BIOSYSTEMS ENGINEERING 167 (2018) 21–31

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

# Synchronous magnetic flux-induced electrical response of orange juice

Lunan Guo [a,b], Liping Xue [d], Yao Zhang [a,b], Dandan Li [a,b], Mengyue Zhang [b], Yamei Jin [a,b], Na Yang [a,b,*], Xueming Xu [a,b,c]

[a] State Key Laboratory of Food Science and Technology, Jiangnan University, 1800 Lihu Road, Wuxi 214122, PR China

[b] School of Food Science and Technology, Jiangnan University, 1800 Lihu Road, Wuxi 214122, PR China

[c] Synergetic Innovation Center of Food Safety and Nutrition, Jiangnan University, 1800 Lihu Road, Wuxi 214122, PR China

[d] Department of Life Science and Engineering, Jining University, Jining 273155, PR China

ARTICLE INFO

*Article history:*
Received 30 July 2017
Received in revised form
30 October 2017
Accepted 7 December 2017
Published online 3 January 2018

*Keywords:*
Orange juice
Soluble solids content
Potential difference
Synchronous magnetic flux

The study proposes a method for measuring the electrical properties of orange juice by using two magnetic fluxes with the same frequency (or synchronous magnetic fluxes) at 400–700 Hz. The juice was passed through two spiral glass tubes, which formed the secondary coils of the transformer with different connection modes. Five measurement points ($a$, $b$, $o$, $-a$, and $-b$) were arranged at different terminals of the two coils to evaluate output voltages ($U_{-aa}$, $U_{oa}$, $U_{-bb}$, and $U_{ob}$) under the fluxes. Control parameters included the excitation voltage ($U_P$), frequency, and phase difference. Results indicated that the output voltage of the juice increased linearly with increasing excitation voltage at all points. In-phase output voltages were higher than reverse-phase output voltages. The value for $\lambda_{-aa}$ ($U_{-aa}/U_P$) remained stable as the excitation voltage increased. In addition, different physicochemical properties of orange juice caused a change in the output voltages, which was consistent with *Ohm's law*. Soluble solids content and $U_{-bb}$ were linearly correlated, showing $R^2$ values at 0.875 and a root-mean-square error of 0.702 Brix° at 20 V and 700 Hz. The method showed potential for the rapid determination of the quality of liquid foods by using magnetic flux-induced electrical parameters.



## 1. Introduction

Orange juice, a widely known beverage worldwide, has been highly consumed because of its characteristic flavour as well as high vitamin C and other bioactive ingredients containing flavonoids, carotenoids, and amino acids (Álvarez, Pastoriza, Alonso-Olalla, Delgado-Andrade, & Rufián-Henares, 2014; Fusco et al., 2017). Evaluation of the physicochemical quality of orange juice includes the detection of soluble solids content (SSC) (Camps, Robic, Bruneau, & Laurens, 2010), titratable acid

* *Corresponding author*. State Key Laboratory of Food Science and Technology, Jiangnan University, 1800 Lihu Road, Wuxi 214122, PR China. Fax: +86 510 85917100.

E-mail address: yangna@jiangnan.edu.cn (N. Yang).

https://doi.org/10.1016/j.biosystemseng.2017.12.003

(Kim, Kim, & Lee, 2016), and pectin content (Croak & Corredig, 2006; Demirdöven & Baysal, 2015), among others (Arendse, Fawole, Magwaza, Nieuwoudt, & Opara, 2017; Fan, Zhang, Li, Huang, & Wang, 2016; Steidle Neto et al., 2017). In particular, SSC is a major factor affecting the maturity and sweetness of orange juice (Magwaza & Opara, 2015; Wibowo et al., 2015). Studies have demonstrated that the factors affecting the quality of fruit juice are closely related to their electrical properties (Harker & Dunlop, 1994; Garcıa, Torres, De Blas, De Francisco, & Illanes, 2004; Żywica & Banach, 2015). Therefore, electrical properties of fresh juice need to be determined in the design and development of a reliable operation.

Research on detection of agri-foods has prompted an interest in the evaluation of their electrical responses under different stimuli (Naderi-Boldaji, Fazeliyan-Dehkordi, Mireei, & Ghasemi-Varnamkhasti, 2015; Zhu, Guo, & Wu, 2012; Żywica, Banach, & Kiełczewska, 2012). The arguments for the introduction of alternative approaches to permittivity, impedance, and conductivity included rapid measurement, less labour, and convenient operation (Nakawajana, Terdwongworakul, & Teerachaichayut, 2016; Nelson, 1991; Prevc, Cigic, Vidrih, Poklar Ulrih, & Segatin, 2013). The relationship between the dielectric parameters and sugar content of honeydew melon, as well as those of watermelon, have been investigated using a network analyser within the radio frequency range (Wenchuan, Nelson, Trabelsi, & Kays, 2008). In addition, the dielectric properties of various juices from 20 MHz to 4500 MHz in the 15 °C–95 °C temperature range could provide useful guidance for juice pasteurisation by dielectric heating (Zhu et al., 2012).

Impedance, admittance, resistance, conductance, equivalent parallel electrical capacitance, and equivalent serial electrical capacitance at specific frequency were used in determining the dilution degree of fruit juice (Żywica, Pierzynowska-Korniak, & Wójcik, 2005). Żywica and Banach (2015) demonstrated that a simple linear correlation between the concentration and conductance of apple juice in the 1–100 kHz range can be used to determine the total soluble solids and to detect adulteration. The aforementioned methods provide electrical information on the food but introduce costly systems. Research has been conducted using sophisticated instruments, such as network analysers, LCR meters, and impedance analysers. Additional studies have been performed to assess the electrical response of foods on the basis of measurable electrical properties by using affordable and low-cost instruments (Ryynänen, 1995).

In a single-phase transformer system, the primary coil and the secondary coil are magnetically connected and bound to two sides of the magnetic circuit. An excitation voltage is applied to the primary coil, generating an alternating magnetic flux in the core, which yields an induced voltage in the secondary coil. Contrary to aforementioned electroanalytical methods, an alternating magnetic flux is used as stimulus; the output voltage of an secondary coil of electrolyte systems can be evaluated (Jin et al., 2015; Yang, Jin & Wang, et al., 2015). According to *Ohm*'s law, the induced voltage can be divided between the internal impedance of the coil and the external impedance of the voltmeter during the measurement (Pryor, 2013). The output voltage changes as physicochemical properties of the secondary coil vary (Jin et al., 2015).

Fruit and vegetable juice containing massive free ions and charge-carrying compounds can act as the media of the secondary coil. Different output voltage response curves can be obtained under these magnetic flux excited by the primary voltage. In the previous study, an alternating magnetic flux was used for the measurement in a system with one magnetic circuit. However, the effect of induced voltage polarity on the output voltage at various measurement points was ignored. In the current study, a system with two magnetic circuits was established. Various electric potential points were measured to investigate the output voltage of orange juice with different physicochemical properties. The approach provides a potential method for liquid food electroanalysis by applying synchronous magnetic flux within two individual magnetic circuits.

## 2. Materials and methods

### 2.1. *Experimental principle*

Details of the measurement set-up are presented in Fig. 1. The set-up included the following (Fig. 1a): 1, AC power source (PS-6102T, Taiwan Pusi Electronics Co., Ltd., Taiwan); 2, primary coil ($N_P = 95$); 3, magnetic circuit (silicon steel core, No. PC80, *Ni* content >80%, length = 520 mm, thickness = 20 mm); 4, sample coil (glass spiral tube as the support of the secondary coil, $N_S = 14$); 5, constant-temperature chamber; 6, glass link hole (measurement points); 7, platinum plate electrodes; 8, voltmeter (UT631, Uni-Trend Group Limited Co., Ltd., Shanghai, China); 9, circulating constant-temperature water bath (MP-5H, Yiheng Scientific Instrument Co., Ltd., Shanghai, China). The juice was injected into a glass spiral tube with an internal diameter of 4 mm, which acted as the secondary coil. The two coils were connected in series by a tube (length: 200 mm), as shown in Fig. 1b. A constant-temperature glass chamber was located outside the secondary coil for circulating cooling water and keeping the temperature constant.

*Lenz's* law and the right-hand rule (Saslow, 2002, pp. 505–558) state that under an alternating magnetic flux, the direction of the induced electromotive force is controlled by the direction of the coil spiral. Therefore, unlike our previous study (Yang, Jin & Bin, et al., 2015), the present study has a system including two sample coils with different connection modes—namely, an in-phase system and a reverse-phase system (Fig. 2). For the in-phase system, two connected coils are in the same spiral direction (anti-clockwise plus anti-clockwise) (Fig. 2a). For the reverse-phase system, two connected coils are in different spiral directions (clockwise plus anti-clockwise) (Fig. 2b).

The measurement points *a*, *b*, *o*, −*a*, and −*b* are presented in Fig. 1a. Therefore, the output voltages $U_{-aa}$, $U_{oa}$, $U_{-bb}$, and $U_{ob}$ can be detected under synchronous magnetic flux. In theory, the output voltage $U_{-aa}$ ($E_{total}$) in the in-phase system would be doubled because induced voltages ($E_{coil1}$ and $E_{coil2}$) in the two coils have a 0° phase difference; however, the $U_{-aa}$ in the reverse-phase system would be zero because induced voltages ($E_{coil1}$ and $E_{coil2}$) in both coils have a 180° phase difference.