CHEMICAL ENGINEERING TRANSACTIONS

VOL. 58, 2017

A publication of AIDIC

The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Remigio Berruto, Pietro Catania, Mariangela Vallone

ISBN 978-88-95608-52-5; **ISSN** 2283-9216

DOI: 10.3303/CET1758057

Impedance Analysis of Sweet Potato Tuberous Roots Accompanying Heating

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We examined whether electrical impedance analysis could be used to monitor the state of sweet potatoes while they are being baked. Impedance measurements that used needle electrodes and adhesive pads as electrodes were compared to determine which was most suitable for measurements during heating. Adhesive pads were selected to measure the temporal changes in impedance of sweet potato because they can be applied non-destructively and can cope with changes in the shape of an object during heating. Adhesive pads were attached to the sides of sweet potato samples that were cut at both ends and were uniform in height, and changes in impedance were measured over time during baking. Cole-Cole plots shrank with heat treatment, suggesting that the impedance measurements were effective for monitoring the state change in sweet potatoes during baking.

1. Introduction

Sweet potatoes are one of the most important crops in terms of global production, as more than 100 million metric tons are produced globally each year. About 74% of global production occurs in Asia (FAOSTAT, 2014). Sweet potatoes are a major crop in Japan and are distributed in the market throughout the year. In addition, the export volume of sweet potatoes from Japan has been increasing, particularly to Hong Kong and Taiwan (Ministry of Finance, 2016).

Sweet potatoes are generally harvested in autumn. After harvest, the sweet potatoes are subject to curing in which the tuber is subjected to high temperature and high humidity for about 1 week to prevent spoilage. After treatment, washing, and sorting, the sweet potatoes are shipped according to demand. In Japan, there are two general ways to sell baked sweet potatoes. Raw sweet potatoes are shipped to supermarkets or convenience stores, baked in an oven dedicated to making baked sweet potatoes, and sold in shops. In the other method, the sweet potatoes are baked in specialised factories and shipped to shops. Sucrose, lactose, and fructose are the three kinds of sugars in raw sweet potato. During storage, starch is changed into sucrose, so sucrose content increases (Lewthwaite *et al*., 1997). Sweet potatoes gain maltose and become sweeter after heat treatment. When starch is heated above the gelatinisation temperature, it changes into α-starch. β-Amylase changes α-starch into maltose, but β-amylase is active only in a limited range of temperatures, which differs among cultivars (Takahata *et al*., 1922). In addition, sugar, starch, and water contents vary among individuals. Variations in the taste of sweet potato products would be reduced if the status of baked sweet potatoes could be monitored non-destructively and the cooking method adjusted according to the characteristics of each individual sweet potato.

We used electrical impedance analysis as a measurement method to estimate the properties of sweet potatoes from the frequency characteristics of impedance. When the measurement target is living tissue, the state of the cell can be estimated. As an advantage, real-time measurements are possible, and this type of analysis is suitable for monitoring and evaluating the characteristics of an object.

Agricultural products, such as potatoes (Ando *et al.*, 2014) and kiwi fruit (Bauchot *et al*., 2000), have been subjects of measurement in previous studies, but sweet potatoes have not been researched. No previous study has measured the temporal changes in impedance of sweet potatoes during baking. The objective of this study was to establish a method to measure impedance changes in sweet potatoes over time during baking and to clarify the correlation between the status and impedance of sweet potatoes.

Please cite this article as: Takatori E., Chosa T., Tojo S., 2017, Impedance analysis of sweet potato tuberous roots accompanying heating, Chemical Engineering Transactions, 58, 337-342 DOI: 10.3303/CET1758057

2. Materials and methods

An impedance meter (ZM-G; Omega Denshi,) was used for impedance measurements in all experiments. The maximum supply signal voltage was 4 Vpp, and the range of frequency was 10 Hz to 100 kHz. Impedance (kohm) and phase angle (degrees) at 556 points were outputted to a computer. The electrodes and the impedance meter were connected with lead wires. Another lead wire was placed on the surface of the sample and grounded.

2.1 Examination of impedance measurement method for sweet potato roots

2.1.1 Impedance measurement of cylindrical samples of raw sweet potato roots by needle electrodes

The measurement target was a cylindrical sample (diameter = 20 mm, height = 60 mm) from a raw sweet potato tuber (‘Beniharuka’ cultivar) harvested from the Tokyo University of Agriculture and Technology Farm (Tokyo, Japan) on November 1, 2016. Both ends of the sweet potato were cut off and the sample was adjusted so that its height was 60 mm. The central part of the sweet potato tuber was hollowed out with a cork borer to prepare a cylindrical sample whose diameter was 20 mm. Two steel pins (diameter = 0.5 mm) were used as needle electrodes and pierced into the upper surface of the sample for the impedance measurements. The impedance was measured at 12 locations by changing the interval between the two needle electrodes to 5, 10, 15, and 18 mm and changing the penetration depth to 10, 20, and 30 mm.

2.1.2 Non-destructive impedance measurements using adhesive pads as electrodes

The same cultivar was sampled as described above. Both ends of the tuber were cut off, and the height was adjusted to 60 mm. Adhesive pads were affixed so as to face each other across the sample. The positions of the adhesive pads were changed on the same surface, and impedance was measured under each condition. First, one adhesive pad (pad A) was attached to the sample so that the centre of the pad was fixed at a height of 30 mm, and the position of the other pad (pad B) was moved vertically at heights of 30, 20, and 10 mm. After measurements were taken under these conditions, pad B was attached to the sample so that the centre of the pad was fixed at a height of 30 mm, and pad A was moved vertically to heights of 40 and 50 mm.

2.2 Temporal impedance measurements of sweet potato tuber during heat treatment

Three ‘Beniharuka’ and ‘Silk Sweet’ sweet potato tubers were harvested on November 10, 2016 from the Tokyo University of Agriculture and Technology Farm. Both ends of the sweet potatoes were cut off, and the samples were adjusted to a height of 60 mm. The samples prepared from ‘Beniharuka’ were called ‘Beniharuka a’, ‘Beniharuka’ b, and ‘Beniharuka c’, and those prepared from ‘Silk Sweet’ were named as ‘Silk Sweet a’, ‘Silk Sweet b’, and ‘Silk Sweet c’. Points at heights of 20 and 40 mm were marked to divide the samples into three parts after the heat treatment. Holes were made in the centre of each sample at heights of 10 and 50 mm to place copper-constantan thermocouples and measure temperature inside the sample. The temperature was recorded by a data logger (8430; Hioki) at 1-min intervals. The thermocouples were not set at a height of 30 mm because they would have obstructed measurement with the impedance electrodes. The temperature at a height of 30 mm was calculated as the mean of temperatures at heights of 10 and 50 mm. A pair of circular adhesive pads (EW-9N03, diameter = 20 mm; Panasonic) was attached as electrodes on the surface of the sample facing each other at a height of 30 mm. A flexible silicone sheet was wrapped around the side of the sample to prevent the adhesive pad from peeling off the surface of the sample. A heat insulating cloth was wrapped around the silicon sheet to make the heat flow in one direction from the bottom to the top of the sample. Impedance and phase angle of the sample were measured before the heat treatment. A hot plate (EHP-400; As One) was used for the heat treatment. A copper-constantan thermocouple was set on the surface of the hot plate and the temperature at the surface of the hot plate was recorded by a data logger at 1-min intervals. The surface of the hot plate was covered with an aluminium foil sheet. After confirming that the surface temperature of the hot plate was maintained at 200 ± 5°C for 10 min, the sample was placed on the hot plate to be heated from the bottom. The sample was covered with aluminium foil during the heat treatment. The time when the sample was set was defined as the starting time (0 min) of the heat treatment. Impedance and phase angle were measured from 10 to 120 min at 10-min intervals.

After the heat treatment, the sample was cut along the locations that were marked before treatment and divided into upper, middle, and bottom parts. Soluble solid content (°Brix) and moisture content (%) were measured in each part. Soluble solid content was measured based on the method of Nakamura *et al.* (2014), and moisture content was measured by coring out the centre of each section with a cork borer and adjusting the sample to 5.00 g. A 15-mL aliquot of water was added and the sample was homogenised for 30 s in a grinding machine (SCM-50; Shibata). Brix degree values of the homogenate were measured three times with a pen refractometer (Pen-1st; ATAGO). The Brix degrees were averaged, multiplied by 4, and converted to soluble solid content before dilution. The remaining part of the tuber sample not used to measure soluble solid content was dried at 50°C for 48 h (Nakamura *et al.*, 2010) in a muffle furnace (Toi shokai) to measure moisture content. Moisture content was calculated using Equation (1).

$$u(\%) = \frac{M_a - M_b}{M_a} \times 100 \qquad (1)$$

Where u is moisture content, M_b is mass before drying, and $M_a$is mass after drying

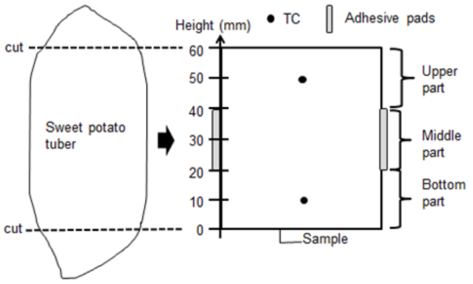

Figure 1: Positions of the thermocouple (TC) setting points and the adhesive pads.

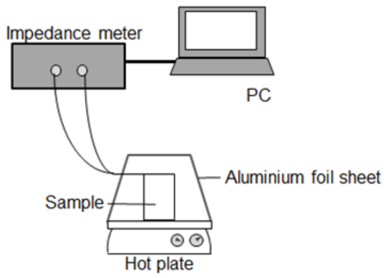

Figure 2: The system of non-destructive impedance measurement.

2.3 Cole–Cole Plot

Resistance and reactance were calculated from the following Equations (2) and (3).

$$R = |Z| \cos\theta \qquad (2)$$

$$X = |Z| \sin\theta \qquad (3)$$

Where R is resistance, X is reactance, Z is impedance, and θ is phase angle

The plot of resistance and reactance is called a Cole–Cole plot. As shown in Figure 3, high frequency current flows linearly inside a healthy plant cell. On the other hand, because of the high electrical capacity of cell membranes, the electrical current flows only through extracellular fluid, which has a relatively high resistance (Ando *et al.*, 2014).

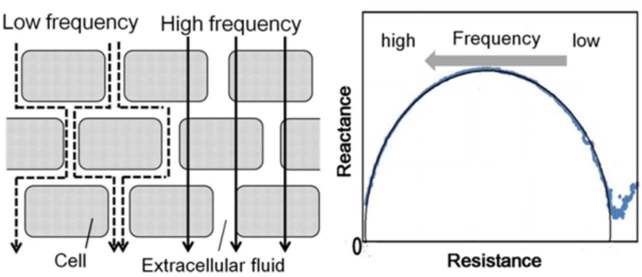

Figure 3: Flow of the electric current in the healthy plant cells and Cole-Cole plot.

3. Results and discussions

3.1 Impedance measurement method for sweet potato tubers

3.1.1 Impedance measurements of cylindrical samples of raw sweet potato tubers using needle electrodes

Figure 4 shows Bode diagrams (impedance and frequency) of the impedance measurements for the cylindrical tuber samples. The longer the distance between electrodes is, the higher the impedance. Impedance decreased as penetration depth increased when electrode distance was held constant.

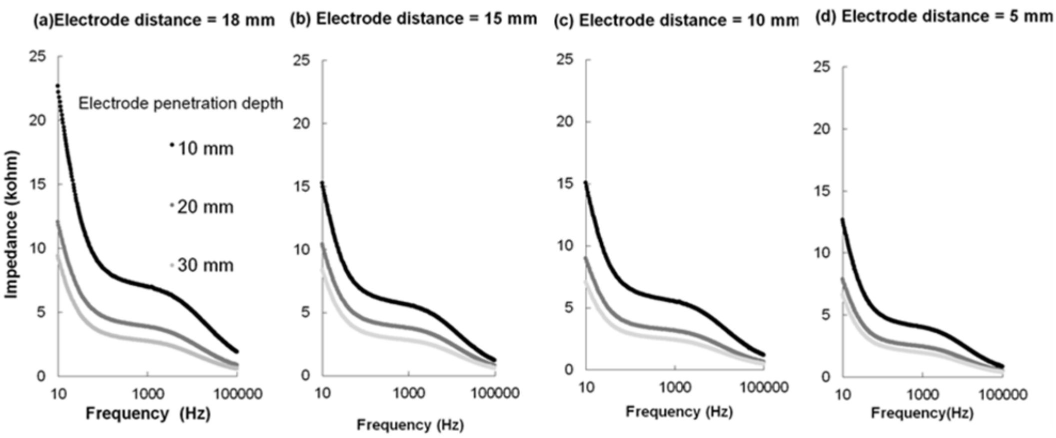

Figure 4: Bode diagrams showing the results of impedance measurements for a cylindrical sample.

3.1.2 Non-destructive impedance measurement using adhesive pads as electrodes

Bode diagrams showing the results of the non-destructive impedance measurements are shown in Figure 5. The lower the position of pad B, the lower the impedance became when the height of pad A was fixed at 30 mm. At frequencies < 1,000 Hz, a larger gap occurred between results obtained when pad B was at heights of 30 and 20 mm. On the other hand, a similar curve and values at the same frequency were obtained when the height of pad A was fixed at 30 mm.

Impedance decreased with heat treatment. Impedance values < 1 kohm are less accurate in the used impedance meter. The samples shrank and became soft during heat treatment, so the needle electrodes were not suitable for measurements because the hole pierced by the needle enlarged, the electrode positions changed, and a space opened up between the needle and the sample. Thus, the adhesive pads were used for the impedance measurements during heating.

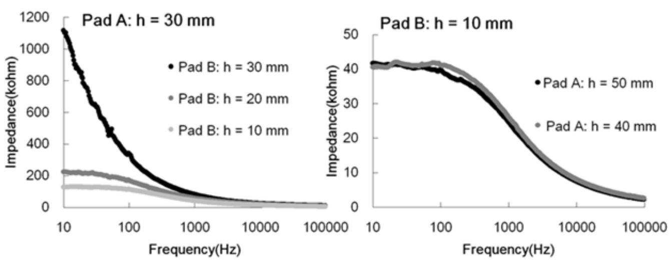

Figure 5: Bode diagrams showing the impedance measurement results using adhesive pads. h, height.

3.2 Temporal impedance measurements of sweet potato tubers during heat treatment

In Figure 6 and 7, the largest arcs in each Cole-Cole plots of each sample were before heat treatment and the second largest arcs were 10 min. The arcs drawn became smaller during the heat treatment in all samples. Soluble solid content (Figure 8) in the ‘Beniharula’ samples increased as temperature increased, but this did not apply to the ‘Silk Sweet’ samples. Saccharification during heating converts α-starch into maltose, and this change occurs at a higher temperature than gelatinisation, at which α-starch is made. β-Amylase, which converts α-starch into maltose, loses enzyme activity at about 75°C. The range of temperature that maltose is produced is limited. A sweet potato can be sweetened by baking it within a limited temperature range.

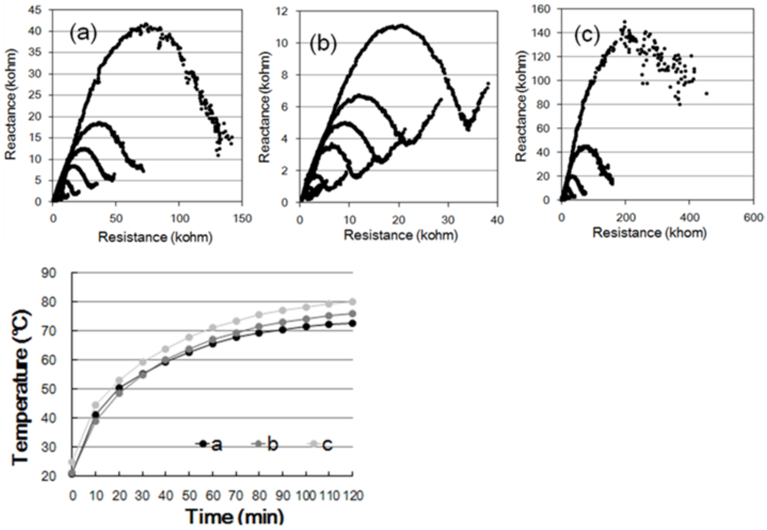

Figure 6: Temporal changes in Cole-Cole plots and temperature at a height of 30 mm in the 'Beniharuka' a, b, and c samples.

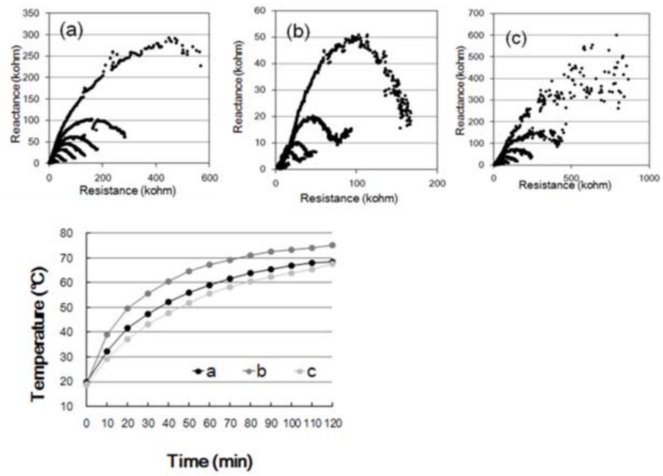

Figure 7: Temporal changes in Cole-Cole plots and temperature at a height of 30 mm in the 'Silk Sweet' a, b, and c samples.

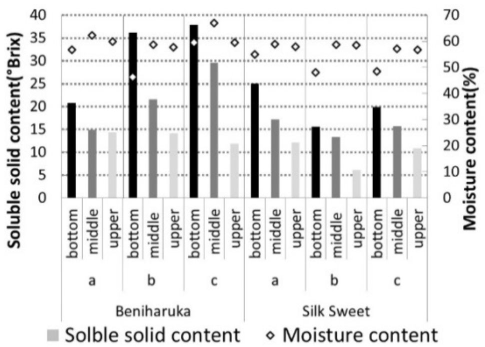

Figure 8: Soluble solid content, and moisture content in ''Beniharuka' a, b, and c ,and 'Silk Sweet' a, b, and c samples.

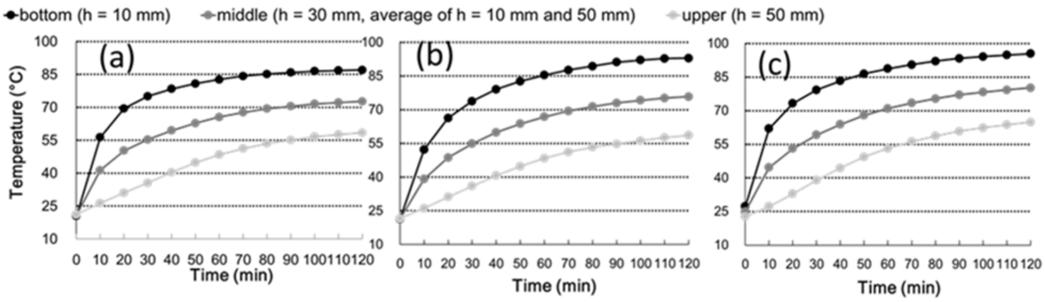

Figure 9: Temporal changes in temperature in 'Beniharuka' a, b, and c samples.

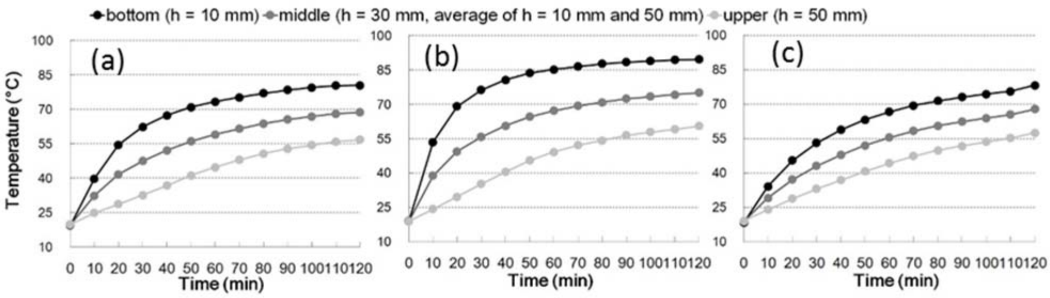

Figure 10: Temporal changes in temperature in 'Silk Sweet' a, b, and c samples.

4. Conclusions

We concluded that non-destructive impedance analysis using adhesive pads as electrodes can be applied as a monitoring method to measure temporal changes in sweet potato during heat treatment. Our future research will focus on fitting measured impedance data to a circular model, which is an equivalent circuit model for cellular tissues, and to clarify the relationship between impedance characteristics and factors related to taste of baked sweet potatoes. It will be necessary to develop a measurement method that can be used in the specialised oven used for baking sweet potatoes.

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