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A Review on Ohmic Heating Technology: Principle, Applications and Scope

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ABSTRACT

Ohmic heating is a novel and alternating thermal processing technology wherein food materials are heated by passing electric current through materials. Ohmic heating has extreme potential for achieving rapid and uniform heating in foods, providing microbiologically safe and high quality foods. Ohmic heating presents a wide range of potential applications including pasteurization, sterilization, aseptic processing, cooking, thawing, blanching, evaporation, extraction, fermentation, and in the military field or long-duration space missions. This review discusses the brief history, basic principle, some process parameters, applicable food products, potential commercial applications and current industrial status of ohmic heating in food industry throughout the world. The review also highlights the scope and work done on ohmic heating in India. The corrosion problems in electrodes and heterogeneous heat generation rate and distribution are interesting area for further research. Ohmic heating is a good comparable with the other ideal technologies like microwave heating, radio-frequency heating and induction heating. More and intensive investigations are required to assess performance and to reduce the overall cost of ohmic heating for viability of commercial application of this technology also in developing countries like India.

Highlights

- The key advantages of ohmic heating are better product quality, less cooking time, lower capital cost, better energy efficiency and environment friendly process.
- Ohmic heating technology is chiefly and commercially industrialized for pasteurization and sterilization but continuous efforts are being made to adopt other applications also in near future.

Keywords: Ohmic heating, Electrical conductivity, Applications, Current status, India

Heating is a traditional and widely used treatment applied for processing and preservation of foods. Today's era demand for high energy efficient and cost effective heating technologies without compromising with safety and quality of products. WHO (2015) estimated 600 million-almost 1 in 10 people in the world-fall ill after eating contaminated food and 420,000 die every year. Children under 5 years of age carry 40% of the food borne disease burden, with 125,000 deaths every year. Consequently, food safety is the biggest issue at present. Besides it, limited and expensive energy sources and high energy demand of food industry had drawn attention of researchers from many decades. In the food industry, thermal processing is one of the most important unit operations for microbial destruction and food preservation. Among traditional preservation methods, canning, freezing and drying are considered the most energy-intensive processing operations (Hendrickson 1996). The total amount of energy needed for processing and packaging is estimated to be between 50-100 MJ per kg of total retail food product (Smil 2008).

Conventional heating processes are based on conduction and convection mechanism, results in very heterogeneous heat treatment and notable loss of textural and microbiological quality of the food (Icier 2012). Homogeneous heat treatment is an essential factor for preventing food borne diseases (ICMSF 1998). In conventional method, the use of high temperatures to destroy microorganisms and inactivate food enzymes usually has adverse effects on sensorial and nutritional properties of food. Although food fortification can overcome certain nutritional degradation, sensorial attributes are difficult to retain. Today's consumer demands for safe and minimally processed foods with natural flavor and ingredients, and preserved health-promoting nutrients.

Heating technologies have observed marvelous advancements with the development of technologies such as ohmic heating, dielectric heating which are highly energetic and efficient as the heat is generated directly inside the food. Ohmic heating is the technology using electrical energy and convert it into thermal energy. It has high energy efficiency because 90% of electrical energy is converted into heat (Skudder 1988). According to International Energy Outlook (2016) electricity is the world's fastest-growing form of end-use energy consumption. World net electricity generation was 21.6 trillion kilowatt-hours (kWh) in 2012 and estimated to be increased to 25.8 trillion kWh in 2020.

Ohmic heating is also called Joule heating, electrical resistance heating, direct electrical resistance heating, electro heating or electro conductive heating. In ohmic heating process, food components become the elements of an electric circuit through which an alternating current (AC) flows, generating heat in the foods based on their intrinsic properties of electrical resistance (De Alwis and Fryer 1990). The energy generation is proportional to the square of the local electric field strength and the electrical conductivity of the product (Ruan et al. 2001). Ohmic heating provides rapid and uniform heating, which reduces the treatment time and results in less thermal damage to vitamins, pigments and other elements (Sastry 2005). In ohmic heating higher temperature in particulates than liquid can be achieved without risks of fouling on heat transfer surface and burning of food product which is impossible for conventional heating. Worldwide researches in the last few decades have shown a large number of potential applications of ohmic heating. It includes blanching, evaporation, fermentation, extraction, sterilization, pasteurization and heating of foods to serving temperature in the military field or long-duration space missions (Sastry *et al.* 2009). Still most applications are waiting for commercial exploitation (Sastry 2005). Ohmic heating has been proved feasible for wide variety of food products viz., milk, fruit- vegetables and their products, meat products, sea foods, flours and starches etc. (An and King 2007). Ohmic heating can produce safe, high quality food and to validate any commercial process.

Brief History

The concept of ohmic heating technology is not new and dates back to 1897 (Jones 1897). In 1841, James Prescott Joule discovered that the passage of electric current releases heat, hence this process is also known as Joule heating. He found that the heat produced was proportional to resistance of the wire multiplied with square of electric current. Electrical resistance is measured in Ohm (Ω). Since the heat results from electrical resistance, it is referred to "ohmic" heating. The application of ohmic heating was first introduced in late 1920s as a successful commercial technique, referred to as the "Electro-Pure" process (Anderson and Finkelstein 1919). In 1930s, 50 industrial electric milk sterilizers were in operation but disappeared in 1950s (Getchell 1935). This application was discouraged apparently due to high electric and processing costs (Fryer and Li 1993). Also, other applications were abandoned because of the problems of improper contact between electrodes and the food product, electrolysis and product contamination due to unsuitable electrode materials (Mizrahi *et al.* 1975). But over last few decades, a number of attempts have been made to use this technology in several food processing applications (De Alwis and Fryer 1990). APV Baker Ltd developed first commercial ohmic heating system for the sterilization of particulate foods (Skudder 1992).

Basic principle

Most foods contain high levels of water and dissolved salts and these solutions can conduct electricity through electrolytic conduction. When electrolytes are placed in an electric field, the ions present within the electrolyte move towards the electrodes with opposite charges. The movement of ions in the electrolyte generates heat. Also the moving ions within it collide to each other, which in turn create resistance for the movement of ions and increase their kinetic energy, thereby heating the product (Singh and Heldman 2014). Similarly, Heat is produced directly within the food itself by Joule heating as alternating electric current is passing through a food material, with the result internal heat generation causing temperature rise (Reznick 1996). An ohmic heater is an electrical heating device that uses a food's own electrical resistance to generate the heat (Fryer *et al.* 1993). Heat is generated instantly and volumetrically inside the food materials (joule effect) due to the ionic motion. The amount of heat generated is directly related to the current induced by the voltage gradient in the field and the electrical conductivity of the materials being heated (Icier and Ilicali 2005b).

The heat generation rate during ohmic heating is described by Samprovalaki *et al.* (2007):

$$Q = \sigma E^2 \qquad \ldots(1)$$

which is equivalent to the more familiar I^2R. Here Q is the internal energy generation rate (W m^{-3}), σ is the local electrical conductivity (S m^{-1}) and E is the electric field strength (V m^{-1}). The voltage distribution is given by

$$\nabla (\sigma \nabla E) = 0 \qquad \ldots(2)$$

Thus depends on the distribution of electrical conductivity within the medium as well as the system geometry. Equation (2) differs from the usual form of Laplace's Equation (3) because it deals with a medium in which the electrical conductivity is a function of both position and temperature.

$$\nabla^2 E = 0 \qquad \ldots(3)$$

The most important parameter in the applicability of ohmic heating is the electrical conductivity of the material. Most foodstuffs, which contain water in excess of 30% and dissolved ionic salts, have been found to conduct sufficiently well for ohmic heating to be applied.

Main components of ohmic heating system

An ohmic heating system for processing certain food basically consists of a heating chamber, a pair of electrodes and an alternating power supply to give electrical energy to system (Castro 2007). The electrodes should be made from most conductive materials and also these should have low cost and corrosion resistance (C-tech innovation 2014). There should also be provision for instant start/stop and process temperature control (Icier 2012).

Process parameters

Many factors like electrical conductivity, field strength, particle size, concentration and electrodes have been found to influence ohmic heating process of a food.

1. Electrical conductivity

Electrical conductivity of food is the most critical property affecting ohmic heating process (Palaniappan and Sastry 1991). The electrical conductivity depends on the temperature, ionic breakup and microstructure setup of the food material and applied field strength (Lima and Sastry 1999). The electrical conductivity increased linearly with the temperature during ohmic heating at constant voltage gradient (Castro *et al.* 2004).

2. Frequency and waveform

Lima *et al.* (1999) showed that altering the frequency and waveform of applied alternating current influence the heating rate. Lakkakula *et al.* (2004) reported that lowering the frequency of alternating current significantly increases the amount of oil extracted. Lowering the frequency of alternating current enhances enzyme stabilization and other processes too (Lima and Sastry, 1999).

3. Particle size and concentration

Palaniappan and Sastry (1991) reported that electrical conductivity decreased as the particle size increased. Sastry and Palaniappan (1992) determined that heating time increased with concentration of carrot cubes.

4. Field Strength

The field strength application results in increasing fluid motion through the capillaries, which is directly proportional to electrical conductivity (Halden *et al.* 1990). Higher strength fields resulted in effective inactivation of microbes (Barbosa-

Canovas *et al.* 1998). An and King (2007) reported that heating rate increases with the increases in voltage gradient.

5. Electrodes

The electrodes are the major factor for heat loss thereby influencing the efficiency of ohmic heating system (De Alwis and Fryer, 1990). Zell *et al.* (2011) reported that thicker the electrode lower the rate of temperature increase which is a reflection of its larger mass and lower electrical resistance. They also evaluated various metals (Stainless steel, titanium, platinized titanium and aluminum) for suitable electrode material. Thinner aluminum was reported to give highest temperature at electrode interface.

Range of Food Products

Ohmic heating can be applied to a large scale of food products.

1. Milk

Ohmic heating technology was first proposed by Anderson & Finkelstein (1919) for milk heating. Plenty of investigations have proved ohmic heating to be superior method for pasteurization of milk which can minimize the fouling problem (Stancl and Zitny 2010). Ohmic heating has not only a thermal lethal effect, but also a non-thermal-lethal effect on microorganisms (Sun *et al.* 2008).

2. Fruits and Fruit products

Many local, commercial, perishable and heat sensitive type fruit products have been tested for example strawberry pulps by Castro *et al.* (2004); sour cherry juice by Icier and Ilicali (2004); apple, orange, and pineapple juices (Amiali *et al.* 2006); pomegranate juice by Yildiz *et al.* (2008); orange juice by Leizerson and Shimoni (2005), Qihua *et al.* (1993) and Icier and Ilicali (2005a); lemon juice by Darvishi *et al.* (2011).

3. Vegetables

Eliot *et al.* (1999) studied the influence of precooking by ohmic heating on the firmness of cauliflower. The experimental data represented that ohmic heating in combination with low-temperature precooking in saline solutions provides a practical solution to HTST sterilization of cauliflower florets. Eliot and Goullieux (2000) concluded that an ohmic pretreatment prevented loss of firmness when compared to a conventional pre-treatment.

4. Meat

Ohmic heating could be a fast-alternative method for meat cooking (Sarang *et al.* 2008) and thawing (Icier *et al.* 2011). Ohmic cooking offers the potential for safer meat products by effectively inhibiting microbial growth through uniform temperature distribution in the product and cooking instantly inside the food (Mitelut *et al.* 2011). Turkey meat was cooked using ohmic heating, yielding high quality products with an 8-15-fold reduction in cooking time (Zell *et al.* 2010).

5. Seafoods

Ohmic heating enhances the effectiveness of the cooking of seafood like shrimps (Roberts *et al.* 2002), surimi (Shiba and Numakura 1992) etc. Ohmic cooking is faster and more uniform giving similar color, texture and yield compared to conventional cooking (Lascorz *et al.* 2016). Yongsawatdigul *et al.* (1995) investigated the feasibility of ohmic heating to maximize the gel functionality of Pacific whiting surimi. The ohmically heated gel showed more than a two-fold shear stress and shear strain over the gel heated in water bath.

Applications

Ohmic heating has great potential in a large number of food processing applications including pasteurization, sterilization, microbial inactivation, enzyme stabilization, extraction, blanching, thawing, starch gelatinization and fermentation.

1. Pasteurization and Sterilization

Leizerson and Shimoni (2005) reported that ohmic heated orange juice contains higher concentrations of flavor compounds and has two times longer sensory shelf life than conventionally pasteurized juice. Elzubier *et al.* (2009) used ohmic heating for sterilization of guava juice. Castro *et al.* (2004) studied on degradation of vitamin C in strawberry products pasteurized by ohmic and conventional heating. They concluded that the presence of electric field did not affect the ascorbic acid degradation.

2. Microbial inactivation

In ohmic heating the low frequency allows cell walls to build up charges and form pores results in reduced D-value as compared to traditional heating methods. This reduction has been observed for *Bacillus licheniformis* and *Escherichia coli* (Pereira *et al.*, 2007), *Bacillus subtilis* (Cho *et al.* 1999), *Streptococcus thermophilus* (Sun *et al.* 2008) and *Byssochlamys fulva* (Castro 2007).

3. Enzyme stabilization

Moreno *et al.* (2013) reported that the polyphenol oxidase (PPO) in apple cubes was completely inactivated by the ohmic treatments. Lakkakula *et al.* (2004) and Loypimai *et al.* (2015) showed that ohmic heating as an effective method for rice bran stabilization (inhibition of lipase enzyme) comparable to the steaming method.

4. Extraction

Katrokha *et al.* (1984) used electrical heating to aid the extraction of sucrose from sugar beets, while Kim and Pyun (1995) used ohmic heating to extract soymilk from soybeans. Lima and Sastry (1999) found that ohmically heated apple tissue prior to mechanical juice extraction significantly increased apple juice yields with respect to non-treated apple tissue. Halden *et al.* (1990) investigated the potential application of ohmic heating to increase dye diffusion in beet. Lakkakula *et al.* (2004) reported that ohmic heating increased the total percent of lipids extracted from rice bran.

5. Blanching

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 (Mizrahi 1996). Wigerstrom (1976) found that electric fields enhanced moisture loss during the blanching of potato slices.

6. Thawing

Ohmic thawing have advantages of less microbial growth and the better quality product compared to the conventional methods (Icier *et al.* 2010). There were significant effects of ohmic heating on thawing rate and energy utilization ratio (EUR) of frozen beef cut (Bozkurt and Icier 2012). The use of ohmic heating system to thaw frozen meat provides less weight loss (Duygu and Umit 2015).

7. Starch Gelatinization

An and King (2007) investigated the application of ohmic heating for gelatinization of rice starch and rice flours. Ohmically heated commercial starch showed the greatest decrease in enthalpy and thus less energy requirement. Wang and Sastry (1997) studied the effect of starch gelatinization on electrical conductivity. The results showed that electrical conductivity of native starch suspensions was linear with temperature.

8. Fermentation

The ohmic heating technique may decrease the lag period of fermentative bacteria and so decrease of fermentation time in processing of yogurt, cheese, beer, or wine (Cho *et al.* 1996).

Advantages of ohmic heating

The advantages of ohmic heating include better product quality, less cooking time, lower capital cost, better energy efficiency and also that it is an environment friendly process. Ohmic heating includes maintaining the color and nutritional value of food, shorter processing times and higher yields as compared to conventional heating (Castro *et al.* 2004; Vikram *et al.* 2005; Darvishi *et al.* 2011). Additionally, ohmic heater cleaning requirements are comparatively less than those of traditional heat exchangers due to reduced product fouling on the food contact surface. De Halleux *et al.* (2005) concluded that industrial application of ohmic cooking would allow energy efficiencies greater than 90% and a reduction in energy consumption of 82 to 97% compared to traditional smoke-house cooking. The ohmic heating is an environment friendly process (Darvishi *et al.* 2011). In general, Ohmic heating systems are advantageous:

- Due to an optimization of investment (increased efficiency, low capital cost),
- Instant shutdown of the system,
- Reduced maintenance costs because of the lack of moving parts
- It can heat particulate foods and liquid–particle mixtures.

- By ohmic heating, high temperatures can be rapidly achieved. For example temperatures for ultrahigh temperature (UHT) processing.
- As there are no hot surfaces for heat transfer, there is low risk of product damage due to burning

Current status all over the world

However, huge research works on ohmic heating technique have been done for investigation of potential applications, optimization of process parameters, improving of equipment materials, various designs and industrial implementation and still continue. Even though this technique is restricted to some countries in the world such as United Kingdome (UK), United States of America (USA), Canada, Japan, Sweden, Italy and Switzerland. At present, the companies manufacturing industrial ohmic heating systems are (Yildiz and Guven 2014):

1. APV Baker Ltd. (UK),
2. C-Tech Innovation (UK),
3. Agro process (IAI Group, Canada),
4. Yanagiya Machinery Co. Ltd. (Japan),
5. Kasag (Switzerland),
6. Alfa Laval (Sweden),
7. Raztek (USA),
8. Emmepiemme SRL (Italy).

It is reported that currently, there are only 18 commercial ohmic heating plants operated throughout the world and is being used for the pasteurization or sterilization of pumpable foods such as fruit and vegetable products (juices, purees, pulps etc.), milk, ice-cream mix, egg, whey, soups, soymilk etc. and aseptic packaging (Castro 2007; Icier 2012).

Works done in India

Parmar *et al.* (2016) designed a laboratory scale ohmic heating system toevaluate the behavior of electrical conductivity of sweet lime juice with temperature and the effect of ohmic heating on the various physicochemical properties of the sweet lime juice. The physicochemical properties were observed to change with change in voltage gradient, treatment time.

Shinwari and Jindal (2015) reported that the electrical conductivity (EC) of rice bran increased significantly with increase in temperature and moisture content but the variation in EC was not significant with the variation in voltage gradient. The ohmic heated rice bran showed very slow increment in free fatty acid (FFA) content as compared to control. Results showed that the ohmic heating system was good in performance.

Gomathy *et al.* (2015) designed a laboratory scale static ohmic heating unit of 1 L capacity. They reported that the ohmic heated pulp showed resemblance to that of the fresh pulp with respect to the biochemical and rheological properties without any structural breakdown upon processing. Results showed that the technique is very effective for pasteurization of papaya pulp.

The Central Institute of Post Harvest Engineering and Technology (CIPHET) developed an ohmic heater for stabilization of rice bran oil. The technology, which is likely to help in scaling up the production of rice bran oil and increasing its shelf life, is the first of its kind in the country.

Kumar *et al.* (2014) constructed a laboratory scale batch ohmic heater for pasteurization of buffalo milk and studied the microbial inactivation effects of ohmic heating and conventional heating. It was found that microbial counts resulting from ohmic heating were significantly lower than those resulting from conventional heating.

Singh *et al.* (2013) investigated the aonla pulp subjected to ohmic heating and found to be superior to conventional one in terms of quality and safe storage. Little changes were observed in Vitamin C, tannin, titratable acidity and color.

CONCLUSION

Ohmic heating has brought a revolution in food processing industry because of its broad area of applications. Its advantages over conventional and novel thermal processing technologies like microwave heating, radio-frequency heating and induction heating has drawn great attention of all the researchers. Better product quality, less cooking time, lower capital cost, better energy efficiency and an environment friendly process are the key advantages. Although this technology is chiefly and commercially industrialized for pasteurization and sterilization but continuous efforts are being made to adopt other applications in near future. Many early problems and hurdles regarding the technology have been or are being eliminated one by one. The corrosion problem in electrodes has not been removed completely is required for more research. Non-uniform heat generation rate and distribution due to electrical heterogeneity of the particle and particle shape and orientation are interesting area for further research. To assess the performance and to reduce the overall cost of ohmic heating for viability of commercial application in developing countries like India, a vast amount of technical and economic studies are still necessary.

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