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Design of High-Frequency Based Measuring Sensor for Grain Moisture Content

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Abstract: Accurate measurements of moisture content are indispensable for maintenance of a detecting sensor is designed in this paper to determine the grain moisture content by measuring dielectric constants. To optimize the performance of the designed sensor, electromagnetic waves with suitable frequencies are chosen first followed by deep studies on its transmission characteristic in grain media. Taking wheat as testing samples and applying a total of six frequencies, the network analyzer from Agilent Technologies E5061A is used to measure the dielectric constant and loss tangent of grains with different moisture content. The variation of dielectric constants against moisture under various frequencies is obtained based on which the grain moisture is deduced. According to high frequency transmission line theory, as the impedance of probes wrapped in wet media varies with dielectric constants and is mismatched with transmission lines, standing waves are generated by the composition of reflected waves and incident waves. The strength of reflections depends on probe and characteristic impedances. The relationship of moisture content and dielectric constant can be deduced by analyzing the dynamic variation of reflected and incident waves. Key hardware circuits have been designed involving the moisture detecting circuit, signal generator circuit, high frequency transmission lines, etc.Calibration experiments are carried out, compared with drying method, a cubic polynomial relationship of moisture and output voltage with $R^2 = 0.995$was obtained by regression analyses. The standard error of predicted results from regression analysis and measured results is 1.09%. It indicates that the proposed method has a high accuracy.

Keywords: grain moisture measurement; high-frequency electromagnetic wave; dielectric constant; sensor

1 Introduction

The quantity of water in grains usually refers to "moisture content". Detecting and controlling the moisture content of grains play a key role throughout different stages of grain purchase, transportation, storage, processing, commerce, etc. It is essential to employ appropriate methods to measure moisture of grains for the quality maintenance purpose. Many measurement methods have been proposed at home and abroad with various characteristics and a wide scope of application. Generally, they can be divided into two main groups: direct method and indirect method. The former, directly detecting the absolute moisture content by weighting crushed grains before and after drying, is the classic and standard method of grain moisture measurement, such as drying method. Although the direct method is precise and has no effect on the nature of grains, it costs too much time and is not suitable for real-time and on-line measurement. On the other hand, indirect methods such as infrared and microwave methods[1-2]have high precision, good repeatability but high costs. In addition, physical parameters of media such as dielectric constant, conductance, dielectric loss, etc. may be used to measure grain moisture content [3]and capacitance method[4]. Kandala et al. measured grain moisture by filling grains between plates of parallel capacitors [5]. Mcintosh et al. proposed a sensor available in storerooms to detect grain moisture information [6].

As highly depending on the working environment, the methods mentioned above only apply to the moisture measurement of bulk grains. For packaged grains, non-destructive measurement of grain moisture requires a simply and flexible means of elongate probes inserting into grain packages. Based on high frequency-based electromagnetic wave measurement methods, this paper proposes measures in the design of moisture sensors to enhance its measuring precision.

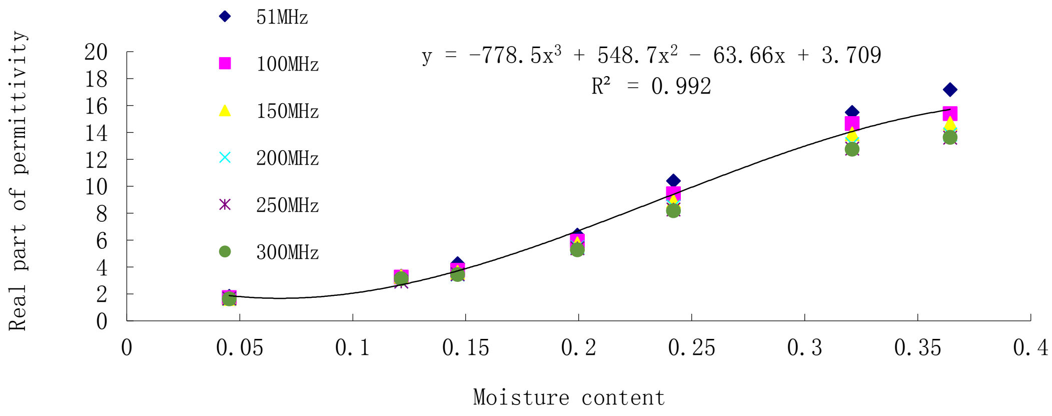
2 Relationship between dielectric constant and moisture content of wheat

The high frequency electromagnetic measurement method is to measure the dielectric constant of grains by high-frequency electromagnetic waves to indirectly determine grain moisture content[7-9]. Testing samples were collected according to the national standard GBT21305-2007 in China (Determination of moisture content of cereals and cereal products) to study the relation of dielectric constant and moisture content. The samples were harvested in June 2013 at Raoyang town in Heibei province (38°15'N，115°44'E). After harvest, the samples were stored in a dry and cool place for one year. Red durum wheat in a volume weight of 750g/L were dried under a constant temperature of 130º±2℃ for 90min±5min and its moisture content was determined. Seven types of tested wheat samples with various moisture content values were then made by mixing water, as listed in Table 1.

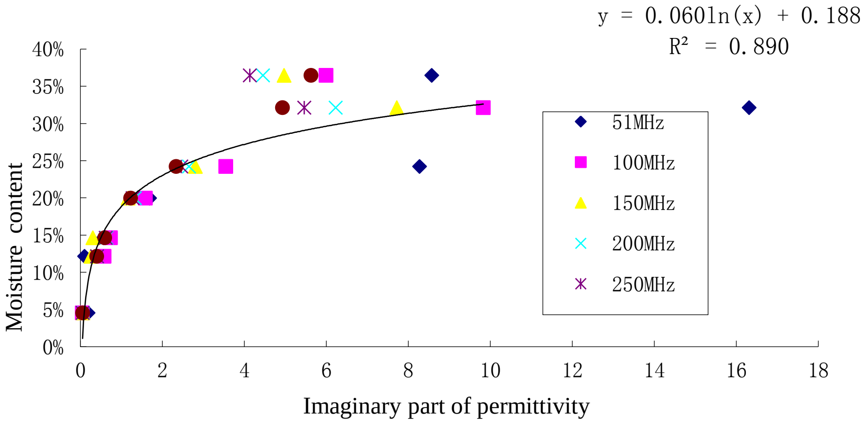
Table 1. The moisture content of wheat samples under investigation (bulk density 750g/L)

Samples	S1	S2	S3	S4	S15	S6	S7
Moisture content （%）	4.52	12.15	14.65	19.94	24.20	32.11	36.54

Dielectric constants of media with different moisture content varies under different frequencies[11]. Nelson studied the frequency characteristics of dielectric constant of different grains [12]. The results indicated that high frequency signals with higher dielectric constants, monotonic variations and less dielectric losses were preferred for moisture measurement. A frequency range of 50MHz～300MHz was recommended [13]. The RF network analyzerAgilentE5061A was used in this study. The dielectric constants of seven samples were measured under six frequencies of 51MHz, 100MHz, 150MHz, 200MHz, 250MHz and 300MHz, respectively. The relationship between dielectric constant and moisture content is plotted in Figure 1. The relations of real part and imaginary part of permittivity and wheat moisture content are shown in Figures 1(a) and (b), respectively. It can be seen that the dielectric constant monotonically increases with moisture content. As a dielectric substance, water molecules have strong polar characteristics. The increase in the dielectric constant of dielectric media is due to the increase in its moisture content.



(a)Relation between real part of permittivity and wheat moisture content



(b)Relation between imaginary part of permittivity and wheat moisture content

Fig.1. Relation between the dielectric constant and wheat moisture content

From Figure 6, it can be seen that the measured results are very close for samples with lower moisture content. However it is not the case for saturated samples. Signals in a medium frequency of 100MHz were taken in the test. The Least Square Method was used to obtain a cubic polynomial relationship between the real part of permittivity and moisture content as follows:

$\varepsilon' = -778.5\vartheta_{\text{wheat}}^3 + 548.7\vartheta_{\text{wheat}}^2 - 63.66\vartheta_{\text{wheat}} + 3.709$ （1）

The coefficient of determination of the real part of permittivity and the fitting curve was calculated as

$R_1^{\ 2} = 0.9988$.

The relationship between the imaginary part of permittivity and moisture content can be expressed in an exponential function as:

$\varepsilon'' = 0.063e^{14.80\vartheta_{\text{wheat}}}$ (2)

The coefficient of determination of formula (2) $R^2 = 0.890$ was derived in this case.

The two different coefficients of determination in Equations (1) and (2) indicate that the real part of permittivity is more related to grain moisture content than the imaginary part of permittivity. In other words, grain moisture content is mainly dependent on the real part of permittivity. Therefore, the moisture of grains can be determined from the real part of permittivity [14]. The dielectric constant in the following sections denotes the real part of permittivity. The high frequency method [15]is proposed based on this principle.

3 Design of moisture measurement sensor system based on high frequency method

3.1 General design

The block diagram of the sensor system of high frequency-based grain moisture measurements is illustrated in Figure 2. A high frequency signal is first produced and transferred to probes inserted into tested grains connected through high frequency transmission lines. The dielectric constant measured is larger than 1 (1 for air) since there is water in grains. It varies in a range of 1～20 for different moisture content. If the probe in tested grains is regarded as the output load of high frequency signals, the load impedance varies with grain moisture content. In this way, the feedback on the signal magnitude through output load changes. The moisture content of grains can be determined according to variation in the signal magnitude.

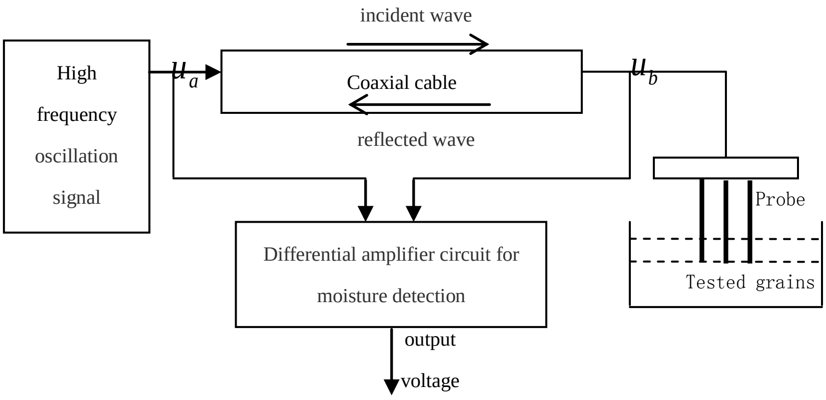


Fig.2. The block diagram of high frequency sensing circuit system

3.2 Signal generator

According to the frequency characteristics of wheat dielectric constant mentioned above, high frequency signals of 100MHz were used in the test. Figure 4 illustrates the high-frequency signal generator circuit. The oscillator output frequency is 100MHz. C1 represents the filter capacitor of power. High frequency signals are output from pin 3 and transmitted to the sensing circuit.

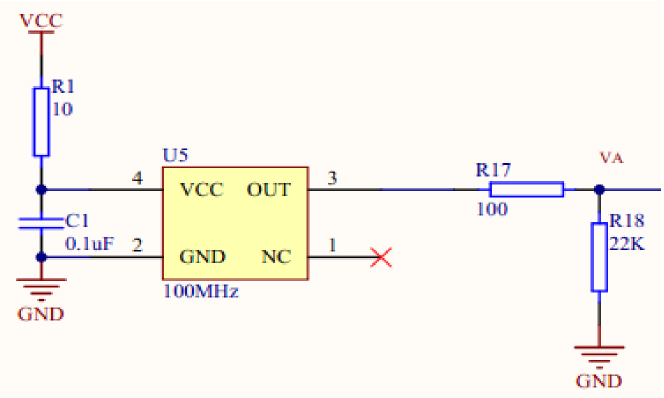


Fig.3. High-frequency signal generator circuit

3.3 Design of the transmission line circuit

The moisture sensing circuit was designed based on the transmission line theory. From Figure 3, it can be seen that high a frequency signal generated from high-frequency oscillation sources was transferred to sensor probes by coaxial cables. As each point has its own distributed parameters, the equivalent circuit of the transmission line is depicted in Figure 5. A high frequency cable of 50Ω was used for coaxial cables. The two points of the transmission line are represented by A and B. The impedance of probes wrapped in grains is denoted by Z_L.

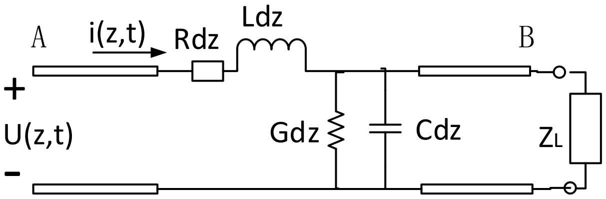


Fig.4 Distributed parameters of high frequency transmission lines

As wrapped in grains, the impedance of probes changes with its surrounding media which leads to the mismatch of terminal impedance and the signal reflex. The composition of incident waves and reflected waves on transmission lines generates standing waves [16,17]. If the cable length is taken as one quarter of the signal wavelength (i.e. 0.75m) and lossless transmission line is assumed, the standing wave ratio can be expressed[18] as $\gamma = \frac{u_{\max}}{u_{\min}} = \frac{1+\rho}{1+\rho}$, where $u_{\max}$ and $u_{\min}$ are the peak and trough of u_{A} and u_{B}, respectively. The peak voltage of the point A can be calculated as:

$$U_{\mathrm{A}} = A(1+\rho) \quad (3)$$

The peak voltage of the point B can be given as

$$U_{\mathrm{B}} = A(1-\rho) \quad (4)$$

Whereρ is the reflection coefficient defined as $\rho = \left|\frac{Z_L - Z_c}{Z_L + Z_c}\right|$ (5)

Therefore, the voltage difference between the points A and B is

$$\Delta U_{AB} = 2A\rho = 2\mathrm{A}\left|\frac{Z_{\mathrm{L}} - Z_c}{Z_L + Z_c}\right| \quad (6)$$

Where Z_c is the characteristic impedance, A is the voltage constant; the resistance of the cable is taken as 50Ω.

In order to simplify the circuit and enhance its reliability, the electric cable of 0.75m was replaced by a 100μH inductor. The equivalent circuit is shown in Figure 5.

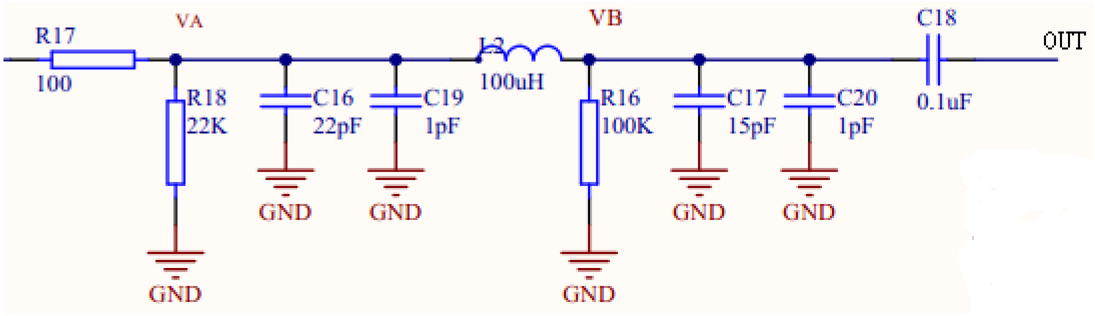


Fig.5. Equivalent circuit of high frequency transmission lines

The high frequency signal output from signal generators was transmitted to transmission lines by R17 and R18. A π-type filter composed of capacitors C16, C17, C19, C20, was used to filter harmonic components. The 0.75m cable was replaced by a 100μH inductorL2 with smaller size and better stability. The voltages at the two ends of the inductor L2 are denoted by VA and VB, respectively.

3.4 Design of sensor probes

As shown in Equation 5, the voltage difference between A and B depends on the impedance of probes. A three-needle type of stainless steel probe was used in this study. This multi-pin probe can be approximated as parallel transmission lines. Its impedance varies between coaxial cables and parallel lines[19-20]. The probes proposed in references [18,19] were used for water content measurement of soil. For the same porous media of grains as soil, the impedance is related to the dielectric constant of tested media. The impedance function of soil water measurements was also applied to this study. The function is shown as follows [20-21].

$$Z_L = -j\frac{Z_0}{\sqrt{\varepsilon}}ctg2\pi f\sqrt{\varepsilon}\frac{l}{C} \qquad (7)$$

where Z_0 is the characteristics impedance of probe in air; f is the frequency of high frequency signal source (100MHz); ε is the dielectric constant of tested grains; l is the length of probes (162mm); C is the velocity of light, i.e. $3\times10^{8}\mathrm{m\cdot s^{-1}}$.

3.5 Design of differential amplifier circuit for moisture detection

Figure 6 shows the differential amplifier circuit of grain moisture detection. There are dynamic standing waves at u_A, u_B which were transmitted to RF input of LTC5507 chips and transformed into DC voltage. After filter, the DC voltage was sent to the differential amplifier circuit. The AD623, serving as an operational amplifier, is powered by a single supply +5v. Programmable adjustment can be made on its gain by changing resistances. Resistances with error smaller than 0.1～1% were used to obtain precise output voltage gains of AD623. Meanwhile, resistances with low temperature coefficient are preferred to enhance the stability of voltage gains and avoid high gain drift. As the output voltage of AD623 relative to the reference terminal, to obtain a high common mode rejection ratio, an earth REF pins were applied. Transient voltage suppressor SMBJ5.0A was used to prevent the over high instantaneous voltage at the output terminal. [22]

$$U_{out} = K_1 \left| \frac{50 + j\frac{Z_0}{\sqrt{\varepsilon}}\, ctg\frac{2\pi f\sqrt{\varepsilon} l}{\sqrt{\varepsilon}}}{50 - j\frac{Z_0}{\sqrt{\varepsilon}}\, ctg\frac{2\pi f\sqrt{\varepsilon} l}{\sqrt{\varepsilon}}} \right| \qquad (8)$$

Where K_1 is a constant which is always taken as 2～2.5V, this output signal includes the dielectric constant information related to grain moisture. From the relation of dielectric constant and moisture content in Equation 1, a nonlinear function of output voltages and moisture content can be established. The coefficient of the nonlinear function was determined by calibration experiments.

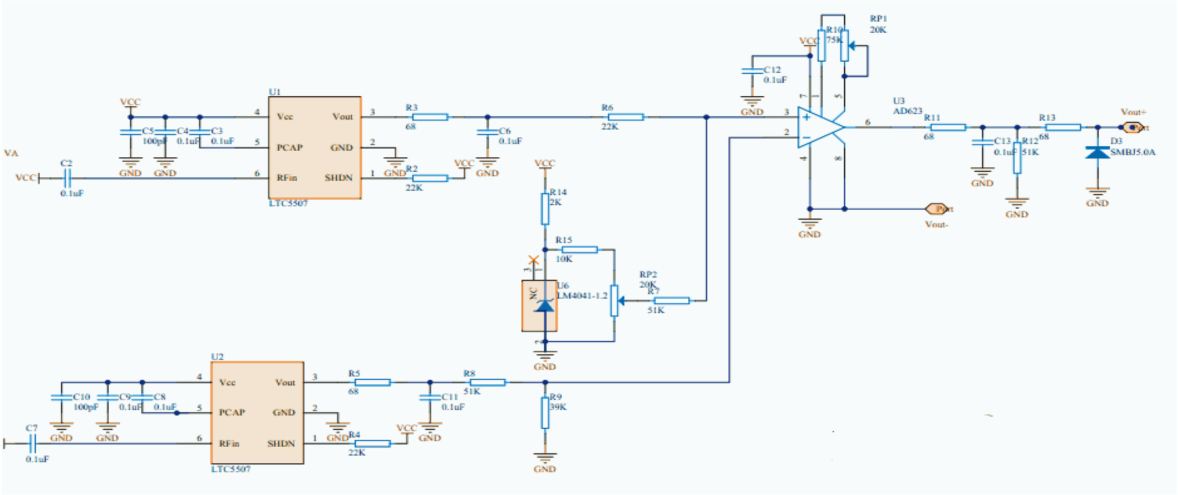


Fig.6. Differential amplifierfor moisturedetection

4 Calibration Experiments

The moisture measurements and calibration experiments were carried out on tested samples based on the proposed moisture sensing circuit. Table 2 lists the measured output voltages of the seven samples with different moisture content. Stable readings of voltage meters for each sample were recorded by inserting probes into the tested grains. Repeat the test for five times and take the average value as the output voltage. The variation of measured voltages listed in Table 2 against grain moisture content is plotted in Figure 7.

Table 2 The output voltageof moisture sensing circuit for wheat with different moisture content

Sample	Moisture content	1st measurement/V	2nd measurement /V	3rd measurement /V	4th measurement /V	5th measurement /V	Average/V
1	4.52%	0.68	0.69	0.71	0.66	0.7	0.69
2	9.78%	0.9	0.93	0.91	0.9	0.9	0.91
3	12.15%	1.02	1.03	1.04	0.98	1.02	1.02
4	14.65%	1.24	1.17	1.23	1.18	1.18	1.2
5	17.15%	1.3	1.31	1.29	1.29	1.23	1.28
6	19.94%	1.33	1.35	1.3	1.34	1.35	1.33

7	36.34%	1.98	2.01	1.95	2	1.97	1.98

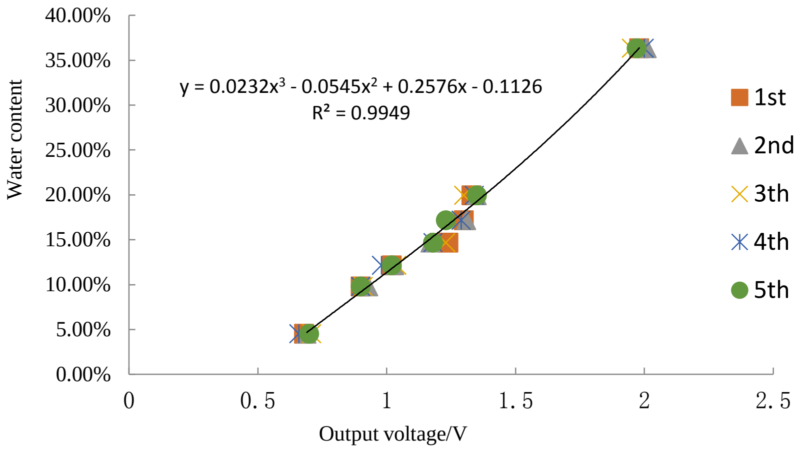


Fig.7. Relation of output voltage of moisture sensing circuit and wheat moisture content

A cubic polynomial function of moisture and output voltage obtained by the least square method can be given as follows using regression analysis

$$\theta_{wheat} = 0.0232U_{out}^3 - 0.0545U_{out}^2 + 0.2576U_{out} - 0.1126 \qquad (9)$$

For the mathematical model derived from the regression analysis , its cross correlation coefficient of predicted and measured results is calculated as

$$\mathrm{R}^2 = \frac{\sum_{i=1}^{n}\left(\hat{\theta}_i - \bar{\theta}\right)^2}{\sum_{i=1}^{n}\left(\theta_i - \bar{\theta}\right)^2} = 0.995 \qquad (10)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i}^{n}\left(\theta_i - \hat{\theta}_i\right)^2} = 0.01089 \qquad (11)$$

The standard error of predicted results from regression analysis and measured results is 1.09%. where n is the total number of samples in the regression analysis and n=7 in this case; θ_i is the moisture content of the ith sample; $\bar{\theta}_i$ is the average value of measurements of all samples; $\hat{\theta}_i$ is the moisture content calculated from the output voltage of the ith sample according to the regression equation; $\bar{\hat{\vartheta}}_i$ is the average value of $\hat{\theta}_i$

The result of $R^2 = 0.995$ indicates a good relativity between regression function and measured data.

5 Conclusions

(1) Real and imaginary parts of permittivity of seven groups of wheat samples with various moisture content are measured. The fitting curve shows that the former has a maximum coefficient of determination with moisture content. It indicates that a precise moisture content can be deduced from the real part of permittivity.

(2)The relationship between the moisture and probe impedance can be determined by the relation of moisture and dielectric constant as well as high frequency transmission line theory. A key grain moisture sensing circuit has been designed to measure grain moisture.

(3) Calibration experiments are carried out on the sensor circuit using drying method. A cubic polynomial relationship of moisture and output voltage with $\mathrm{R}^2 = 0.995$was obtained by regression analyses. The standard error of predicted results from regression analysis and measured results is 1.09%. It indicates that the proposed method has a high accuracy.

It is worth noting that the measuring error of the designed sensor meet the precision demand for wheat. While for other grains, no calibration experiments are conducted and further work should be done.

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