International Journal of Chemical Studies

P-ISSN: 2349–8528
E-ISSN: 2321–4902
IJCS 2019; SP6: 778-782

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(Special Issue -6)
3rd National Conference
On
PROMOTING & REINVIGORATING AGRI-HORTI, TECHNOLOGICAL INNOVATIONS
[PRAGATI-2019]
(14-15 December, 2019)

Ohmic heating, a novel technology for processing of liquid foods: A review

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Abstract
Ohmic heating is a thermal process in which heat is generated internally by passing alternating electrical current through a body such as a food system, that serves as an electrical resistance; therefore this technology can also be referred as electro-conductive heating, joule heating, electro-heating, electrical resistance heating and direct electrical resistance heating (Sastry, 2008). The main advantage of ohmic heating is the rapid and relatively uniform volumetric heating in which we can use large size heating tubes with lower shear rates and it allows the heating of fragile particles. Electrical conductivity is the main parameter in ohmic heating and for purely liquid foods, the electrical conductivity increases linearly with temperature but in overall it falls as the concentration of solids increases. Proper electric conductance management is essential to successfully apply ohmic heating. During batch heating tests, the temperature difference in the smaller ohmic unit (4.8 cm long) ranges from 1 to 2 ºC and in the larger unit (30.4 cm long) it showed considerable differences in temperature along its axis for different voltage gradients. A wide range of ohmic heating applications have been reported in different products such as sour cherry juice; orange juice; apple, orange, and pineapple juices; grape juice and pomegranate juice. In ohmic heating processing, the effect on the quality and shelf life of apricots in syrup was studied by using a continuous pilot scale ohmic unit which comprises a hopper containing the product, a pump, a control system, a heating column, a holding and cooling tube, a storage tank for recycling, an aseptic tank to store the treated product and an aseptic filler.

Keywords: Ohmic heating, liquid foods

Introduction

Different emerging technologies for thermal food processing were developed and today's era demands for those technologies which result in high quality with minimum processing. Ohmic heating is the volumetric method of heating in which heat is generated internally within the food mass. Ohmic heating is an emerging method of thermal processing which have the feature of HTST treatment (Halden *et al.*, 1990) [11] with lower energy inputs (Choi *et al.*, 2011; Sastry *et al.*, 2011) [7, 29]. During ohmic heating (Fig.1) the alternating current is passed through the food material, where food acts as a resistor to the flow of electric current and leads to the instant volumetric heat generation by following the Joules first law of heating (Pereira & Vicente 2010; Lima *et al.*, 1999 and 2001; Wang, 2014) [26, 18, 19, 34]. Ohmic heat treatment of food material has been found to reduce microbial load of the food material simultaneously with the inactivation of the inherent enzymes (Demirdoven & Baysal 2014; Yildiz & Baysal 2006; Jakob *et al.*, 2010) [9, 36, 14]. Despite the problems of electrochemical degradation associated with it, ohmic heating has been successfully studied for its use in preheating, blanching, pasteurization and extraction (Leizerson, & Shimoni, 2005; Lima & Sastry, 1999; Lakkakula *et al.*, 2004) [17, 19, 20, 16].

A majority of studies that have explored the effect of ohmic treatment have focused on a number of commercial products from pulp (strawberry), or puree (pea) to juice (grape), etc. (Castro et. al, 2004; Icier et. al, 2008; Icier *et al.*, 2006) [5,12,13]. However, the present chapter is confined to put some light on the studies conducted on ohmic heating of various liquid food material and its effects on various parameters of the food material.

Ohmic Heating of Tomato Juice

The rate of change of the electrical conductivity of tomato juice with temperature for 70 V/cm has been fund higher compared to other lower voltage gradients applied. As the voltage gradient increased, time and system performance coefficient (SPC) decreased. The voltage gradient has a statistically significant effect on the electrical conductivity and SPCs. Linear model has been observed

to be the most suitable model for describing the electrical conductivity curve of the ohmic heating process of tomato juice. Makroo *et al.* (2016) [22] investigated the effects of ohmic heat treatment on the enzyme inactivation in tomato juice and characteristics of the paste prepared from the treated juice. PG (Polygalacturonase) and PME (Pectin methyl esterase) enzyme inactivation achieved in 1 min of ohmic heating at 90°C was similar to that of conventional hot water heating of 5 min at the same temperature. The kinetic analysis showed that the PME & PG inactivation and ascorbic acid degradation followed the first-order trend in ohmic as well as conventional treatment of tomato juice, however total color change (E) found to follow least-squares non-linear parameter algorithm behavior. Thermal treatments lead to the increased release of phyto-chemicals from the matrix which results in a significant (p<0.01) increase in lycopene content during the early phases of the treatments. Tomato juice inoculated with pathogens was treated by ohmic heating at 80 °C with pulse waveform (0.1 duty ratio) and different frequencies (0.06, 0.2, 0.5, and 1 kHz) by Kim *et al.*, 2017. The electric field strength was fixed at 47.7 V/cm. Pulsed ohmic heating prevented electrode corrosion sufficiently at low frequencies (0.06-0.2 kHz). Pulsed ohmic heating at low frequency effectively inactivated the bacteriophage surrogate as well as pathogenic bacteria without producing sub-lethal injury. The increased electroporation effect at low frequencies was suggested as a reason for the reduced resuscitation level. Moreover, quality of tomato juice was not degraded and electrode corrosion was not observed regardless of frequency. Therefore, Kim *et al.*, 2017 recommend using low frequency pulsed ohmic heating for tomato juice processing rather than higher frequency.

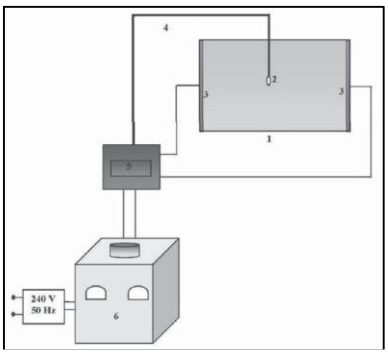

Fig. 1. Schematic diagram of a basic lab scale ohmic heating setup. 1 Ohmic cell, 2 Thermocouple probe, 3. Electrodes, 4 hermocouple wire, 5 Temperature controller and indicator, 6 Variac transformer. (Makroo *et al.*, 2016a) [23]

Ohmic Heating of Apple Juice

Fruit Pectin methyl esterase (PME) activity is responsible for clarification of juices and wines and for reduction of viscosity. For that reason, PME is commonly used for improving the texture and firmness of processed fruit, as well as in the extraction and clarification of fruit juices. Commercial preparations of PME are produced from fungal sources, especially from A. niger (Jayani *et al.*, 2005). During the conventional thermal processing, the inactivation of exogenous pectin methyl esterase in apple juice has been found to follow first-order kinetics (Wilinska *et al.*, 2008). Mixed apple juice having the pH, saccharide concentration and total soluble solids of 3.55, 124 g/l and 13.46 °Brix, respectively was ohmically heated using a frequency of 50 Hz and voltage adjustable by a power relay (Jakob *et al.*, 2010) [14]. The same trend has been observed when experiments for the same materials were carried out under ohmic heating (Jakob *et al.*, 2010) [14]. During ohmic heating, same intervals of temperature were applied as for conventional heating experiments, which imply that the rate of inactivation was not very different. The inactivation curves were evaluated by the multi-temperature method, using the first-order kinetic model.

Ohmic Heating of Citrus and Lemon Juice

To avoid microbial spoilage, it is necessary to cause inactivation by applying heat. Although the technology of ohmic heating appears to be promising and highly effective, there is little information concerning the effects of this technique on specific food products compared to conventional pasteurization. Ohmic, as well as conventional thermal treatments, reduced microbial counts by at least 2-3 orders of magnitude compared to their number in fresh orange juice, which was 102.5 colony-forming units (CFU)/mL. Both conventional and ohmic heating leads to the browning of orange juice. The release of flavor compounds in ohmic-heated orange juice can be explained by two corresponding phenomena. On the one hand, thermal treatment may cause a release of bonded components from the medium. Due to the short residence time during ohmic heating, the released flavor compounds are not quickly degraded as during conventional pasteurization. Therefore, higher flavor compounds concentrations can be retained in orange juice after ohmic heating Fig.2. Ohmic heating has been found suitable for products with a high carotenoid content. No non-thermal effects of ohmic heating have been shown to be detrimental for these molecules. Pasteurization with ohmic heating proved to be a very good alternative for protecting epoxy-xanthophylls, which are strongly degraded during conventional heating. Other xanthophylls were also significantly more preserved during ohmic treatment (Achir *et al.*, 2015) [1]. The most interesting aspect of the ohmic heating treatment is the lack of overheating due to heat transfer aspects (Leizerson & Shimoni 2005) [17]. Cristina *et al.* (1999) [8] reported that the electrical conductivity was dependent on the concentration (°Brix) and the temperature (20-80°C) for lemon juice. The electrical conductivity increases with increasing concentration up to approximately 30°Brix, when it starts to decrease. The decrease in electrical conductivity may be due to the increase in viscosity of the juices with concentration which decreases the mobility of the ions. The time required to heat the lemon juice from 20 to 74ºC at 30 V/cm was 1.64, 2.18 and 4 times longer than at 35, 45 and 55 V/cm, respectively (Darvishi *et al.*, 2011).

Ohmic heating of grape juice

Grape juice production includes washing, crushing and mash heating steps before pressing. Pressing step of production is highly affected by juice yield and nutritional composition of grape juice. And this process of fruit juice is a slow, laborious and highly energy-consuming step in the production. So that various method has been investigated to improve efficiency and increase the yield of fruit juices in pressing step. Novel techniques such as PEF, ohmic heating, and microwave heating could be applied to increase pressing yield for different fruits (Baysal *et al.*, 2011) [2]. Hot pressing of grape mashes for juice production has been shown to increase the juice yield 50% to 70%. Higher yields have been observed in OH comparing the conventionally heated grape mash. The increase in yield has been found 10.14% for ohmic heating and 5.23% for conventional thermal heating group comparing the control group (unheated). The ohmic heating application indicates the highest total phenolics, highest a (red color) and minimum color differences (E) as compared with the conventional thermal heating. As a result, ohmic heating applications can be used as a pre-treatment for the grape juice production line (Baysal *et al.*, 2011) [2]. In the grape juice the ohmic heating rate increases as the voltage gradient increases. The critical PPO deactivation temperature at 40 V/cm is lower than that of at 20 and 30 V/cm probably because of the faster increase in electrical conductivity at higher voltage gradients causing higher deactivation in PPO. At constant voltage gradient and at 60 °C, a small increase in the activity with holding time could be observed until the deactivation started after a certain span of time (min). The one step first order kinetic model has been found to adequately describe the deactivation kinetics of PPO, for the temperature range of 70–90 °C (Icier *et al.*, 2008).

Ohmic Heating of Sugarcane Juice

Numerous investigations have been carried out to devise a treatment that can increase the shelf life of sugarcane juice to allow its entry into the mainstream juice processing industries. Thermal processing is the most common method studied for sugarcane juice preservation (Chauhan, *et al.*, 2007; Mao *et al.*, 2007; Sangeeta *et al.*, 2013) [6, 20, 28]. Although thermal treatment is very effective for microbial and enzyme inactivation, the use of high temperatures (80-90°C) is known to cause off flavor and discoloration in the processed product (Wang & Sastry 2002) [34]. Ohmic heating has been applied to different commercial food products (like strawberries, grapes, orange juice) and has been rendered as a time-efficient process (Saxena *et al.*, 2016a) [31]. The analysis of OH-treated juice samples has shown a significant increase ($p < 0.01$) in the % reduced activity of PPO initially, at 24 V/cm and 32 V/cm (EFS) which gradually decreased as the treatment time was increased (Fig. 3). This behavior of the enzyme, when exposed to low electric field strengths, suggests possible biochemical reactions that might have occurred due to changes in the molecular spacing that accelerated the inter-chain reactions (Saxena *et al.*, 2016b) [30]. The kinetic analysis has found that the biphasic model was best fit to depict the inactivation of PPO in sugarcane juice suggesting the presence of two iso-forms of the PPO enzyme. The trend for the decimal reduction time (D value) for both labile and stable fraction, suggests that the efficiency of PPO inactivation increases with both electric field strength (EFS) and temperature. The ZV values (V cm-1) of the labile fractions are easier to inactivate at 60–70 °C while the stable fractions become susceptible to inactivation at 80–90 °C. Saxena *et al.* (2016a) [31] suggested that ohmic heating is an energy efficient method that can be thought of as an alternative for the preservation of sugarcane juice. Complete inactivation of yeast and molds could be achieved by the OH-treatment. The ohmic heating process method for sugarcane juice can be improved in many ways such as the use of improved packaging material, use of class-I preservatives like salt, lemon to aid further reduction in treatment time and prolong the shelf life of the product.

Ohmic Heating of Watermelon Juice

Most of the watermelons are either eaten fresh or processed into juices due to their high sensorial and nutritive attributes. However, the presence of an enzyme such as Polyphenol oxidase (PPO), pectin methylesterase (PME), and peroxidase catalyze browning reactions that bring about undesirable changes in the color and flavor of the product (Aguiló-Aguayo *et al.*, 2009). Thermal treatment at 90 °C for few minutes leads to the slight decrease in lycopene content Sharma *et al.*, 2008 [32]. Kong *et al.*, 2010 [15]. Rawson *et al.*, 2011 [27] suggest that the changes in the lycopene content may be due to the destruction by heat and oxidation resulting in fragment products like acetone, methyl-heptenone, laevulinic aldehyde, and glyoxal. Ohmic heating and hot water heating (0-60 seconds at 90 C) of watermelon juice causes 2.35 - 3.94% and 1.67 - 4.27% change in lycopene content respectively. Total phenolic content (TPC) of fresh watermelon juice has been reported around 11-12 mg Gallic acid equivalents (GAE)/100 ml (Makroo *et al.*, 2016a, Rawson *et al.*, 2011) [23, 27]. The thermal treatment leads to the reduction in bioactive compounds of plant material due to oxidation, thermal degradation, leaching (Guida *et al.*, 2013) [10] a similar reduction in TPC of watermelon juice has been observed when it was exposed to OH thermal treatments. Hot water and OH treatment of watermelon juice for 1 min at 90°C results in 42.6% and 39.7% reduction in TPC respectively. During ohmic heating, the significant change occurs in pH of watermelon juice probably due to electrochemical effects. OH treatment causes lesser changes in the total change in color (E) of watermelon juice when compared with conventional thermal treatment of same temperature histories. Hue angle increases at a higher rate in HW than that of OH treatment (Makroo *et al.*, 2016a) [23].

Ohmic Heating of Pomegranate Juice

In spite of having the ability to get shorter treatment time in ohmic heating, Yildiz *et al.* (2009) [36] performed OH of Pomegranate juice by adjusting the voltage gradient (10-40 V/cm) to obtain the same thermal history within the conventional method. Total phenolic content and rheological properties could result in differences in the heating rates of the pomegranate juice under same ohmic heating conditions. Pomegranate juices represented non-Newtonian dilatant type of fluid behavior. This type of fluid behavior could be due to the passed particles from kernels or husk during the extraction. The increase in viscosity with an increase in shear rate (shear thickening behavior) could be due to these deflocculated particles. The extraction with without peel resulted to different consistency, color, and total phenolic contents. The heating process, either ohmic or conventional, causes an increase in phenolics amount. Ohmic heating did not cause any different effect in rheological properties, and total phenolic contents of pomegranate juice than the conventional heating.

Ohmic heating provokes less browning during heat treatment rather than the conventional heating (p<0.01). Ohmic heating can be applied as an alternative heating method providing rapid and uniform heating (Yildiz *et al.*, 2009) [36].

Ohmic heating of milk

The technology of ohmic heating is promising as a more effective and cheaper method for the pasteurization of liquid type food products than conventional methods Sun *et al.*, (2009) [33]. Alkaline phosphate (ALP) is a membrane-bound glycoprotein, widely distributed in animal tissues and microorganisms. Milk ALP is a dimeric metalloenzyme comprised of two similar subunits of molecular weight of about 85 kDa. The enzyme requires two metals for maximal activity: zinc is essential and magnesium is stimulatory (Castro *et al.*, 2001) [4]. Jakob *et al.*, 2010 [14] studied the caprine milk ALP activity loss under ohmic heating measured in the temperature range of 52–64 °C. The values of both the rate constant k10 and activation energy Ea of caprine milk ALP were higher for ohmic heating than for conventional heating. The former parameter was higher by 45% and the latter one by 18%. Sun *et al.* (2009) [33] studied the ohmic heating of skimmed milk and found that there was a multiplier effect of the ohmic and hot-water treatment (sublethal-ohmic heating and lethal-hot water heating treatment) on microorganism cell death. However, no cell death was observed after sublethal-ohmic heating treatment. This indicates that the electric current of sublethal-ohmic heating treatment caused a certain extent of non-thermal effect to microorganisms and this effect did not lead to cell death but decreased the heat resistance of microorganisms. However, on the contrary, Palaniappan *et al.* (1992) [25] have reported that there is no difference between the effects of ohmic heating and conventional heating under the condition of identical thermal histories on the death of yeast cells at currents ranging from 0.5 to 1.0 A of 60 Hz. The current and frequency (7 A and 20 kHz) applied by Sun *et al.* (2009) [33] were much higher than those used in the experiments of Palaniappan *et al.* (1992) [25].

Ohmic Heating of Liquid Egg

Liquid egg products are so sensible to heat treatments that it can result in many undesirable changes which would provide the occurrence of many undesirable changes. To avoid these undesirable changes, ohmic heating could be applied to liquid whole egg products as a faster and homogeneous alternative heating method (Bozkurt & Icier 2009) [3]. Ohmic heating could cause minimal structural changes because of its ability to heat the liquid whole egg faster and uniformly, or electrical effects rather than thermal effects could affect its rheological behavior unexpectedly because of the higher amount of the denaturation of proteins and other structural breakdowns (e.g. electroporation effects) (Bozkurt & Icier 2009) [3]. The liquid whole egg has been heated ohmically by matching the same heating curve of the conventional method to examine the effect of heating methods on the apparent viscosities of the liquid whole egg by Bozkurt & Icier (2009) [3]. It was found that the time required reaching to 60 from 20 °C was 80 s. The total solid content and pH values of liquid whole egg were determined as 26.67 and 7.48, respectively. The change in consistency coefficient of liquid whole egg products during ohmic and conventional heating was investigated. Consistency coefficient values were in the range of 0.0074–0.0132 and 0.0071–0.0131 for ohmic heating and conventional heating, respectively. There was a decrease in the values of the consistency coefficient up to 50°C and sharply increased at 60°C. Structural changes in proteins as a result of increasing temperature could be the reason of a sharp increase in the consistency coefficient at 60°C. Because the same heating curve was matched by both methods, the different activation energy for apparent viscosity showed also different effects of heating methods, possibly electrical effects and/or effects of fast homogeneous heating. On he other hand, the temperature was a prominent factor in changes of rheological properties of the liquid whole egg during heating. The results indicated the importance of the accurate determination of the rheological behavior for the design of the ohmic heating systems (Bozkurt & Icier 2009) [3]. Finally, Bozkurt & Icier (2009) [3] suggested that Ohmic heating could be an alternative heating method for the liquid whole egg.

Conclusion

Ohmic heating has been studied in various ways for different food products such fruit juices, liquid whole egg, milk etc. The uniformity, consistency or viscosity, particle size, electrical conductivity are the main properties of food material which affect its ohmic heating behavior. During ohmic heating, liquid food material has been observed to get heated more rapidly and uniformly as compared to that of conventional heating. Inactivation of enzymes and microorganisms has been found to follow the same trend as that of conventional heating, however, the rate of inactivation has been reported to be higher than that of conventional heating due to various probable reasons such as rapid and uniform heating, electrical or non-thermal effects etc. No detrimental effects have been reported to the nutritional parameters of the liquid food while processed with ohmic heating. When processing a liquid food material by ohmic heating, physical parameters such as color and rheology can be also retained similar or better than that of conventional heating. Application of higher frequency and higher current has shown significant non-thermal effects on microbial inactivation as compared to the lower frequency and lower current. Hence it can be concluded ohmic has a great scope of industrial application in food processing particularly for liquid foods, it could be proven to minimize the various negative effects of conventional thermal processing techniques.

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