Ohmic Heating: A Review and Application in Food Industry

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ABSTRACT
Heat is used in many ways including in food processing. Heating methods are first used after the invention of electricity, include ohmic heating. This paper is written to review ohmic heating thoroughly in food industry, including the brief history, principle and its application. Ohmic heating is a development of conventional heating where it generates heat from alternate electrical current. In the process, the conductivity ($\sigma = LI/AV$) plays a big role as it is used to spread the heat evenly and quickly. The ionic substance such as salts and sugar increase the conductivity. The basic principle of Ohmic Heating is the use of Ohm's law ($R = V/I$) because this technology is based on the electrical resistance of food. The world has developed with the growth of technology, ohmic heating used in many aspects of life including the food production commercially as it has many advantages that it is able to uniformly heats the product, low cost on maintenance, has high energy efficiency, able to produce high quality food and environmentally safer. The lack of general studies about ohmic heating also makes it difficult to control the system. It is also known ohmic heating is unable to work effectively for non-conductive foods. Regardless to the pros and cons, ohmic heating has been applicated commercially for pasteurizing, sterilizing, food thawing and blanching and fermentation.

Keywords: *alternating current, conductivity, ohmic heating, ohm's law, electrical heating*

1. INTRODUCTION

Ohmic heating is a development of conventional heating. Conventional heating requires more time in which protein denaturation occurs and destroys nutrients in food [1]. In ohmic heating, the heat spreads evenly and quickly throughout the product due to the increasing of permeability cell wall, which this phenomenon will speed up the heating process with minimal damage to nutrition [2]. Ohmic heating is distinguished from other electrical heating methods by the presence of electrodes in contact with the food, frequency, and waveform [7]. This technology is based on the electrical resistance of food. Heating occurs when an alternating electrical current pass through the food, which results in the internal generation of heat [8]. The use of ohmic heating back then was difficult to apply as the development of technology not yet as advance as this decade. As ohmic heating has various advantages in term of time and cost, the disadvantage of ohmic heating is known with its limitation of object that can be heated. Ohmic heating works well to liquid foods such as fruit and vegetable products, milk, ice-cream mix, eggs, whey, soups, stews, fruits in syrup, heat-sensitive liquids, and soymilk for the purpose of heating, pasteurization and sterilization [6]. This paper reviews the history, principles, advantages and disadvantages and application of ohmic heating systems and compares them with other heating options, with the aim of increasing understanding of ohmic heating systems and increasing the utilization.

2. HISTORY

In 1841, James Prescott Joule discovered that the current electricity gives off heat (joules) and the heat released is produced from resistance or ohms (Ω) [3]. Ohmic heating has been used for the first time in the early 20th century, when it was used for pasteurizing milk by flowing fluid on plates with different electric voltages [4,5]. Later in 1920s ohmic heating introduced as commercial technique with the name "Electro-Pure". Then in 1930s, 50 milk sterilizers were made but in the 1950s the application was discontinued due to the high use of electricity and costs. Conventional heating has many disadvantages, which has longer cooking times and the coating of the cookware absorbs more heat, thereby reducing product quality. Also causes heat loss during the production process due to conduction, convection and radiation heat transfer mechanisms.

The wasted heat will be a loss for the industry [3]. Previous invention use ohmic heating in the making of Frankfurt-type sandwiches by passing an electric current for a certain period of time. However, this method disappeared due to the lack of resources and technology [1]. In the last two decades, materials and designs for Ohmic heating have been improved. In the 1980s, Electricity Research and Development Centre (UK) revised this technology and improved the design procedures of ohmic heating systems. APV Baker Ltd holds the patent for industrial use of this technology [6].

3. PRINCIPLE

Ohmic heating (also known as Joule heating) is a method of heating that is using the electrical resistance of food. The basic principle of ohmic heating is the change in electrical energy into heat energy in an electrical conductor [2]. Heating occurs when an alternating electrical current passes through the food, which results in the internal generation of heat [8]. Heat is generated instantly and volumetrically inside the food materials (joule effect) due to the ionic motion [6]. The amount of heat generated is directly relate to the current induced by the voltage gradient in the field, and the electrical conductivity [9]. The electrical conductivity of food material depends on various factors such as temperature, voltage gradient, food composition such as sugar content, etc [6]. Electrical conductivity increases in the presence of ionic substances like acids and salts, however, decreases with nonpolar components (fats, lipids, etc.) [10]. The basic principle of ohmic heating is the using of ohm's law in the process, which described as equation (1) [14],

$$R = V/I \tag{1}$$

R (ohm) is the resistance between two points in a circuit, V is the voltage (volt) and I is the current (ampere).

Electrical conductivity (σ) is a measure of how well a material accommodates the movement of an electric charge. Electrical conductivity also plays a big role as it is one of the reasons the heat is able to spreads quickly and evenly. The current is carried by ions, and therefore the conductivity increases with the concentration of ions present in solution, their mobility, and temperature of the water. The conductivity of the solution can be increased significantly by adding mineral salts, mineral acids, carboxylic acids, some complexes of acids with amines, stannous chloride, and some tetra alkyl ammonium salts [11,12]. Other study reported that electrical conductivity decreased as the particle size increased[5]. Calculating the electrical conductivity can be done by using the equation (2) [5].

$$\sigma = LI/ AV \tag{2}$$

L is the gap between two electrodes (m); A is the cross-section area of the sample in the heating cell (m^2); I is the current (A); and V is the voltage (V) [13]. The heat generation rate during ohmic heating is described as equation (3) [3],

$$Q = \sigma E^2 \tag{3}$$

Q is for internal energy generation rate, σ is local electrical conductivity, and E is electric field strength. Field strength does effecting the heat transfer, greater the electric field intensity, higher the electrical conductivity and faster the heating rate. The field strength application results in increasing fluid motion through capillaries, which is directly proportional to electrical conductivity [21,22]. The electric field strength can be varied by adjusting the electrode gap or the applied voltage[16].

Ohmic heating is a development of conventional heating. Some studies stated that it is similar to microwave heating as it turns electrical energy to heat due to ion movement and friction [16]. Alternating current power supply is used in ohmic heating thus the heating can be done continuously. The illustration of ohmic heating in a system is illustrated in Figure 1 [15].

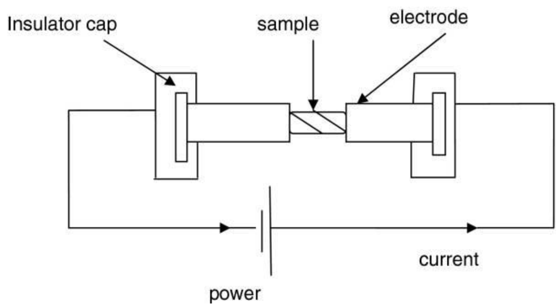

Figure 1. Ohmic heating is using Alternating Current (AC) as the power supply and the current flows into the two electrodes in the circuit. As the illustration shows the sample is in between the electrodes which act as direct heating process. Insulator cap is used as a protection from injury while using [15].

Frequency and waveform of applied voltage affects the electrical conductivity values and the process of heating the samples. The common frequencies employed for ohmic heating of foods are 50 Hz and 60 Hz [15]. Lowering the frequency of alternating current significantly increases the amount of oil extracted and also enhances enzyme stabilization and other processes [23] .

4. ADVANTAGES AND DISADVANTAGES

The advantage of ohmic heating is that it uniformly heats in contrast with the non-uniform distribution of microwave heating. Most importantly, the required temperature is achieved quickly and able to shutdown of the system in instance [18]. Ohmic heating has high energy efficiency as the study shows that 90% of electrical energy is converted into heat. Ohmic heating can produce safe, high quality food, and to validate any commercial process by experimentally demonstrating its application. The shelf life of ohmically processed foods is comparable to that of canned and sterile, aseptically processed products [15,17]. Ohmic heating can be used to pasteurize, fermenting and sterilizing foods. Ohmic heating has low maintenance cost as it is lack of moving parts, also reducing the problems or surface fouling during heat transfer [3,18].

The disadvantage of ohmic heating is the lack of studies about ohmic heating in results, it is hard to locate the cold-spots and overheated regions since there is no validation technique to do it. Also, there is limitation of data to indicate the factors behind the heating time. As a commercial method, it also needs more adequate safety and quality-assurance protocols [18]. The particle size affecting the heating time and heating rate in ohmic heating. The bigger the particle, the heating rate decreased and the heating time increased [5,19]. Food containing fat globules is not effectively heated during ohmic heating process, as it is non-conductive due to lack of water and salt. Based on this study, ohmic heating is unable to work effectively for non-conductive foods which means for most solid foods. Solid foods have high density and high specific heat which slower the heating time [5, 20].

5. APPLICATIONS OF OHMIC HEATING IN FOOD INDUSTRY

Applications existing for Ohmic heating include: blanching, thawing, on-line detection of starch gelatinization, fermentation, peeling, evaporation, dehydration, fermentation, and extraction.

5.1 Pasteurization and Sterilization

Pasteurization involves heating food to a temperature that kills disease-causing microorganisms and substantially reduces the levels of spoilage organisms. Pasteurization or pasteurization kills microbes (mainly bacteria) in food and drink, such as milk, juice, canned food, and others [24]. Ohmic heating is very often used in pasteurization or sterilization of food products resulting in excellent quality. Pasteurization and sterilization both can be used for milk and other liquid products depends on the purpose. If the purpose to kill pathological microorganism, pasteurization will be used in the process. Instead, sterilization may kill all the microorganism in the product including the good one for body. Ohmic heating can be used for ultra-high temperature (UHT) sterilization of foods, and especially those that contain large particles (up to 2.5 cm) that are difficult to sterilize by other means [15]. The pasteurization of milk was carried out using ohmic heating by pumping milk between two metallic plates with a voltage difference between them [16]. Microorganism killed by pasteurization are acid producers such as streptococci, lactobacilli, microbacteria, coliforms, and micrococci. The gas producers are coliforms, *Clostridium butyricum*, *Torula cremoris*. The ropy or stringy fermentation's microorganism are *Alcaligenes viscolactis* and *Enterobacter aerogenes*. The proteolytic organisms are *Bacillus spp*., *Pseudomonas spp*., *Proteus spp*., *Streptococcus liquefaciens*. The lipolytic organisms are *Pseudomonas fluorescens*, *Achromobacter lipolyticum*, *Candida lipolytica*, and *Penicillium spp*. Pasteurization can be done through these methods which are Vat Pasteurization, High Temperature/Short Time (HTST), Ultra-pasteurization (UP) and Ultra-High-Temperature (UHT) [24, 26].

5.2 Food Thawing and Blanching

Ohmic heating system is an innovative method used in thawing frozen food. Ohmic heating can be used to thaw frozen foods placed between two electrodes and applying an alternating current to it. The advantages of this process include, water and waste water are not generated, thawing can be relatively uniform due to volume heating and the process can be easy to control [15]. Thawing was done to shrimp blocks which successfully thaw the product without increase in moisture content of the product [25]. The use of ohmic heating system to thaw frozen meat provides less weight loss [27]. Blanching by ohmic heating may considerably reduce the extent of solute leaching, as compared to a hot water process in a short blanching time regardless of the shape and the size of the product. In the research found that electric fields enhanced moisture loss during the blanching of potato slices [28, 29].

5.3 Fermentation

Recently the use of ohmic technology has also begun to be applied to the fermentation on cocoa products and on arabica coffee products to reduce the acidity of coffee beans [31]. During fermentation the temperature used is different based on the optimum temperature of the microorganism. The optimum fermentation temperature of *Saccharomyces cerevisiae* is generally about 30°C, while the optimum temperature for enzymatic hydrolysis is generally about 50°C. In order to combine both optimum temperature conditions, the temperature setpoint generally used is 37~38°C [31]. The design of fermenter using ohmic heating system is shown in Figure 2 [31]. The fermenter controlling unit has been proven to be able to maintain, control and monitor the temperature condition in the reactor in real-time. The energy efficiency achieved the value of 81.96% up to 86.29%. The ohmic-based fermenter was able to produce a high uniformity of temperature distribution both for liquid and non-liquid products, especially wet products, or high moisture content products.

The electrodes are placed in between the fermenter reactor tube and transmitting the electric current. In the fermenter reactor the materials will be placed which designed to be able to do batch and continuous fermentation process. This design is a prototype of the fermenter that can be developed for commercial used in food industry as it has a high energy efficiency and a high uniformity of temperature distribution.

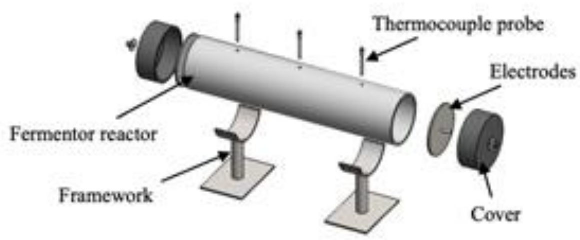

Figure 2 Design of ohmic based fermenter

Table 1 Studies of Ohmic Heating in Food Processing

Application	Electrical Properties	Temperature (◦C)	Time	Overall Outcomes	References
Black garlic pre-treatment	110, 120 and 130 V (Voltage); 5.38 S/m (EC); 11, 12, 13 V/cm (Electric Field Strengths/EFS)	60, 70, 80	10,15,20	Combination 130 V at 70◦C in 10 minutes caused greater concentration of reducing sugars (3.7 ± 0.02 mg/g sample and cuts down the time to attain the characteristic colour of black garlic from 30 to 12 days	34
Carrot juice pasteurization	60 kHz (AC); max,120 V/cm	15-80	7	The OH-treated juice presented greater colour preference ($p < 0.05$) and has a high level of acceptance among consumers	35
Inactivation kinetics (Weibull model) and morphological changes of Salmonella spp. in infant formula	60 Hz; 6 V/cm	50, 55, 60	45, 24, 5	Combination 130 V at 60◦C, OH presented a more intense inactivation rate than conventional heating Improving the nutritional value and food safety	36
Liquid egg pasteurization (combined with concurrent external heating)	50 V; 20 kHz	20-63.3	1.5-3.5	OH treatment combined with concurrent external heating approaches reduced the process time and prevented local overheating.	37
Meatballs pre-cooking	15.26 V/cm; 1.5-2.25 s/m	20-75	1.5min	OH increased cooking yields, reduced the numbers of total mesophilic aerobic bacteria, mould yeast, Staphylococcus aureus and completely eliminated Salmonella spp.	38

5.4 Extraction

Ohmic heating can also be used for extraction which are sugar beets, soymilk from soybeans, juice extraction such as apple and orange juice yields [3]. Ohmic heating is used to extract some components from plant waste as it heats the material rapidly with high energy efficiency in comparison to the conventional heating, therefore it can be an appropriate alternative method for extraction of pectin industrially. The pectin was extracted from the waste of orange, which give the best results in energy efficiency and yield were obtained at the voltage gradient of 30 V/cm, pH of 1.5 and S/L ratio of 1:20 g/ml [32]. Ohmic heating was used to extract anthocyanins from black rice bran, Anthocyanins is the pigment for dark purple colour in food industry. The colourant powder prepared by ohmic heating assisted (CP-OHM) had higher colourant yield, anthocyanin pigments, and bioactive compounds than conventional method [33]. The quality of products treated by ohmic heating can be improved depends on the characteristics of the product and the treatment applied. Table 1 provides summary of past research using ohmic heating in the food processing.

6. CONCLUSION

Ohmic heating is advantageous in food processing especial the liquid and semi solid foods. It is able to produce better product quality, with less cooking time, low maintenance cost, better energy efficiency and environmentally friendly. The method works better for materials with ionic particles that has high conductivity to spread the heat. More studies are needed to develop the utility and features of the technology and provide adequate protocols while applicating the system. The applications of this technology are for sterilization, pasteurization, fermentation, thawing, blanching and other food process that hasn't been mentioned such as extraction, gelatinization and dehydration.

REFERENCES

1. W. Müller, L. Ferreira Marczak and J. Sarkis. Microbial inactivation by ohmic heating: Literature review and influence of different process variables. Trends in Food Science & Technology. 2020, pp.650-659. doi: 10.1016/j.tifs.2020.03.021
2. Supratomo, Salengke, Mursalim and R. Syahrir, Seminar Nasional: Perhimpunan Teknik Pertanian Indonesia. Penggunaan Pemanas Ohmik untuk Ekstraksi Karagenan Murni dari Rumput Laut Euchema cottonii. Seminar Nasional: Perhimpunan Teknik Pertanian Indonesia, 2018.
3. T. Kumar. A Review on Ohmic Heating Technology: Principle, Applications and Scope. INTERNATIONAL JOURNAL OF AGRICULTURE, ENVIRONMENT AND BIOTECHNOLOGY. 2018. doi: 10.30954/0974-1712.08.2018.10
4. A. de Alwis and P. Fryer. The use of direct resistance heating in the food industry. Journal of Food Engineering. 1990, pp. 3-27. doi: 10.1016/0260-8774(90)90036-8S.
5. S. Palaniappan and S. Sastry. Electrical Conductivities of Selected Solid Foods During Ohmic Heating. Journal of Food Process Engineering. 1991;14(3):221-236. doi: 10.1111/j.1745-4530.1991.tb00093.x
6. F. Icier. Ohmic Heating of Fluid Foods. Novel Thermal and Non-Thermal Technologies for Fluid Foods. 2012, pp. 305-367. doi: 10.1016/b978-0-12-381470-8.00011-6M.
7. M. Ramesh. Sterilization of Foods. Encyclopedia of Food Sciences and Nutrition. 2003, pp. 5593-5603. doi: 10.1016/b0-12-227055-x/01148-2
8. R. Pereira and A. Vicente. Environmental impact of novel thermal and non-thermal technologies in food processing. Food Research International. 2010, pp. 1937. doi: 10.1016/j.foodres.2009.09.013S.
9. S. Sastry and Q. Li. Modeling the ohmic heating of foods. Food Technology. 1996; pp. 246–248.
10. G. Ozkan, B. Guldiken and E. Capanoglu, Effect of Novel Food Processing Technologies on Beverage Antioxidants. Processing and Sustainability of Beverages. 2019;:413-449. doi: 10.1016/b978-0-12-815259-1.00012-4
11. S. Zhuiykov. Semiconductor Nano-Crystals in Environmental Sensors. Nanostructured Semiconductors. 2018, pp. 475-538. doi: 10.1016/b978-0-08-101919-1.00009-x
12. J. Bhagwan, N. Kumar and Y. Sharma, Characterization, and Optimization of Mn O Nanofibers for Improved Supercapacitive Properties. Nanomaterials Synthesis. 2019;:451-481. doi: 10.1016/b978-0-12-815751-0.00013-4H.
13. Darvishi, M. Khostaghaza and G. Najafi, Ohmic heating of pomegranate juice: Electrical conductivity and pH change. Journal of the Saudi Society of Agricultural Sciences. 2013;12(2):101-108. doi: 10.1016/j.jssas.2012.08.003
14. C. O'Sullivan. Ohm's law and the definition of resistance. Physics Education. 1980, pp. 237-239. doi: 10.1088/0031-9120/15/4/009

15. K. Varghese, M. Pandey, K. Radhakrishna and A. Bawa. Technology, applications and modelling of ohmic heating: a review. Journal of Food Science and Technology. 2012, pp. 2304-2317. doi: 10.1007/s13197-012-0710-3

16. V. Silva, L. Santos and A. Silva. Frontispiece: Ohmic Heating: An Emerging Concept in Organic Synthesis. Chemistry - A European Journal. 2017. doi: 10.1002/chem.201783362

17. P. Skudder, Ohmic heating: new alternative for aseptic processing of viscous foods, Food Engineering, 1988, 60, 99–101.

18. M. Sakr and S. Liu, A comprehensive review on applications of ohmic heating (OH). Renewable and Sustainable Energy Reviews. 2014, pp. 262-269. doi: 10.1016/j.rser.2014.07.061

19. M. Zareifard, H. Ramaswamy, M. Trigui and M. Marcotte, Ohmic heating behaviour and electrical conductivity of two-phase food systems. Innovative Food Science & Emerging Technologies. 2003, pp. 45-55. doi: 10.1016/s1466-8564(02)00088-7

20. N. Kaur and A. Singh, Ohmic Heating: Concept and Applications—A Review. Critical Reviews in Food Science and Nutrition. 2015, pp. 2338-2351. doi: 10.1080/10408398.2013.835303

21. I. Castro, J. Teixeira, S. Salengke, S. Sastry and A. Vicente, Ohmic heating of strawberry products: electrical conductivity measurements and ascorbic acid degradation kinetics. Innovative Food Science & Emerging Technologies. 2004;5(1):27-36. doi: 10.1016/j.ifset.2003.11.0018

22. K. Halden, A. De Alwis and P. Fryer, Changes in the electrical conductivity of foods during ohmic heating. International Journal of Food Science & Technology. 2007, pp. 9-25. doi: 10.1111/j.1365-2621.1990.tb01055.x

23. N. Lakkakula, M. Lima and T. Walker, Rice bran stabilization and rice bran oil extraction using ohmic heating. Bioresource Technology. 2004, pp. 157-161. doi: 10.1016/j.biortech.2003.08.010

24. S. Watts, A mini review on technique of milk pasteurization. Journal of Pharmacognosy and Phytochemistry, 2016, 99-101.

25. M. Balaban, T. Henderson, A. Teixeira and W. Otwell, Ohmic thawing of shrimp blocks. Developments in food engineering. Proceedings of the 6th International Congress on Engineering and Food, Chiba, Japan, eds J. Yano, R. Matsuno & K. Nakamura, Blackie Academic and Professional Press, London, 1994.

26. S. Oliver, B. Jayarao and R. Almeida, Foodborne Pathogens in Milk and the Dairy Farm Environment: Food Safety and Public Health Implications. Foodborne Pathogens and Disease. 2005, pp. 115-129. doi: 10.1089/fpd.2005.2.115

27. B. Duygu and G. Ümit, Application of Ohmic Heating System in Meat Thawing. Procedia - Social and Behavioral Sciences. 2015, pp. 2822-2828. doi: 10.1016/j.sbspro.2015.06.400

28. S. Mizrahi, Leaching of soluble solids during blanching of vegetables by ohmic heating. Journal of Food Engineering. 1996, pp. 153-166. doi: 10.1016/0260-8774(95)00074-7

29. K. Wingerstorm, 3,997,678 (1976).

30. H. Chen and L. Wang, Technologies for Biochemical Conversion of Biomass, Academic Press, 2017.

31. D. Sagita, D. Darmajana, D. Hidayat, Novrinaldi and A. Sitorus, Design and performance of ohmic-based fermentor model for controlling fermentation process. IOP Conference Series: Earth And Environmental Science, 542. doi: 10.1088/1755-1315/542/1/012033

32. H. Saberian, Z. Hamidi-Esfahani, H. Ahmadi Gavlighi, A. Banakar and M. Barzegar, The potential of ohmic heating for pectin extraction from orange waste. Journal of Food Processing and Preservation. 2017;42(2):e13458. doi: 10.1111/jfpp.13458

33. P. Loypimai, A. Moongngarm, P. Chottanom and T. Moontree, Ohmic heating-assisted extraction of anthocyanins from black rice bran to prepare a natural food colourant. Innovative Food Science & Emerging Technologies. 2015, pp. 102-110. doi: 10.1016/j.ifset.2014.12.009

34. K. Ríos-Ríos, M. Gaytán-Martínez, D. Rivera-Pastrana, E. Morales-Sánchez, M. Villamiel, A. Montilla, . Ohmic heating pretreatment accelerates black garlic processing. LWT 2021;151:112218.

35. L. Negri Rodríguez, R. Arias, T. Soteras, A. Sancho, N. Pesquero, L. Rossetti, Comparison of the quality attributes of carrot juice pasteurized by ohmic heating and conventional heat treatment. LWT 2021;145:111255.

36. R. Pires, J. Guimarães, C. Barros, C. Balthazar, A. Chincha, M. Freitas et al. Ohmic heating increases inactivation and morphological changes of Salmonella sp. and the formation of bioactive compounds in infant formula. Food Microbiology 2021, pp. 103737.

37. C. Wang, Y. Llave, N. Sakai, M. Fukuoka Analysis of thermal processing of liquid eggs using a high frequency ohmic heating: Experimental and computer simulation approaches. Innovative Food Science & Emerging Technologies 2021, pp. 102792.
38. I. Sengun, G. Yildiz Turp, F. Icier, P. Kendirci, G. Kor. Effects of ohmic heating for pre-cooking of meatballs on some quality and safety attributes. LWT - Food Science and Technology 2014, pp. 232-239.