USING CAPACITIVE SENSING TO DETERMINE THE MOISTURE CONTENT OF WOOD PELLETS – INVESTIGATIONS AND APPLICATION

Anton Fuchs[1,2], Michael J. Moser[1], Hubert Zangl[1], Thomas Bretterklieber[1]
[1]Institute of Electrical Measurement and Measurement Signal Processing
Graz University of Technology, Austria
[2]Virtual Vehicle Competence Center (ViF), Graz, Austria
Email: anton.fuchs@tugraz.at

Abstract- This paper discusses a measurement principle for online moisture determination of wood pellets that is based on capacitive sensing. To ensure reliability and proper operation of the sensing device even under harsh industrial conditions, a robust principle based on a frequency hopping approach is required. Therefore, we investigate the impact of multiple carrier frequencies and analyze the frequency dependency of the material permittivity. Two different electrode topologies, one based on parallel plates and the other on a planar structure, are tested using a laboratory prototype in a drying chamber. Investigations on the applicability of capacitive moisture measurement are carried out using stationary conditions. The non-invasive and in-situ moisture content determination of wood pellets in a screw conveyor is presented as an application of the proposed principle.

Index terms*:* Capacitive sensing, moisture content, wood pellets, screw conveyor

I. INTRODUCTION

Having good and reliable instrumentation for the determination of moisture content in solid material is of importance for many fields of applications in industry [1]. The use of coal dust or wood chips in furnaces, storage of crops, fertilizers, processing of powders in pharmaceutical industry or processing of corn, milk powder, coffee, etc. in food industry are just a few examples that make moisture sensing in bulk solids necessary or at least desirable. In all these applications, the moisture content of the material may have an effect on corrosion and decomposition of materials, affects discharging behavior for solids, the lifetime of food products, or the effective calorific value of fossil fuels. The determination of the moisture content is also required for accurate billing, since the amount of water in a product may significantly affect its nominal weight and price.

Various techniques are known to estimate the moisture content in granular material and powders: A standard technique is usually based on oven drying [2], which is destructive and time consuming and requires taking representative samples of the transportation medium. Microwave spectroscopy has been found to be a suitable technique to determine the moisture content in granular material and agricultural goods [3, 4]. Electrical Time Domain Reflectometry (ETDR) is used to measure the material moisture content by means of exploiting the time needed for an electromagnetic pulse to travel forth and back through a sensing probe [5]. The moisture content can also be determined by using neutron moisture gauges, which exploit the dependency of neutron parameters on the average hydrogen concentration [6]. Infrared and laser light absorption spectroscopy are applied for the measurement of the surface moisture content in various substances [7].

Capacitive sensing has gained increasing importance in the last decades and is successfully employed in various applications in industrial and automotive technologies [8]. Due to the high relative permittivity of water ($\varepsilon_{r,water}$ of about 80), capacitive techniques are typically well-suited for moisture measurement in bulk solids [1, 9].

Dry wood has a relative permittivity $\varepsilon_{r,wood}$ typically between 2 and 3.5, but at the same time wood can contain more than 50 % water relative to its total mass, causing significant changes in permittivity [10]. The variation of the material permittivity and hence the variation of the moisture content can be measured as a change in capacitance when the test material is located in-between two electrodes.

However, the use of a parallel-plate structure with bulk solids as a dielectric to be examined may be restricted since the distance between the plates is limited for certain applications. A planar structure may therefore be more versatile and allows suitable, predefined penetration depths of the electric field according to the inter-electrode gaps.

II. MEASUREMENT SETUP

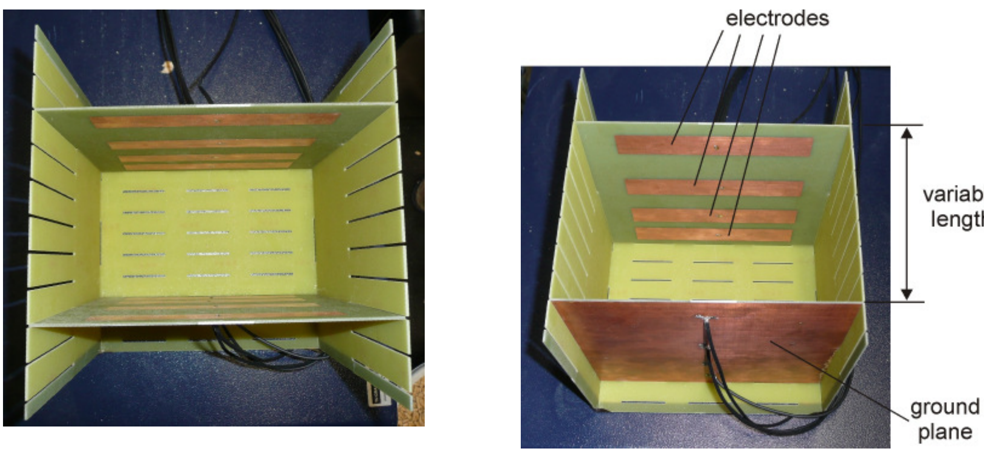
a. Test Box

For the sake of reliability and reproducibility of measurement results, stationary conditions are used to determine the material moisture content. Such conditions can be typically found in industrial applications when material is stored e.g. in a silo.

The test box is made of a two-sided copper coated printed circuit board (PCB) material. The material in-between the thin copper layers is non-conductive and structures such as electrodes can be easily manufactured. Two opposed faces of the box are equipped with four horizontal electrode stripes each, which have different distances between each other and are placed on the inner sides of the box. For abrasive or aggressive material, the electrodes can be coated with a non-conductive protection layer (e.g. ceramic or plastic layer), which allows contactless and non-invasive measurement. The outer sides are solid copper layers that are kept on electric ground potential to serve as guard electrodes and allow well-defined electric fields and reproducible measurement conditions.

The test box is designed to enable investigations with a variable length in-between the two faces with electrodes. The inner electrodes are connected with shielded wires and are fed through the box walls to connect the evaluation circuitry.

Figure 1 shows the setup of the empty box that is then filled with the test material and Figure 2 shows the electrode topology used for the test box.



(a) (b)

Figure 1. Photos of the test box with electrode topology [13].

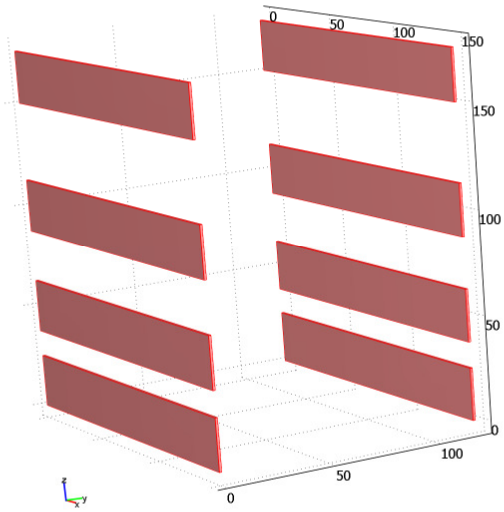


Figure 2. Electrode topology with increasing vertical inter-electrode gaps. The ground planes on either side are not shown. Dimensions are given in mm.

For the measurements, the wood pellets are inserted into the test box with their "natural" moisture content and are dried in a drying chamber. A high precision digital scale is used as a reference measurement method, since the loss of moisture results in a measurable loss of weight. Figure 3 shows the setup with the drying chamber on the scale and the box with material inside the chamber. The weight signal of the scale is recorded on a measurement PC.

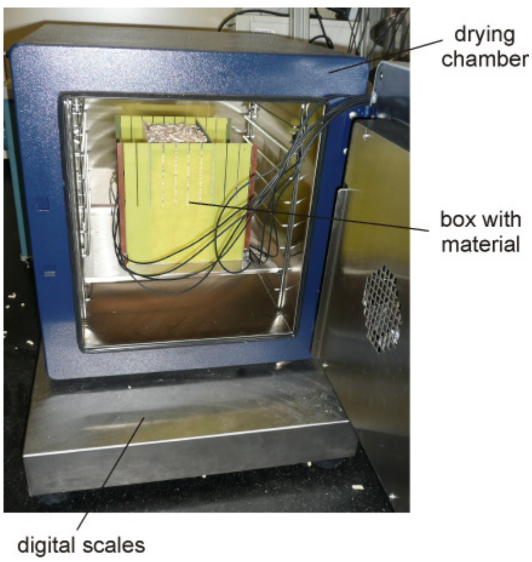
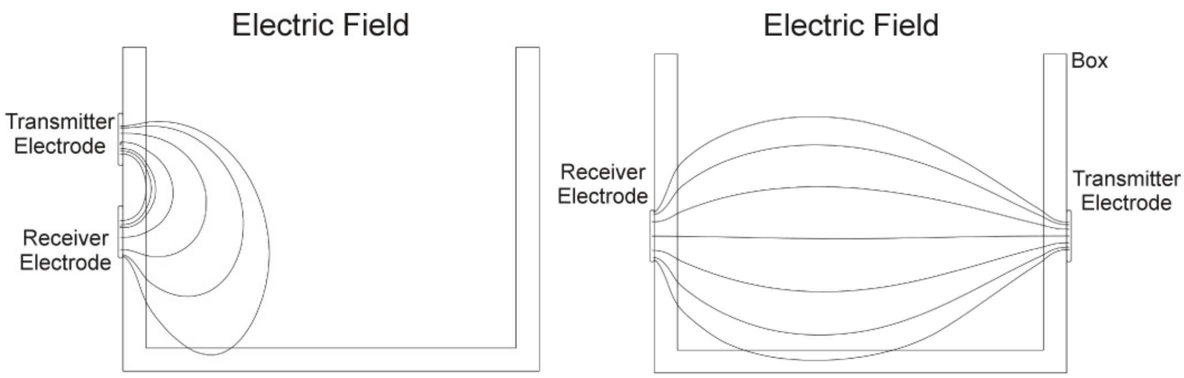


Figure 3. Photo of the measurement setup with drying chamber on a digital scale and the test box with material inside the drying chamber [13].

With the test box, two different setups can be investigated without hardware modifications – a parallel plate setup and a planar setup. Figure 4 shows the two types of sensing setups with the electric field obtained from Finite Element Method simulations plotted between transmitter and receiver electrodes. It can be seen that for the given dimensions, the planar setup features less penetration depth and rather local sensitivity, which is dependent on the gap between the electrodes and which hence can be considered in the design of the electrodes. The parallel plate setup on the other hand measures "through" the box and hence also center regions are considered for this type (i.e. also the moisture content of the material in the center affects the capacitance).



(a) (b)

Figure 4. Two types of measurement setups that can be investigated without a need for additional hardware modification. (a) Planar type and (b) Parallel plate type.

b. Capacitive Measurement Equipment

The sensing unit basically consists of a 12-bit Capacitance-to-Digital integrated circuit [14] that has been connected to an Analog Devices Blackfin DSP board [15], which is linked to the in-house Local Area Network. A National Instruments LabView 8.2 application on a standard PC carries out further signal processing and visualization.

The inter-electrode capacitance between a transmitter electrode and one (or more) receiver electrodes are obtained by exciting the transmitter with a certain carrier frequency. With our sensing unit, we can select several electrodes to be used as transmitters and receivers and we can also select several carrier frequencies from about 500 kHz to about 30 MHz.

c. Material under Test

Wood pellets are cylinder-shaped with uniform diameter and usually vary in length. For the pelleting process wood is dried, milled and pressed through a matrix. Lignin, which is a natural component of wood, serves as a binding agent in the pelleting process and no further additives are required. For the investigations carried out, the material diameter was 6 mm and the length of the material was in the range from 3 mm to 32 mm. Even though a moisture content of 10 % or 12 % will affect the calorific value of wood pellets only by a few per cent [11], any amount of energy to heat up and to evaporate bound water is taken from the combustion and makes this process less effective at the combustion site. Detecting small changes in material moisture, as expected for a variety of applications, is of course a central issue with electrical measurement [10].

For wood and wood pellets, the moisture content is commonly measured as weight loss by convection drying until a constant mass in hot air at 103 °C in a drying chamber [12].

III. ANALYSIS OF THE FREQUENCY DEPENDENCY

An industrial sensing device that has to be operated under harsh environmental conditions has to feature a robust design. This does not only include a resistant, non-invasive principle, but also robustness in terms of Electromagnetic Compatibility (EMC). One commonly used approach to improve EMC for capacitive sensing is frequency hopping, allowing the device to switch to a different carrier frequency when narrow band distortions occur.

The permittivity of wood (pellets) shows both a certain temperature dependency as well as a frequency dependency and hence the capacitance measured is temperature and frequency dependent [16]. We therefore analyze the narrow band frequency dependency of the material using the measurement setup presented in Section II.a.

a. Measurement Procedure

The inter-electrode capacitance for the steady drying material is measured for different electrodes and different carrier frequencies. A full measurement cycle comprises the subsequent measurement of seven electrode patterns and one reference measurement for four different carrier frequencies each. Figure 5 shows the seven different measurement cases for the planar (cases 1, 3, 4) and the parallel plate (cases 5 to 8) setup. Case 2 is a reference measurement of an unconnected electrode to observe e.g. the drifts over time of the measurement circuitry. Measurement results reveal that this drift can be neglected. The frequencies used for each case are 9.05 MHz, 9.85 MHz, 9.90 MHz, and 11.56 MHz, simulating the frequency hopping procedure. With the frequency range of about 2.5 MHz between the lowest and the highest frequency applied, the impact of different carrier frequencies can be investigated.

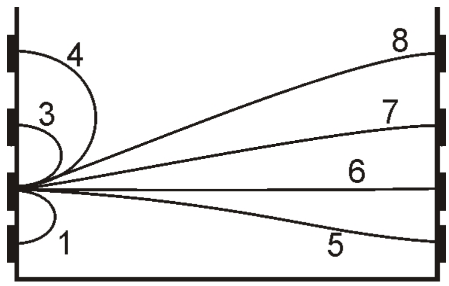


Figure 5. Seven different cases for the measurement procedure.

b. Measurement Results for Frequency Dependency Analysis

For the carrier frequencies used and for the different electrode topologies investigated (see cases in Figure 5), measurement results are reliable and the impact of carrier frequency variations within a small range is of minor importance. Figure 6a shows the normalized capacitance over time for the planar type (case 1 in Figure 5). During the first couple of minutes the capacitance increases due to the increasing temperature in the warm-up of the drying chamber. After this phase, constant material temperature can be assumed in the sensitive measurement volume and the capacitance decreases due to the decreasing moisture content of the wood pellets. For this electrode pattern (case 1 in Figure 4), the setup is sensitive to regions close to the box wall (also compare Figure 4a). Figure 6b shows the capacitive measurement data over weight information acquired with the digital scale. Also here, the warm-up of the cold material with high moisture content (i.e. high material weight) causes a non-monotonous characteristic while the further characteristic during the drying phase is rather linear. After about eight hours of drying, no significant capacitance variation can be observed.

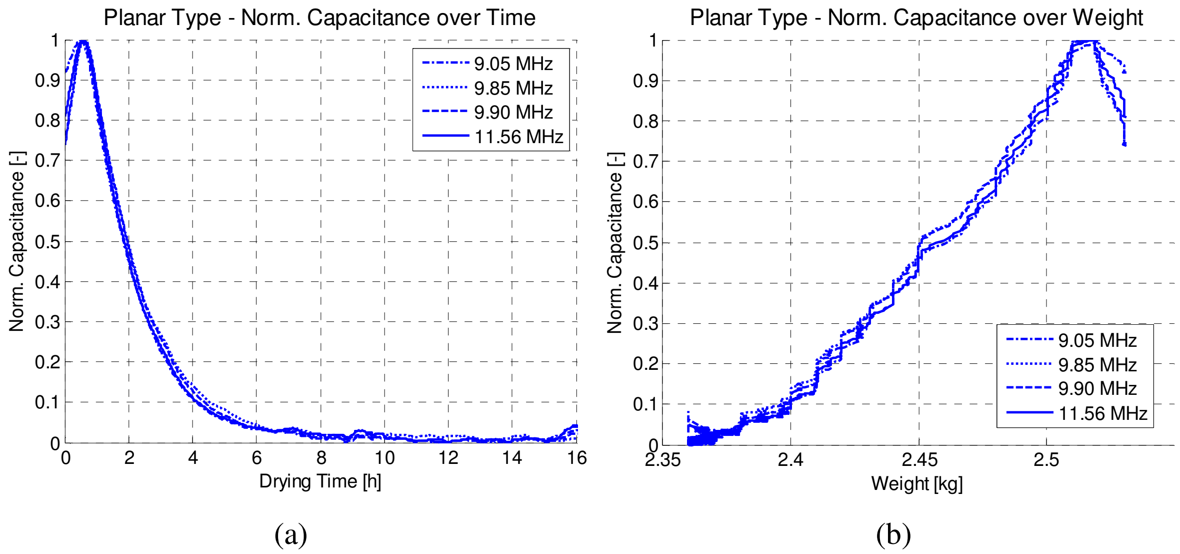


Figure 6. Characteristic of the normalized capacitance for the planar configuration during the drying process: (a) Normalized capacitance over time and (b) Normalized capacitance over weight. Please note that the temperature of the pellets increased at the beginning of the drying process. This implies that the readouts above 2.5 kg are strongly affected by the temperature change. Below this weight, the characteristic is mainly determined by the moisture content [13].

Figure 7 shows measurement results for the parallel plate configuration (i.e. case 6 in Figure 5). In this configuration, the setup is also sensitive to center regions (compare Figure 4b).

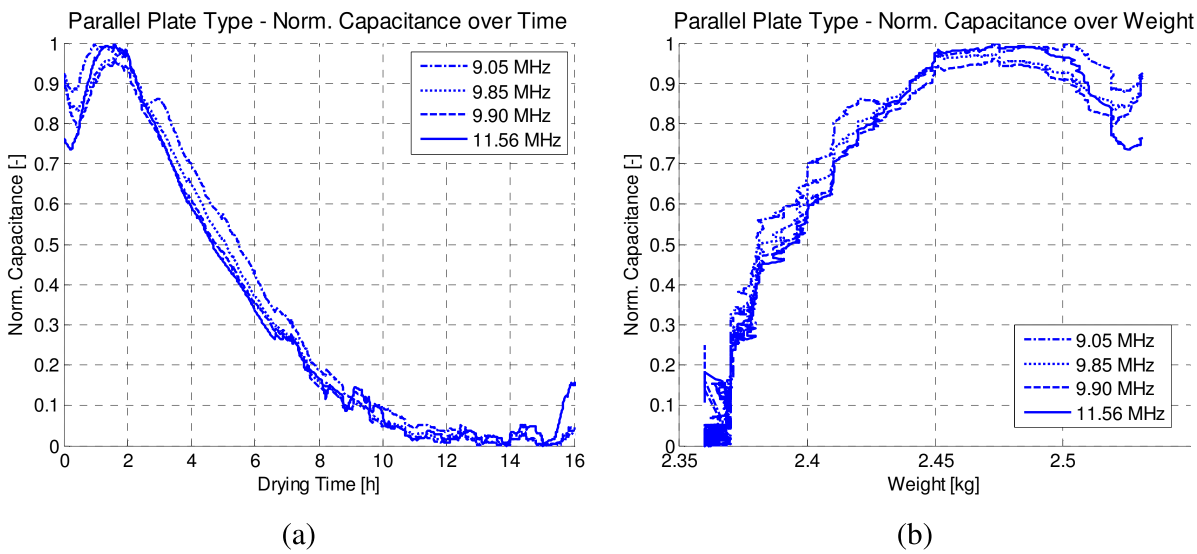


Figure 7. Characteristic of the normalized capacitance for the parallel plate configuration during the drying process: (a) Normalized capacitance over time and (b) Normalized capacitance over weight [13].

As can be seen in the measurement results of Figure 6 and Figure 7, it takes longer for the material in the middle of the box to heat up and dry than for regions close to the box wall. The weight signal of the scale over drying time is shown in Figure 8. Also the weight signal indicates that after about eight hours, the material can be considered as fully dried.

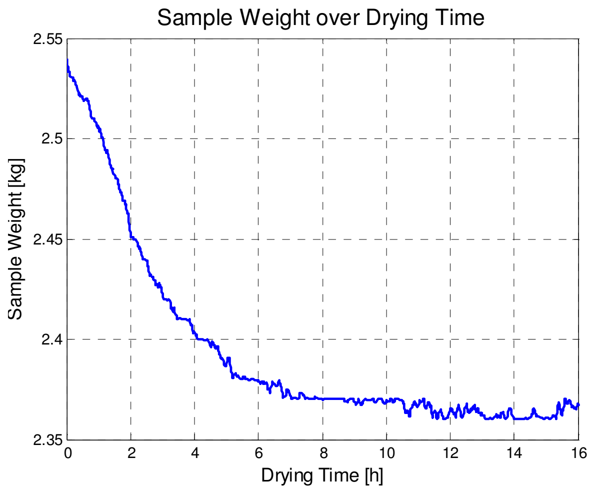
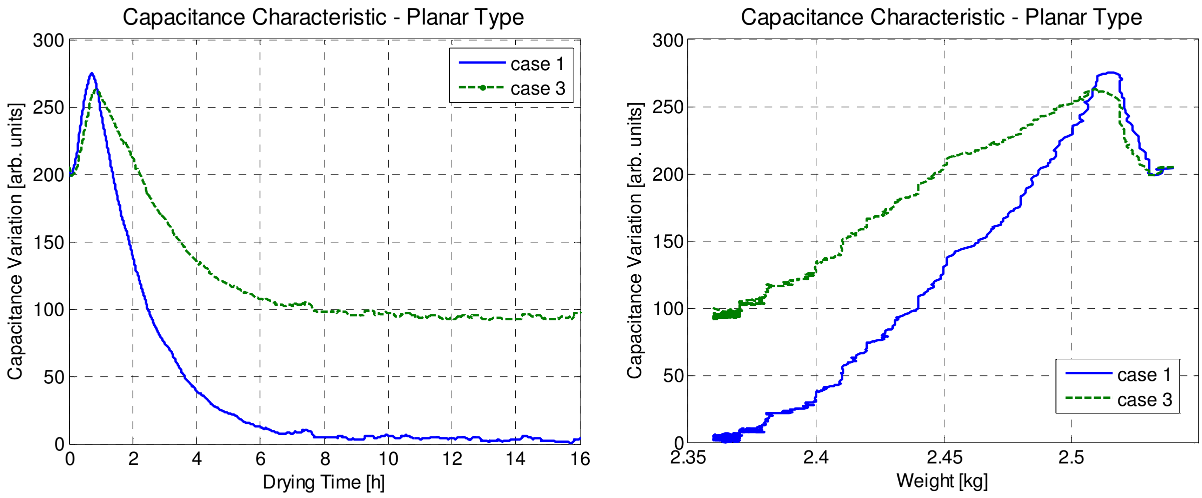


Figure 8. Weight signal over drying time obtained by means of a digital scale [13].

IV. MOISTURE MEASUREMENT WITH SPATIAL RESOLUTION

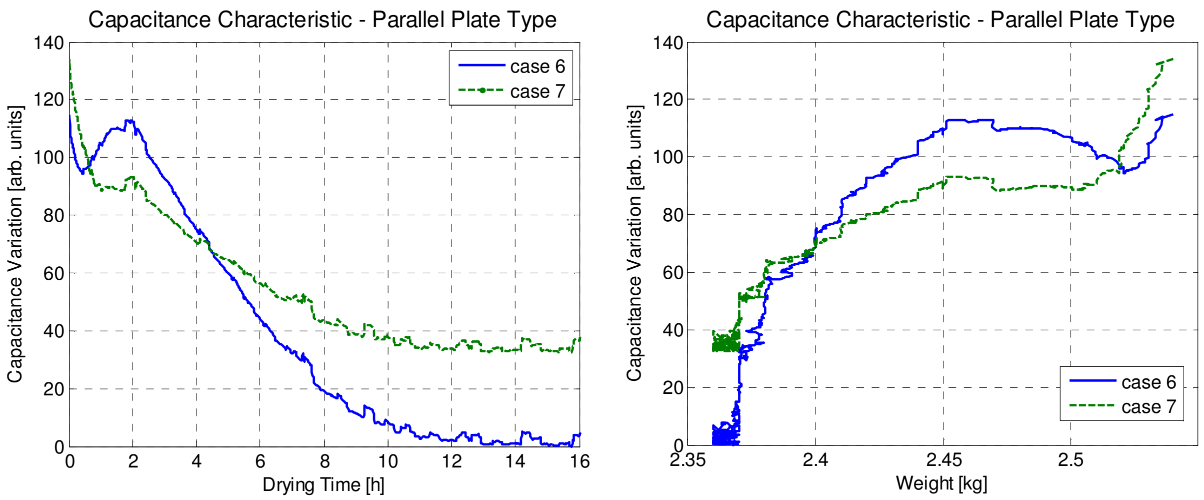
The electrode patterns shown in Figure 5 are used with a constant carrier frequency of 9.85 MHz to measure the moisture content of the test material. Figure 9 shows the measured capacitance variation during the drying process for the planar type setup (i.e. case 1 and 3 in Figure 5). It can be seen that for the smaller gap (case 1), the setup features higher sensitivity. The capacitance increases during the first period of drying since the material is heated up and hence the capacitance is affected due to the temperature dependency. After reaching constant temperature, the capacitance decreases due to decreasing material moisture. Material closer to the box wall obviously reaches constant temperature earlier than material in center regions, which can be seen in the time shifted peak in Figure 9a (the sensitive volume for case 3 covers deeper layers while case 1 is highly sensitive to layers close to the box wall).

Figure 10 shows measurement results for the parallel plate type setup (case 6 and 7 in Figure 5). Overlapping effects of drying (i.e. loosing moisture) and heating up (i.e. increasing material temperature) again can be made responsible for the non-monotonous characteristic at the early drying phase. The occurrence of this effect is delayed since this setup is also sensitive to center regions.



(a) (b)

Figure 9. Measurement results of inter-electrode capacitances for the planar type setup (case 1 and case 3 in Figure 5) for (a) Capacitance variation over drying time and (b) Capacitance variation over recorded weight.



(a) (b)

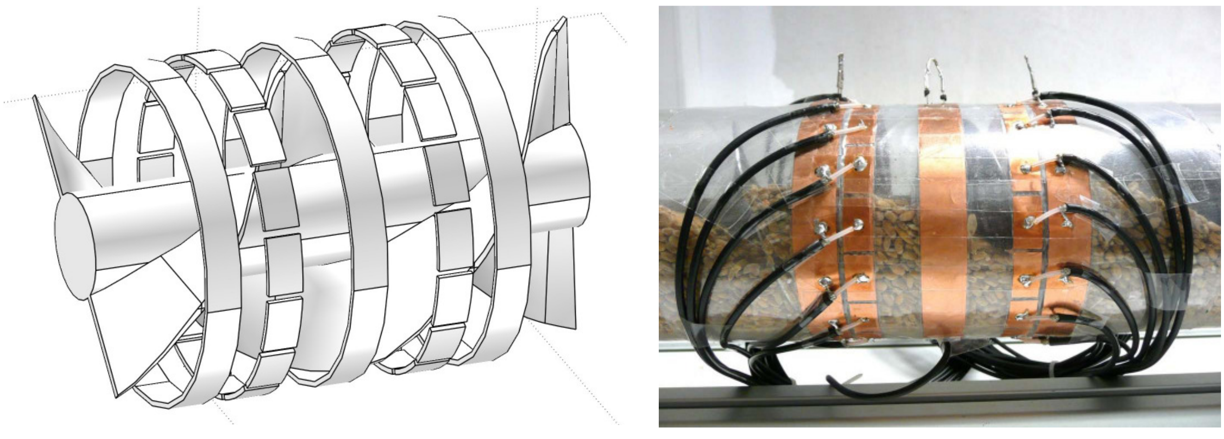
Figure 10. Measurement results of inter-electrode capacitances for the parallel plate type setup (case 6 and case 7 in Figure 5) for (a) Capacitance variation over drying time and (b) Capacitance variation over recorded weight.

V. APPLICATION: SCREW CONVEYOR

Screw conveyors operated at low speed are standard feeder devices with biomass combustion systems [17, 18]. The fed materials for these applications are typically wood pellets or wood chips. For an efficient control of the mostly continuously driven combustion process, information on the water content of the material (i.e. material moisture) is of interest, as there is a direct impact on the calorific value [11]. This is particularly important with inhomogeneous material such as wood chips, as with this material sudden variations of the moisture content are more likely to occur. In previous investigations [19, 20], it could be shown that both fill level and revolution speed of a screw conveyor can be measured by means of capacitive sensors.

A screw conveyor for laboratory purposes has been developed, comprising a metal screw driven by a DC motor housed in an acrylic pipe. The dimensions of the conveyor are: 1000 mm total in length, 100 mm screw and inner pipe diameter, and the wall thickness of the acrylic pipe of 5 mm.

The electrode topology of the measurement setup basically comprises two segmented transmitter rings and a single receiver ring electrode in-between the transmitter layers (see Figure 11). The second transmitter layer is used to observe radial movement of material. For experiments reported in this paper, only one transmitter layer has been employed. Each transmitter layer consists of 16 electrodes.



(a) (b)

Figure 11. Screw conveyor measurement section: (a): Electrode setup (from left to right: shielding ring, segmented transmitter ring of first transmitter layer, common receiver ring, segmented transmitter ring of second transmitter layer, shielding ring and (b): Photo of the setup [10, 20].

Standard wood pellets made from spruce were used as test material. For one measurement, the capacitance between one transmitter electrode and the common receiver is determined, the circuitry then switches to the next transmitter etc. This is performed continuously at an overall rate of about 20 Hz for a full measurement cycle or 320 single measurements per second. The excitation frequency of the transmitter segments with respect to ground was set to 10 MHz.

To investigate if the determination of the moisture content is also applicable during operation of the screw conveyor, samples of different moisture content are conveyed through the setup. The revolution speed of the conveyor is kept constant. The procedure comprises the following steps:

1. Six to ten revolutions of the screw without material (to verify that the capacitance values do not drift over time).
2. Seven to ten revolutions of the screw filled with constant amount of material with certain moisture content.
3. Another six to ten revolutions of the screw without material.

This procedure is repeated for five samples with a material moisture content of 3.2 %, 4.1 %, 5.1 %, 6.7 %, and 8.4 %.

A typical measurement matrix for the measured capacitances of the 16 electrodes obtained during operation for the procedure described above is shown in Figure 12. The periodicity is due to the revolution of the screw with its metal blade. It can be seen that during material transportation, the material covers the bottom electrodes 6 to 12 and hardly affect top electrodes.

When the maxima in the signals of the capacitance matrices are evaluated (i.e. when a maximum value is calculated for each electrode during conveying of material with specific moisture content), the dependency of the capacitance maxima on the material moisture content can be analyzed.

It can be assumed that a variation of the bulk density is negligible for an insertion of constant amounts of material per screw revolution, especially when the signals of the bottom electrodes are evaluated.

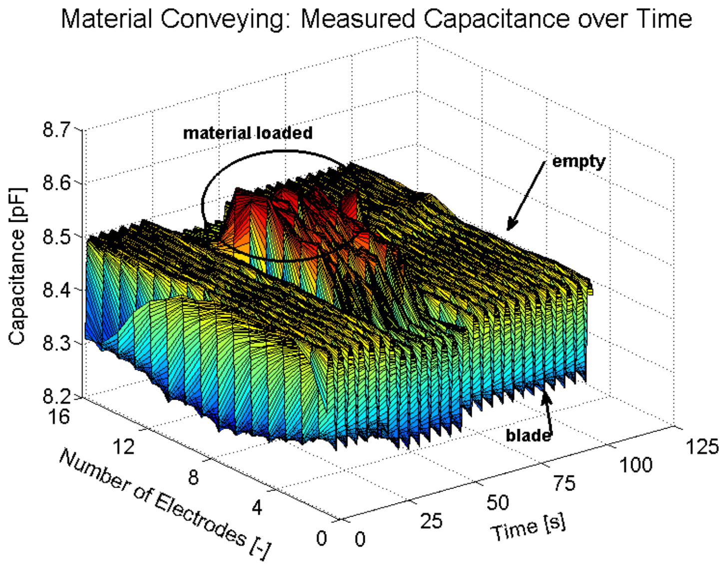


Figure 12: Capacitance measurement matrix over time for material with a moisture content of 8.4 % [10].

Figure 13 shows the trend of capacitance maxima for increasing material moisture content obtained at the bottommost electrodes 8 and 9. It is evident that the increase is monotonous and can hence be used to estimate online and non-invasively the material moisture content during operation of a screw conveyor.

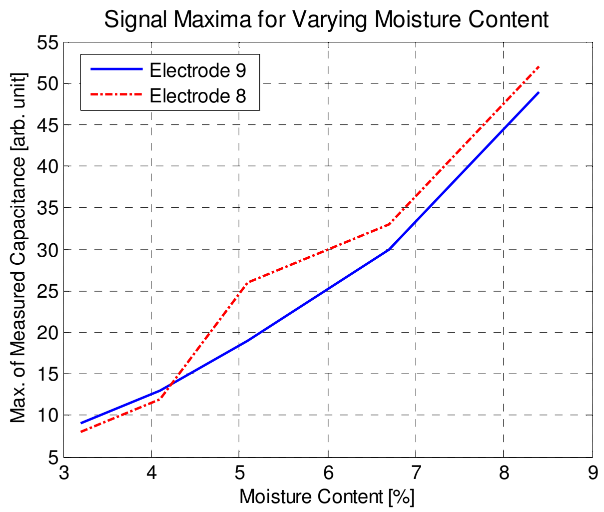


Figure 13: Maxima of the capacitance signals for varying moisture content for the bottom electrodes 8 and 9 [10].

VI. CONCLUSION

This paper presents investigations of capacitive electrode topologies for moisture determination in wood pellets. A test box has been designed that allows both investigations of a planar and a parallel plate type setup. The impact of different carrier frequencies in a narrow bandwidth is analyzed. It is shown that the frequency dependency of the test material's permittivity is minor for the investigated frequency range between 9.05 MHz and 11.56 MHz. Therefore, a frequency hopping strategy to improve the robustness of this measurement principle can be used. The measurement of material moisture for the planar type and the parallel plate type setup is demonstrated. The measurement principle is also used in a dynamic process, the transport of material in a screw conveyor.

VII. ACKNOWLEDGEMENTS

This work was partially funded by the Austrian Science Fund through the Translational Research Project number L355-N20.

VIII. REFERENCES

[1] A. Fuchs, H. Zangl, G. Holler, "Capacitance-Based Sensing of Material Moisture in Bulk Solids: Applications and Restrictions", Part IV - Capacitive Sensors, *Smart Sensors and Sensing Technology* in Book Series *Lecture Notes in Electrical Engineering*, Springer-Verlag, 2008, pp. 235-248.

[2] I. McFarlane, "Control of Final Moisture Content of Food Products Baked in Continuous Tunnel Ovens", *Measurement Science and Technology*, vol. 17, 2006, pp. 241-248.

[3] L. Gradinarsky, H. Brage, B. Lagerholm, I. Björn, S. Folestad, "In Situ Monitoring and Control of Moisture Content in Pharmaceutical Powder Processes Using an Open-Ended Coaxial Probe", *Measurement Science and Technology*, vol. 17, 2006, pp. 1847-1853.

[4] A. Kraszewski, S. Trabelsi, S. Nelson, "Moisture Content Determination in Grain by Measuring Microwave Parameters", *Measurement Science and Technology*, vol. 8, 1997, pp. 857-863.

[5] M. Khoshbakht, M. Lin, "Development of an Electrical Time Domain Reflectometry (ETDR) Distributed Moisture Measurement Technique for Porous Media", *Measurement Science and Technology*, vol. 17, 2006, pp. 2989-2996.

[6] A. Nagy, P. Vertes, "Correction for Dry Bulk Density in Measurements with Neutron Moisture Gauges", *Journal of Scientific Instruments*, vol. 2 (1), 1968, pp. 1097-1100.

[7] C. Edwards, G. Barwood, S. Bell, P. Gill, M. Stevens, "A Tunable Diode Laser Absorption Spectrometer for Moisture Measurements in the Low Parts in 10^9 Range, *Measurement Science and Technology*, vol. 12, 2001, p. 1214-1218.

[8] G. Brasseur, "Design Rules for Robust Cacacitive Sensors", *IEEE Transactions on Instrumentation and Measurement*, vol. 52, no. 4, 2003, pp. 1261-1265.

[9] D. Wobschall, D. Lakshmanan, "Wireless Soil Moisture Sensor Based on Fringing Capacitance, *Proc. of IEEE Sensors 2005*, Irvine, California, October 31-November 3, 2005, pp. 8-11.

[10] M. Moser, A. Fuchs, H. Zangl, "Investigations on Capacitive Moisture Measurement in Screw-Conveyed Wood Pellets", *Proc. of the Microelectronics Conference ME2008*, October 15-16, 2008, Vienna, Austria, pp. 175-179.

[11] H. Serup (editor), "Wood for Energy Production, Technology - Environment – Economy", Second revised edition, The Danish Center for Biomass Technology, 2002.

[12] P. Jensen, H. Hartmann, T. Böhm, M. Temmerman, F. Rabier, M. Morsing, "Moisture Content Determination in Solid Biofuels by Dielectric and NIR Reflection Methods", *Biomass and Bioenergy*, vol. 30, 2006, pp. 935-943.

[13] A. Fuchs, M.J. Moser, H. Zangl, T. Bretterklieber, Investigations on the Impact of Different Carrier Frequencies for Capacitance Based Moisture Content Determination in Bulk Solids, to be published in *Proc. of the 6th International Conference for Conveying and Handling of Particulate Solids*, Brisbane, Australia, August 3-7, 2009.

[14] T. Bretterklieber, H. Zangl, M. Motz, T. Werth, D. Hammerschmidt, "Versatile Sensor Front End for Low-Depth Modulation Capacitive Sensors", *Proc. of the IEEE International Instrumentation and Measurement Technology Conference*, Vancouver Island, Canada, May 12-15, 2008, pp. 830-835.

[15] D. Hrach, H. Zangl, A. Fuchs, T. Bretterklieber, "A Versatile Prototyping System for Capacitive Sensing", *Sensors and Transducers Journal*, vol. 90, 2008, pp. 117-127.

[16] W. L. James, “Dielectric Properties of Wood and Hardboard: Variations with Temperature, Frequency, Moisture Content, and Grain Orientation”, *USDA Forest Service Research Paper*, FPL 245, 1975.

[17] C. Rorres: The Turn of the Screw: Optimal Design of an Achimedes, Screw, *Journal of Hydraulic Engineering*, vol. 126, no. 1, 2000, pp. 72-80.

[18] J. Dai, J. Grace, A Model for Biomass Screw Feeding, Powder Technology, 2007, Article in Press, DOI:10.1016/j.powtec.2007.10.032.

[19] A. Fuchs, H. Zangl, G. Brasseur, Mass Flowmeter for Screw Conveyors Based on Capacitive Sensing. *Proc. of the IEEE Instrumentation and Measurement Technology Conference*, Warsaw, Poland, May 1-3, 2007, pp. 1-5.

[20] M.J. Moser, A. Fuchs, H. Zangl, Non-Invasive Capacitive Sensor for the Determination of Revolution Speed and Fill Level in Screw Conveyors, *Proc. of the 7th IEEE Conference on Sensors 2008*, Lecce, Italy, October 26-29, 2008, pp. 49-52.