Effects of Test Cell Loading Methods on Dielectric Measurements of Granular Materials

Zoltan Gillay(1), **David B. Funk**(1), **Piroska Hartyani**(2)

(1)USDA - Grain Inspection, Packers and Stockyards Administration -
Technology and Science Division, 10383 N. Ambassador Dr. Kansas City, MO, 64153;
(2)Central Food Research Institute, Herman Otto 15, 1022 Budapest, Hungary
Emails: Zoltan.Gillay@usda.gov, David.B.Funk@usda.gov, P.Hartyani@cfri.hu

ABSTRACT

This paper demonstrates the practical significance of subtle orientation differences due to different loading methods when measuring dielectric characteristics of granular materials with non-spherical particles. We discovered that different types of loading methods yield different orientations for granular material. These subtle orientation differences cause significant moisture differences among the measurements using different loading methods despite the use of an effective density correction. Several confirmations that the moisture differences are caused by an "orientation effect" are presented.

Keywords: grain, orientation, granular, dielectric

1 INTRODUCTION

Dielectric-type grain moisture meters play an important role in determining grain moisture in all phases of production, marketing, and processing. Despite nearly one hundred years of development, several problems remain to be solved. Because of the differences among the various makes of moisture meters and their need for greater precision, the United States Department of Agriculture—Grain Inspection, Packers and Stockyards Administration (GIPSA) has developed the Unified Grain Moisture Algorithm (UGMA) to improve accuracy and assist manufacturers in designing new meters. The use of this algorithm in new moisture meter design should promote greater consistency in grain moisture measurement. The UGMA is based on density-corrected dielectric measurements at 149 MHz [1],[2].

The laboratory system that was used to collect dielectric data for several crop years for many grain types used a standard test weight funnel (Ohaus 4321 Filling Hopper) that was positioned 50 mm over the center of the test cell. Although this "Funnel" loading method had yielded good results in the laboratory, it was realized that it might not be the most practical approach for commercial instrumentation. The initial purpose of this present research was to test alternative test cell loading methods with respect to the funnel method to assess the latitude afforded instrument designers in creating UGMA-compatible instrumentation. Further investigations were conducted because we found significant differences in dielectric characteristics and predicted moisture contents with the alternative loading methods with respect to the funnel method—despite the use of an effective density correction.

1.1 Background

The complex dielectric constant is inherently a volume-based parameter, but grain moisture is expressed as a percentage of the total grain mass (water and dry material). This means, for example, that the greater the amount of grain packed in the test cell, the higher the apparent dielectric constant will be. If a moisture measurement method assumes a nominal bulk density for each grain type, moisture accuracy is significantly poorer than what is possible with an effective density correction. This is because the bulk density of grain samples within most grain types varies by more than twenty percent of the nominal value.

Prior research showed that the Landau-Lifshitz, Looyenga equation [3] as restated by Nelson [4] (1) was very successful in correcting density differences for each grain type due to test cell filling speed and vibration (settling). However, it was not so effective in correcting density differences due to compaction from pressure applied to the upper surface of the grain in the test cell. Furthermore, this equation was not effective in correcting density differences due to filling speed and settling if the measured density did not accurately reflect the actual density of the grain within the sensed volume of grain. This finding emphasizes the futility of measuring bulk density externally and then applying a mathematical bulk density correction to dielectric measurements [5].

$$\varepsilon_{corrected} = \left[\left(\varepsilon_{sample}{}^{1/3} - 1\right) \cdot \frac{\rho_{target} \cdot V}{m_{sample}} + 1\right]^3 \tag{1}$$

Where $\varepsilon_{corrected}$ is the density corrected dielectric constant, ε_{sample} is the dielectric constant of the sample, ρ_{target} is target density, V is the test cell volume, and m_{sample} is the mass of the sample.

2 MATERIALS AND METHODS

2.1 The Measurement Setup and the Loading Methods

In this study we used a test cell designed, fabricated, and calibrated by Kurt C. Lawrence and Stuart O. Nelson (USDA Agricultural Research Service) [6]. A duplicate of this test cell was used to develop the UGMA. The test cell consisted of three parallel aluminum plates with 31.4 mm spacing and 90 mm height. The length of the test cell was approximately 600 mm and the grain filled section was 154 mm. A sliding gate, consisting of a 6 mm thick PVC plate, was positioned under the center. The volume of the grain section was 861 ml. In 2007, when we attempted to transfer the UGMA method to a smaller, more practical size test cell, we discovered some discrepancies that led to this study of the impact of loading methods on dielectric measurements.

Three loading methods were compared in this research (Fig. 1): the original funnel loading method, a slow-pouring (manual) method, and a fast-drop method. The slow pouring method differed from the funnel loading method because of slower filling and because the grain stream was moved back and forth across test cell opening during loading rather than allowing the grain to flow lengthwise in the test cell from a fixed grain stream location. The fast-drop method consisted of a hopper with the same (horizontal) cross-sectional area as the test cell. A sliding metal gate was positioned 50 mm above the test cell. Sufficient grain was loaded into the loading hopper so that the test cell was overfilled when the gate was quickly removed. The same zigzag strike-off motion was used to remove the excess grain for all three loading methods.

Fig. 1: *Loading methods: funnel, slow pouring, and fast drop.*

An Agilent[1] E4991A RF Material/Impedance Analyzer was used to record complex reflection coefficient data. The weight and the temperature were recorded also.

2.2 Samples and Data Analysis

Two sets of samples – one dry and one moist – for each of seven grain types (barley, corn, soybeans, rapeseed, oats, sunflower, and wheat) were prepared for the experiment. The dry samples were used for the initial test because of their stability during the large number of measurements (20 per loading method). The moist samples were prepared by adding measured quantities of distilled water to dry samples. The moistened samples were allowed to equilibrate under refrigeration before testing.

The data for the moist samples showed distinct trends due to moisture loss. For purposes of assessing variability, the trends in the data were removed by linear regression. A few "outlier" measurements were observed and removed. The moisture calculation was based on the UGMA algorithm. An appropriate test cell model was used to calculate the dielectric constant, LLL density correction was applied to the dielectric constant to minimize the variability due to packing density variations, and the 2006 set of unifying parameters and calibration were used to predict moisture. Temperature correction was applied to the predicted moisture to minimize the effect of the sample temperature.

2.3 Two-dimensional Fourier Analysis

Orientation of the kernels was investigated in part of the research. A visible assessment was not sufficient, so image analysis was used to reveal the trend of the orientation of the kernels. We took pictures of grain loaded in a clear acrylic box. Side views showed clear differences in orientation for different loading methods, but the top view analysis required an objective means of assessing the orientation differences. Mathcad® [7] programming and its built-in image analysis functions were used to create 2-dimensional Fourier transformed and enhanced pictures (Fig. 2). In the second panel of Fig. 2, the intensity of the points represents the magnitude of the Fourier coefficient, and the positions of the points relative to the center represent the direction and spatial frequency of the sine components. Because of the complexity of the grain image, abundant points were observed on the 2-dimensional Fourier transformed image. In the next step we averaged the intensity of the points through the picture vertically and horizontally, then smoothed it, and plotted it on an x-y coordinate system. Fig. 2 demonstrates the steps of the method for a side view picture with barley loaded by funnel into the acrylic box. The third step may be interpreted as follows: Since the dotted line, representing the horizontal direction is below the solid line, there are fewer high spatial frequency points in the horizontal direction, so the alignment of the elongated kernels is predominantly horizontal—as is obvious from inspection of the photograph in this extreme case.

---

[1] The mention of firm names or trade products does not imply that they are endorsed or recommended by the U.S. Department of Agriculture over other firms or similar products not mentioned.

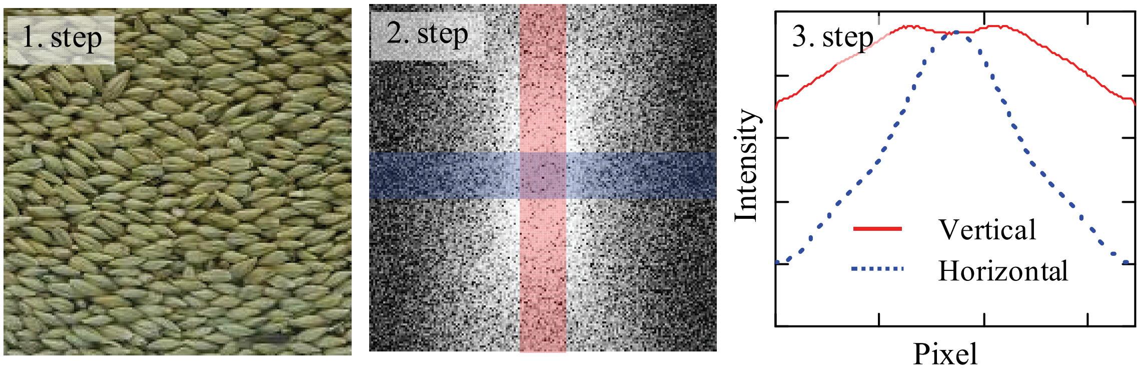

Fig. 2: *2-d Fourier analysis. 1st step: Picture of grain. 2nd step: 2-dimensional Fourier transformation. 3rd step: Mean intensities of the Fourier transformed picture within selected horizontal and vertical regions.*

3. RESULTS AND DISCUSSION

3.1 Predicted Moisture Differences among Various Loading Methods

The results of the different test cell loading methods were compared to determine the relative level of moisture measurement sensitivity to the loading method. We measured seven grain types in dry and moist states using the funnel, slow manual pouring (from side to side, moving back and forth along the test cell), and fast-drop methods, with 20 repetitions. The average moisture results for the manual and fast-drop methods were compared to the moisture results obtained using the funnel loading method. The results are shown in Fig. 3.

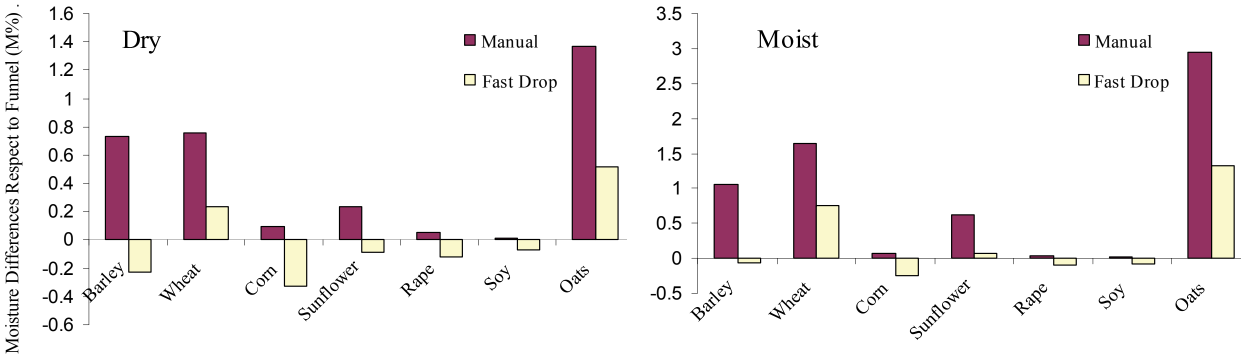

Fig. 3: *Moisture prediction differences using the slow pouring and fast drop methods relative to the funnel method for dry and moist samples.*

The differences among loading methods were highly significant, both practically and statistically. Slow pouring tended to yield higher moisture results than either of the other two methods. Fast-drop and funnel loading were the most similar of the three methods. The moisture differences among loading methods were extremely small for grains with nearly spherical kernels (soybeans and rapeseed).

The LLL density correction drastically reduced the differences in the dielectric constant among loading methods for corn, rapeseed, and soybeans; but for some types, particularly oats, wheat (fast-drop) and sunflower (slow-pour), the differences between methods were actually larger with the density correction than without it.

3.2 Reasons for the Differences

3.2.1 Packing Density

The different loading methods revealed significantly different sample masses, as shown in Fig. 4. This led to the hypothesis that the LLL density correction equation was simply not the right function for correcting moisture differences due to different loading methods.

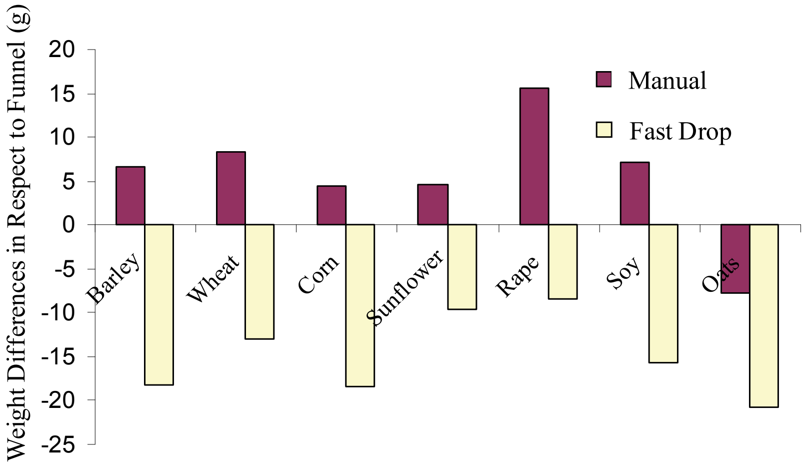

Fig. 4: *Sample mass differences for slow pouring and fast-drop loading relative to funnel loading.*

This hypothesis was tested by computing the correlation between sample mass differences and predicted moisture differences (with respect to the funnel loading method) for the slow pour loading method and the fast drop loading method for all grain samples together. The correlations were practically zero in both cases, suggesting that the basic density correction algorithm was not at fault.

3.2.2 Hull

The presence of a significant hull was another possible element playing a role in the effectiveness of density correction for different grain types and different loading methods. To investigate this hypothesis, an additional test was performed using samples of Long Grain Rough rice and Long Grain Milled rice. The results are shown in Fig. 5.

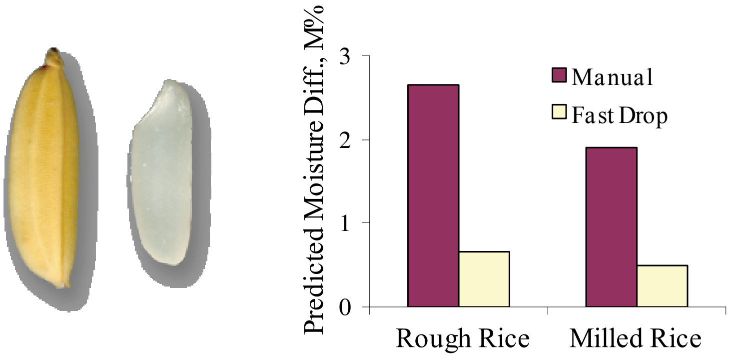

Fig. 5: *Comparison of the predicted moisture differences with slow pouring and fast drop loading in relation to funnel loading for rough and milled rice.*

These data showed similar trends in differences among loading methods for both rough and milled rice. Therefore, the presence of a hull did not appear to be primarily responsible for the moisture measurement differences with different loading methods.

3.2.3 Shape

The mean differences of the predicted moistures (Fig. 3) suggested that the highly elongated grain types had larger predicted moisture differences (with respect to funnel loading) than did grains with more nearly spherical kernels. To test this hypothesis, a "shape factor" (2) was defined using the measured typical dimensions (length, width, and height) for each grain type:

$$Shape\_Factor = Length^2 / (Width \cdot Height) \tag{2}$$

Of the grains tested, oats had the highest shape factor, followed by barley, wheat, sunflower, corn, soybeans, and rapeseed. The predicted moisture differences between the manual and fast-drop loading methods and the funnel method were highly correlated with the calculated shape factor. For slow pouring the r^2 was 0.92 and for fast-drop loading it was 0.56. This suggested that kernel shape was a significant factor in causing the differences observed for different loading methods.

3.2.4 Orientation Effect

Photographs of grain in the transparent test cell (such as Fig. 6) were examined to better understand the causes of the apparent orientation effect. The most striking observation from the side view was that for funnel loading and slow pour loading, elongated kernels tended to be aligned horizontally. Additionally, the layer of kernels next to the walls tended to be aligned parallel to the walls. With fast-drop loading, kernels were oriented more randomly. This observation seemed to be contrary to the observation that fast-drop loading results were more similar to funnel loading results than to manual slow-pour moisture difference results.

Fig. 6: *Side view of transparent test cell (barley) loaded by funnel loading, slow pouring, and fast drop.*

Top views of partially filled test cells (Fig. 7) provided insight regarding the orientation of kernels within the inner part of the test cell. Because the orientation differences were not visually observable, a 2-D Fourier analysis, as described in Section 2.3, was applied to discern the orientation trends. The results of the analysis for barley are shown in Fig. 8 for each loading method.

Fig. 7: *Top views of (half of) test cell with oats loaded by funnel loading, slow pouring, and fast-drop.*

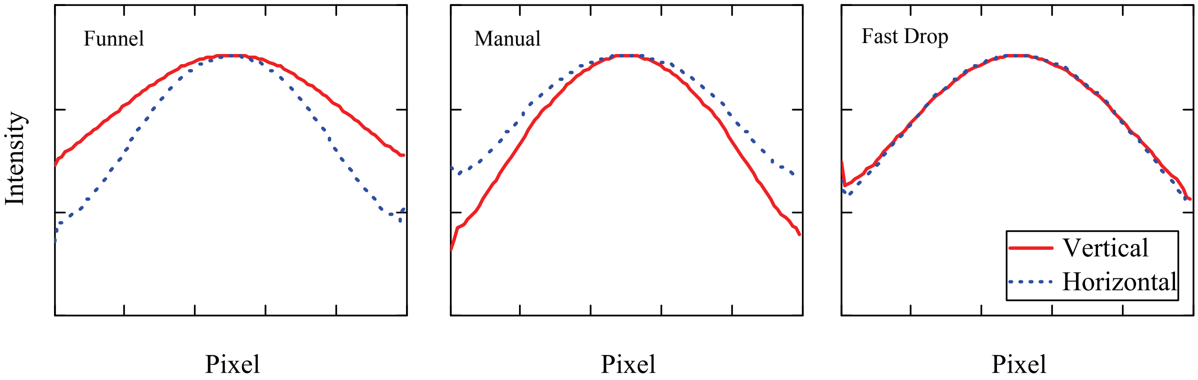

Fig. 8: *Smoothed Fourier coefficients for top-view photographs of oats with three loading methods.*

Fourier analysis of the top views revealed that with funnel loading, elongated kernels such as oats tended to align parallel to the walls as the direction of grain flow (Fig. 8). With slow pour loading, kernels tended to be oriented perpendicular to the walls except in the layer nearest the walls. With fast-drop loading, kernels were more randomly oriented. This demonstrated that different types of loading caused significantly different kernel orientations in the test cell.

The effects of such systematic kernel orientation differences can be understood by considering how kernels interact with the electric field (E) in the test cell [8],[9], as shown schematically in Fig. 9. Elongated kernels that are parallel to the electric field contribute more strongly to the measured dielectric constant (effective capacitance) than kernels that are oriented perpendicularly to the electric field. Therefore, the same amount of moist material in a test cell will exhibit a higher dielectric constant if elongated particles are aligned more closely with the electric field. Our test cell work in quasi-TEM mode was below about 250 MHz, and we used the 149 MHz frequency for moisture prediction. Therefore, in our test cell the electric field was perpendicular to the test cell plates.

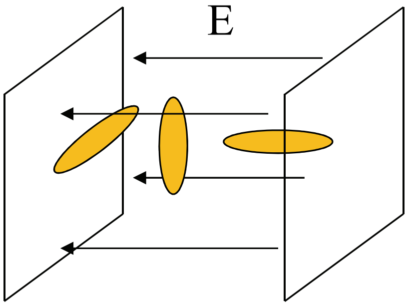

Fig. 9: *Three axes of kernel orientation in the test cell with respect to the electric field.*

With this discovery, we realized that only the top view provided information as to whether the kernels were parallel or perpendicular to the electric field. Fig. 8 shows that for manual pouring, the kernels tended to orient perpendicular to the test cell walls and parallel with the electric field. This suggested that the dielectric constant and the predicted moisture should be higher manual pouring than for the other loading methods. This is consistent with the moisture results demonstrated in Fig. 3, where all the elongated grains with manual pouring showed the highest moisture differences relative to the funnel loading method.

Fast-drop loading, in contrast, caused kernel orientation to be aligned more randomly. This suggested that predicted moisture for elongated kernels with that loading method should be should be lower than using the manual method. That pattern was observed for all grains with highly elongated kernels (Fig. 3). The expectation that the fast-drop loading results should be higher than funnel loading was not consistent for all grains. The significantly lower sample mass for fast-drop loading (Fig. 4) may have contributed to that result.

4 CONCLUSIONS

The mean differences among the loading methods were highly significant both for sample weight and moisture content. Furthermore, the differences varied by grain type. Grain types whose shapes were more nearly spherical showed much smaller differences among loading methods.

The differences in dielectric constant and predicted moisture were shown to be highly correlated to kernel shape. Analysis of kernel orientation within the test cell suggested that systematic differences in kernel orientation for different loading methods were responsible for the differences in predicted moisture results and the failure of the LLL equation to correct for loading method differences. These effects were consistent with electromagnetic theory regarding orientation of elongated particles in an electric field. Therefore, grain moisture meters that use the LLL density correction must provide a consistent loading mechanism for best accuracy and calibration transferability.

These results suggest that the orientations of particles under measurement are generally not random; they do show significant trends. This understanding may be an important contribution to dielectric measurements of grain. Besides packing density and temperature, kernel orientation differences caused by the loading method can contribute significantly to inaccuracy and inconsistency in dielectric measurements—and moisture measurements based on the dielectric method.

REFERENCES

[1] D. B. Funk, "An investigation of the nature of the radio-frequency dielectric response in cereal grains and oilseeds with engineering implications for grain moisture meters." Ph.D. thesis, Physics and Engineering, University of Missouri-Kansas City, 2001.

[2] D. B. Funk, Z. Gillay and P. Meszaros, "Unified moisture algorithm for improved RF dielectric grain moisture measurement," *Meas. Sci. Tech.*, vol. 18, no. 4, pp. 1004-1015, 2007.

[3] H. Looyenga, "Dielectric Constants of Heterogeneous Mixtures," *Physica* vol. 31, pp. 401-406, 1965.

[4] S. O. Nelson, “Correlating dielectric properties of solids and particulate samples through mixture relationships,” *Trans. ASAE,* vol. 35, no. 2, pp. 625-629, 1992.

[5] B. Gillay and D. B. Funk, “Efficacy of the Landau-Lifshitz, Looyenga Mixture Equation for Density-Correcting Dielectric Measurements of Yellow-Dent Corn Subjected to Vibration and Pressure,” Paper number 026038, *2002 ASAE Annual Meeting.*

[6] K. C. Lawrence, D. B. Funk and W. R. Windham, “Parallel-plate moisture sensor for yellow-dent field corn,” *Trans. ASAE*, vol. 42, no. 5, pp. 1353-1357, 1999.

[7] *Mathcad 14.0 M35*, PTC, 2007.

[8] A. H. Sihvola and J. A. Kong, "Effective permittivity of Dielectric Mixtures," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 26, no. 4, pp. 420-429, 1988.

[9] W. R. Tinga and W. A. G. Voss. "Generalized approach to multiphase dielectric mixture theory," *Journal of Applied Physics*, vol. 44, no. 9, pp. 3897-3902, 1973.