsilon_m)_{\max}\varepsilon_c S}{2(\varepsilon_m)_{\max}y_c+\varepsilon_c y_m} < C_{\max} \\ \frac{\varepsilon_0(\varepsilon_m)_{\min}\varepsilon_c S}{2(\varepsilon_m)_{\min}y_c+\varepsilon_c y_m} > C_{\min} \\ R_m \geq \frac{R_c}{K} \cdot \frac{(2\varepsilon_m y_c+\varepsilon_c y_m)^2}{\varepsilon_0\varepsilon_c^2 S y_m} \\ \min(x_m, y_m, z_m) > L \\ y_v > \delta \\ x_m = y_m \\ z_m = \frac{V-\sqrt{2}y_m^3\cdot\tan(\alpha_{\max})}{y^2} \end{cases}, \quad (20)$$

where C_{dy} is the measurable dynamic capacitance range of the measurement circuit, [$C_{\max}$, $C_{\max}$] is the measurable statistic capacitance range, L is the corn bridge size, and δ is the minimum safe thickness of the measurement cavity.

2.2. Experiments

Three experiments needed to be conducted, including one lab experiment and two field experiments. The purpose of field experiment was to calibrate the moisture content calculation equation (without considering the porosity distributions), and then observe the influence of filling layer porosity on the measurement accuracy. The purpose of lab experiment was to calibrate the calculation equation of moisture content considering the porosity distributions. Finally, the accuracy of the calibrated model was verified by field experiment.

2.2.1. Sample Preparation

The fresh corn used in this study was a native variety named Changcheng 799#, which was obtained from Zhencheng Farm in Xinzhou Shanxi Province, China. The average initial moisture content was 27.9% w.b. measured using an air convection oven (Model DHG070B, Shanghai Anting Scientific Instrument Factory, Shanghai, China) according to the standard oven method [13]. The impurities and broken grains of corn to be dried were filtered through a filter screen and an air separator before entering the dryer, and the impurity content was less than 1%. The fresh corn was dried to achieve the different target moisture content necessary for the lab experiment [23].

2.2.2. Experimental Apparatus and Method

The capacitance sensor used in this study was a parallel plate capacitor manufactured according to the design example in Section 2.1, and the capacitance was measured by the designed measurement circuit board. The calibration experiment of the field experiment was also conducted at Zhencheng Farm. The target moisture content of corn drying was 14.5% w.b. The online moisture measurement device equipped with the capacitance sensor was installed between the grain discharge bucket and the elevator bucket of 5HP-50 double tower dryer, as shown in Figure 3. The corn was let out of the dryer through the grain discharge bucket, and flowed into the measurement device by free falling. After the measurement, the corn was discharged from the bottom into the elevator bucket to recover the material. The corn in each position of the drying bed was collected in a discharge bucket, which represented the average discharging grain state. The samples collected here reflected the overall drying process. A few corns were sampled manually at grain outlet of the online moisture content measurement device every 30 min. The corn temperature was measured using an infrared thermometer (Model: MT4 MAX, −30 °C to 350 °C, accuracy 0.1 °C, Fluke Testing Instruments (Shanghai) Co., Ltd., Shanghai, China).

Figure 3. Installation position of the online moisture content device in the drying process.

In the lab experiment, the porosity of the experimental sample was measured using a self-developed porosimeter, as shown in Figure 4. The relevant indicators of the porosimeter are provided in the paper by Li et al. [26]. The capacitor was placed into the measuring chamber of the porosimeter to measure the porosity of the capacitor without corn filling. Then, the capacitor was filled with the corn sample using a free-falling style at a certain height. The corn porosity was changed by applying different pressures to the upper surface of the capacitor. The excess sample was scraped off with a scraper to ensure constant volume filling. Finally, the porosity of the sample was calculated using Equation (21):

$$p = p_t + p_0 - \frac{V_c - V_0}{V_c} - 1, \tag{21}$$

where p is the porosity of corn sample, p_0 is the porosity of the capacitor without material filling, p_t is the porosity of the capacitor material filling, V_c was the chamber volume of the porosimeter, and V_0 is the volume of the capacitor.

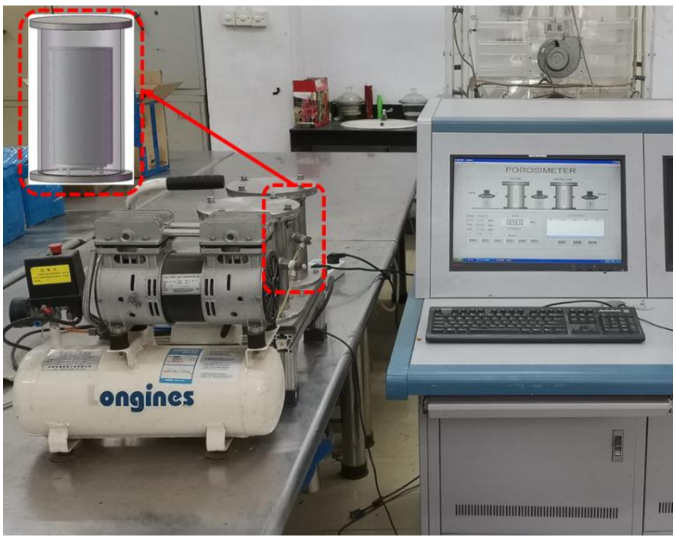


Figure 4. Experimental apparatus for measuring the porosity.

3. Results and Discussion

3.1. Sensor Design

A high-precision and high-reliability capacitance digital conversion chip AD7793 (Analog Devices, Inc., Norwood, MA, USA) featuring a 32 kHZ working excitation frequency, a measurable dynamic capacitance range of −4 to 4 pF, and a minimum resolution of 0.004 pF was adopted as the core of the circuit [27]. The maximum measurable capacitance can be expanded by configuring the offset capacitance (for example, when the offset capacitance is 17 pF, the measurable range is 13 to 21 pF and the maximum measurable capacitance is 21 pF). In addition, the change in the equation of the dielectric constant with corn moisture content can be obtained by fitting the experimental data of the corn dielectric constant with moisture content at a 32 kHZ frequency according to Song et al. [28]:

$$\varepsilon_m = 3.467M - 44.582\left(R^2 = 0.989\right) \tag{22}$$

In this study, the proposed sensor had a measurement range of 0% to35% w.b. and a resolution of 0.1% w.b. To shorten the feeding and discharging period to ensure rapid measurement, a small amount of corn sample (about 600 g) should be filled. Thus, according to the calculation function of corn bulk density [29], the calculated total volume of the sensor to be designed was 0.0007 m^3. Moreover, according to the relative research [22], the corn repose angle is supposed to be 35°. In addition, the cavity was composed of PVC insulating plastic with a dielectric constant of four. Therefore, when the filling corn moisture content was 35% w.b., the distribution nephogram of the sensor capacitance with the thickness of the material and the thickness of the cavity wall was obtained by calculating the above parameters and solving Equation (20), as shown in Figure 5.

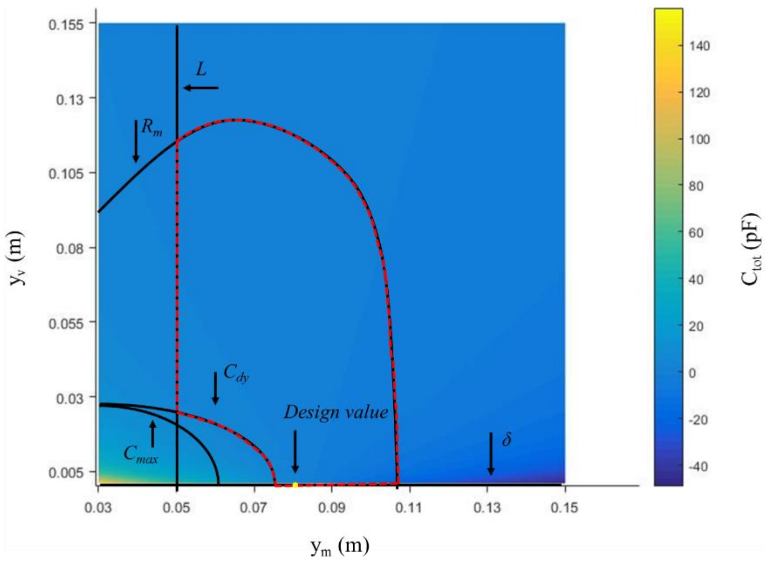


Figure 5. The distribution nephogram of sensor capacitance under different corn thicknesses and cavity wall thicknesses. Note: the filling corn moisture content was 35% w.b.

Figure 5 shows the sensor capacitance decreased rapidly with the increasing thickness of the corn and increasing thickness of the cavity wall, and the influence of the thickness of the cavity wall on the capacitance is more significant. Therefore, the thickness of the cavity wall is also an important parameter when considering the appropriate plate spacing in the process of designing a parallel plate capacitance sensor. In addition, $C_{\max}$ is the maximum measurable capacitance isoline, that is, the maximum capacitance value under the constraints of the capacitance measurement circuit described above, and the measurable region is above the curve. R_m is the isoline whose resolution is less than 0.1% w.b. when the corn moisture content is 10% w.b., and the measurement resolution in the area under the curve met the design requirements. C_{dy} indicates the capacitance range of isoline, that is, when the size of the sensor on the line is selected, the difference between the maximum capacitance and the minimum capacitance is the maximum measurable dynamic capacitance range of the measurement circuit (8 pF). In addition, considering the requirements regarding mechanical strength and smooth corn flow, the sensor's minimum plate spacing (L) should be no less than 50 mm, and the minimum thickness of cavity wall (δ) should be no less than 2 mm, as shown in the corresponding mark in Figure 5. Based on the above discussion, the area enclosed by the red dotted line in Figure 5 is the dimension point meeting the design requirements. For the measurement circuit to be full scale at the maximum moisture content, the dimension point should be close to C_{dy}. In this study, the point pointed by the design value in Figure 5 was selected as the actual sensor size, corresponding to $x_m = y_m = 80$ mm, $z_m = 31$ mm, and $\Delta_z = 79$ mm. The sensor structure is shown in Figure 6. with this sensor structure and size, the measured capacitance range was 0.17 to 8.17 pF.

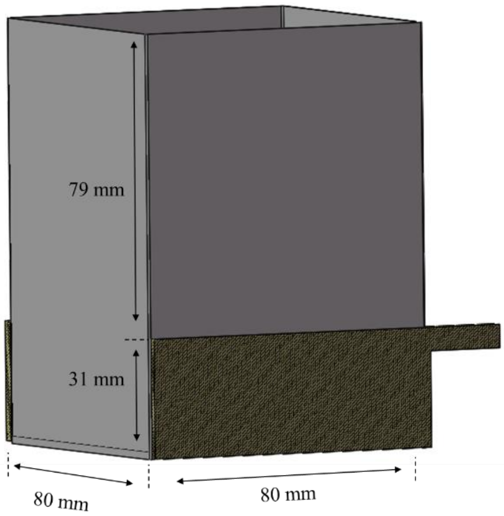


Figure 6. The structure and size of the designed sensor.

3.2. Effect of Porosity on Moisture Content Measurement

A total of 22 sets of experimental data in the calibration experiment were obtained after drying, as shown in Table 1. The data were fitted with the capacitance and temperature of corn measured by the online moisture content measurement device at the same time according to a previous study [14], and Equation (23) was obtained. The results of the variance evaluation are also provided in Table 2. Table 2 shows that, for the obtained model, the sum of squares (SS) was 161.604, the mean square (MS) was 32.318, the statistic F was 40730.27, and the corresponding confidence level P was less than 0.001. Based on the above data, the mathematical model established had strong significance. Thus, this equation can be used as a standard algorithm for online corn moisture content measurement.

$$\begin{gathered} MC = 0.3453C^2 + 0.01908Tg + 0.1295Tg \times C - \\ 3.08C - 1.386Tg + 38.25 \end{gathered} \tag{23}$$

where C is the capacitance, MC is the moisture content, in wet basis, Tg is the paddy temperature.

Table 1. Experimental values of response variables for the calibration experiment.

Drying Time (min)	Moisture Content (%w.b.)	Temperature (°C)	Capacitance (pF)	Drying Time (min)	Moisture Content (%w.b.)	Temperature (°C)	Capacitance (pF)
0	22.42	21.2	4.31	330	18.39	28.2	2.68
30	21.84	21.6	4.09	360	18.33	28.8	2.66
60	20.89	22.4	3.67	390	17.43	29.2	2.26
90	23.58	22.7	4.7	420	17.64	29.4	2.36
120	22.56	23.5	4.33	450	16.81	29.9	1.98
150	23.22	23.7	4.56	480	16.04	30.1	1.61
180	22.45	24.5	4.29	510	16.18	30.4	1.68
210	19.85	24.9	3.31	540	16.51	31.5	1.83
240	19.2	26.2	3.04	570	15.85	31.9	1.51
270	19.93	27.5	3.32	600	15.61	32.3	1.39
300	19.56	27.5	3.18	630	14.67	32.8	0.89

Table 2. Results of the variance evaluation.

Source	Df	SS	MS	F	*p*
C	1	0.004	0.0037	4.63	0.047
Tg	1	0.008	0.0079	9.92	0.006
C^2	1	0.023	0.0226	28.52	<0.001
Tg^2	1	0.008	0.0076	9.62	0.007
$C{\cdot}Tg$	1	0.008	0.0085	10.66	0.005
Model	5	161.591	32.318	40,730.27	<0.001
Error	16	0.013	<0.001		
Total	21	161.604			
R^2	0.99				
Adj-R^2	0.99				
Pre-R^2	0.98				

At room temperature (25 °C), the measured capacitance of the corn samples with a moisture content of 14.7%, 18.2%, 21.5%, 24.3%, and 26.4% w.b. at different porosities were substituted into Equation (23). The corn was filled into the online measurement device, and the calculated value and measured moisture content were recorded separately. The calculated moisture content was compared to the actual measured moisture content, and the calculated moisture content deviation is shown in Figure 7.

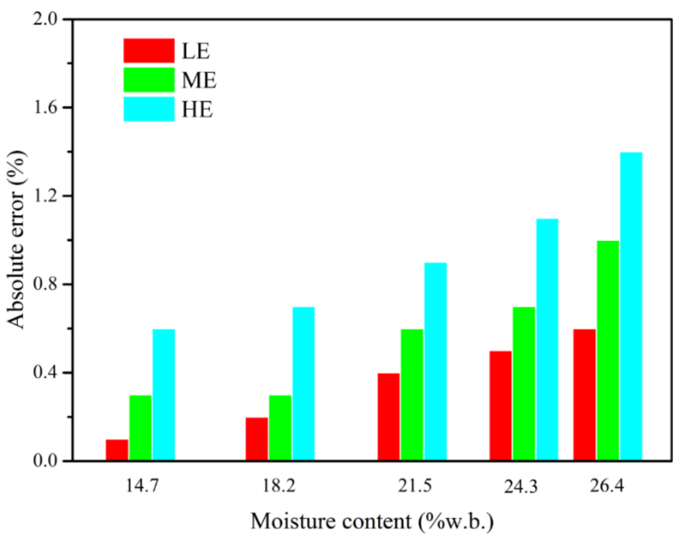


Figure 7. The moisture content deviation under different porosities. Note: LE, ME, and HE represent a low, medium, and high degree of extrusion, respectively.

Figure 7 shows that the porosity change in the cavity, caused by different extrusion pressures, will significantly interfere with the moisture content measurement. For corn with the same moisture content, the measurement absolute error was larger when the extrusion force was larger. For example, when corn with 21.5% w.b. moisture content was filled into the cavity through free falling (porosity was 42.5%), the measured value of moisture content was 21.4% w.b. and the absolute error was 0.1%. When this moisture content was fed back to the dryer controller as data, it was acceptable in the industrial grain drying process. The absolute error was 0.4% when slight extrusion was applied (porosity was 41.27%). When the extrusion force was applied continuously, the measurement deviation increased gradually. For example, the measurement deviation was 0.9% with a high degree of extrusion (porosity is 39.5%). This moisture content used as data feedback to the controller might lead to overshoot of the controller and other negative phenomena, thus affecting the grain quality after drying. The measurement accuracy of corn with high moisture content was considerably affected by changes in porosity. For example, the measurement absolute error range of corn with 26.4% w.b. moisture content was 0.6% to 1.4%, which is much higher than the measurement absolute error of corn with 14.7% w.b. moisture content (0.1% to 0.6%).

In the actual drying process, corn with the same moisture content often shows different porosities under the high dust conditions, fluctuations in flow state, changes in the impurity rate, changes in the filling way, and other interferences. When the same batch of grain with uniform texture is filled into the test cavity, the inner gap of the material pile with low porosity is relatively tight. According to Lichtenecker's dielectric constant calculation function [30], in the same mixed material system, the dielectric properties of materials were also different when the volume ratio of each component was different. Under normal pressure, the permittivity of air is approximately equal to one, whereas that of corn is greater than one. Therefore, for gas–solid two-phase systems, such as corn pile, the pile with lower porosity corresponds to a larger dielectric constant, producing a higher capacitance value, so the measurement error might be larger. In addition, increasing the moisture content leads to a decrease in the internal space of a single grain, and to a gradual increase in the internal friction coefficient on the grain surface and the viscosity force among grains [31], resulting in the adhesion and the agglomeration among grains, which is generally manifested as a decrease in the porosity of the grain pile, thus affecting the measurement accuracy. From the above analysis, we concluded that the changes in the pore distribution of the test cavity caused by the changes in the drying environment and the material properties significantly affected the online moisture content measurement during the drying process. To reveal the change law and to propose a solution to reduce the measurement error, the porosity, which is a basic physical parameter of agricultural materials, can be unified and quantified to establish the characteristic function to reveal the capacitance characteristics of the filling layer to identify the path to optimizing online moisture content measurement technology in the industrial grain drying process.

3.3. Calculation Function

Relevant studies showed that temperature has a significant effect on the dielectric properties of grain. Therefore, it was necessary to analyze the interaction effects of process variation on the measured capacitance of the sensor to fully determine the variation law of capacitance in the filling layer and obtain the calculation function in the process of online moisture content measurement by capacitance method. Table 3 shows the measured corn capacitance under different moisture content, temperature and porosity by the measurement device developed in this study. Analysis of variation was used to determine the effect of process variables on the response and to fit second-order polynomial models to the experimental data. After multiple regression fitting of the experimental data, the ternary quadratic mathematical equation describing the corn capacitance and moisture content, temperature, and porosity was established, as shown in Equation (24), in which P was the porosity. The correlation coefficient (R^2) of the fitting function was 0.999, which indicated that the predictions were in close agreement with the measured values.

$$C = 10.25 + 0.4409MC + 0.14336Tg - 0.668P + 0.001019MC \times Tg + 0.005868MC \times Tg \\ -0.003144Tg \times P + 0.001911MC^2 + 0.001046Tg^2 + 0.00895P^2 \quad (24)$$

Table 3. Obtained capacitance of corn samples in different moisture contents, temperatures, and porosities.

Moisture Content (%w.b.)	Porosity (%)	Temperature (°C)				
		5	12.5	20	27.5	35
14.7	38.4	0.93	1.35	1.89	2.54	3.32
	41.5	0.7	1.05	1.51	2.1	2.8
	44.6	0.64	0.92	1.31	1.82	2.45
17.6	38.4	1.64	2.07	2.63	3.3	4.1
	41.5	1.36	1.73	2.21	2.81	3.53
	44.6	1.26	1.55	1.96	2.49	3.14
20.55	38.4	2.63	3.09	3.67	4.37	5.19
	41.5	2.29	2.68	3.19	3.82	4.56
	44.6	2.12	2.44	2.88	3.43	4.1
23.5	38.4	3.5	3.99	4.59	5.31	6.16
	41.5	3.11	3.53	4.06	4.71	5.48
	44.6	2.89	3.32	3.69	4.27	4.97
26.4	38.4	4.38	4.89	5.51	6.26	7.12
	41.5	3.94	4.37	4.93	5.6	6.39
	44.6	3.66	4.03	4.51	5.11	5.83

The results of variance analysis of Equation (24) are shown in Table 4. The moisture content, temperature, porosity, and their interactions all significantly influenced capacitance, among which moisture content had an extremely significant influence. The *F*–value of the model was 49.57; however, the *p*–value was less than 0.0001, which proved that model was significant and the experimental results were not random. Both $Adj–R^2$ and $Pre–R^2$ were 0.998. These consistent results further demonstrate the effectiveness of model. Therefore, the fitting mathematical model can be used to predict corn moisture content in the drying process.

Table 4. Variance evaluation of linear, quadratic, and interaction terms for the response and coefficient of the prediction models.

Source	Df	SS	MS	*F*–Value	*p*–Value
MC	1	170.919	18.9910	7637.55	<0.001
T	1	0.602	0.6022	242.20	<0.001
P	1	0.551	0.5510	221.59	<0.001
$MC{\cdot}T$	1	0.104	0.1037	41.72	<0.001
$MC{\cdot}P$	1	0.151	0.1505	60.55	<0.001
$T{\cdot}P$	1	0.284	0.2841	114.25	<0.001
MC^2	1	0.534	0.5344	214.90	<0.001
T^2	1	0.056	0.0559	22.48	<0.001
P^2	1	0.726	0.7263	292.09	<0.001
Model	9	0.123	0.1233	49.57	<0.001
Error	65	0.162	0.0025		
Total	74	171.080			
R^2	0.999				
$Adj\text{-}R^2$	0.998				
$Pre\text{-}R^2$	0.998				

In order to verify the accuracy and rationality of Equation (24), parameters, such as moisture content, temperature, and porosity were randomly set as the conditions of the validation experiments, which are listed in Table 5. The moisture contents of paddy were 15.2%, 20.6%, and 25.4% w.b., respectively. The calculated capacitance obtained by subbing moisture content, temperature, and porosity into Equation (24) was taken as the predicted value, and the measured capacitance obtained by the developed instrument was taken as the measured value for error analysis. Table 5 shows the results of the validation. Compared with the measured values of capacitance, the relative difference between the model predictions and the measured values was in the range of 3.42% to 8.11%, and the average relative difference was 5.83%. The results of the validation experiments demonstrated that the capacitance predicted by measurement device and the function of capacitance was in good agreement with the measured value, and the feasibility of predicting function of corn capacitance was thus validated.

Table 5. Results of validation experiments.

No.	Moisture Content (%w.b.)	Temperature (°C)	Porosity (%)	Predicted Capacitance (pF)	Measured Capacitance (pF)	Relative Error (%)
1	15.2	5	38.8	1.03	1.09	5.5
2	15.2	20	43.1	1.52	1.64	7.31
3	20.6	30	43.2	3.82	4.16	8.11
4	25.4	15	42.1	4.03	4.19	3.79
5	25.4	25	42.1	4.95	5.31	6.86
6	20.6	10	39.1	2.83	2.93	3.42

3.4. Validation Experiment

To verify the reliability of the mathematical model of moisture content prediction, the model was written into the microcontroller of the online moisture content measurement device. The moisture content value of corn during drying was predicted online, and the predicted value was compared to the measured value. The verification experiment of online moisture content measurement was also conducted at Zhencheng Farm. The moisture content measurement device continuously collected corn temperature and capacitance values during the drying process, and Equation (23) was used to calculate the online moisture content value without porosity compensation. The sensor full of corn was removed every 30 min and placed into the porosimeter to measure the porosity of the corn, and Equation (24) was used to calculate the moisture content value after porosity compensation. A few corns were sampled at the outlet of the grain hopper of dryer, and the moisture content of the samples was determined by the standard oven method [13]. The calculated results were compared to the online measurement results of moisture content online device simultaneously. The experimental results are shown in Figure 8.

As shown in Figure 8, the online moisture content measurement value is in good agreement with the offline measurement value as a whole, and the dynamic change trend in the moisture content and porosity with drying time is consistent. In the early stage of drying, the fluctuations in the online and offline measurement values were both relatively large. When the moisture content was greater than 22.45% w.b., the absolute error of measured moisture content was between −2.4% and 1.2%. The moisture content of corn decreased gradually with the drying process, and the absolute error of moisture content measurement also decreased gradually. When the moisture content was below 17.43% w.b., the measured moisture content value without porosity compensation was basically consistent with the value after porosity compensation, with a deviation of −0.4–0.6%. In the whole drying process, the online moisture content value without porosity compensation fluctuated widely, with an absolute error of −2.4% to 0.6% and an average absolute error of 0.79%. After porosity compensation, the fluctuation in the online moisture content value significantly reduced. The absolute error of moisture content measurement was −0.62% to 0.67%, and the average of absolute values of error was 0.32%, which is more accurate than the device (absolute error of ±0.4%) developed by Mai et al. [14]. Therefore, by introducing the quantitative porosity parameter, the variation law of the capacitance in the filling layer can be more comprehensively revealed. The online measurement accuracy of moisture content in the drying process was also significantly improved, especially for grain with high moisture content, which is crucial for the data feedback for closed–loop and optimal control in the initial stage of the drying process.

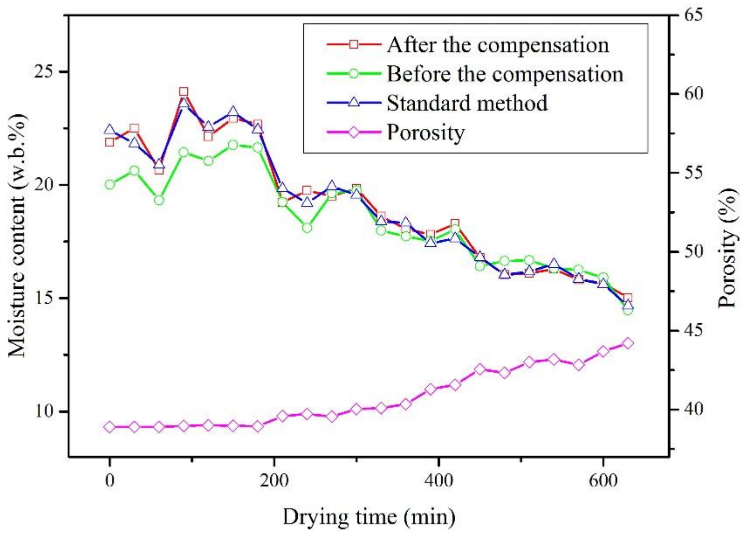


Figure 8. Comparison of discharged grain moisture content determined by the online method and the standard method.

4. Conclusions

The key findings of this study can be summarized as follows:

(1) The optimal size of the sensor was obtained by modeling. The length and width of the measurement area were both 80 mm, the height of sensor was 31 mm, and the optimized height was 79 mm;
(2) The absolute error of online corn moisture content measurement increased with increasing corn porosity in the filling layer. Moreover, the measurement accuracy of corn with high moisture content was more susceptible to the change in porosity, and the maximum measurement error reached 1.4%;
(3) The mathematical equation for moisture content calculation was obtained, and the statistical analysis results and the validation experiment showed that the equation had good agreement with actual measurements and reliability;
(4) The field corn drying experimental results showed that after porosity compensation, the fluctuation of moisture content was significantly reduced. The absolute error of the measured value was –0.62% to 0.67%, and the average of absolute values of error was 0.32%.

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Nomenclature

C	Capacitance (pF)
S	Plate area (m^2)
d	Spacing (m)
y	Thickness (m)
V	Volume (m^3)
M	Moisture content (%w.b.)
p	Porosity
G	Grain mass (kg)
Subscripts	
z	Height of capacitor (m)
T	Temperature (°C)
Greek symbols	
ρ	Density (kg·m^3)
ε	Dielectric constant
α	Response angle (°)
c	Cavity
m	Material
d	Dry basis

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