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An Overview of Ohmic Heating Technology and Its Application in Food Industry

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ABSTRACT

Due to the increasing population growth today, the need for new technologies for better food processing is felt more and more. New thermal and non-thermal technologies based on physical techniques for food preservation have the ability to meet consumer demands and deliver processed foods with high quality and long shelf life, without additives. Among these heating and food processing methods are Pushed Electric Fields (PDE), High Voltage Electric Fields (HVED), Moderate Electric Fields (MEF), Ohmic Heating (OH), Pulsed Ohmic Heating (POH). Meanwhile, one of the great alternative methods for heating is ohmic heating. The ohmic heating process is an alternative method that uses electrodes to convert electrical energy into heat. Electrical conductivity of heating materials is one of the factors that determine the effectiveness of ohmic heating system. Ohmic heat can be produced effectively and efficiently from materials with electrical conductivity between 0.01 and 10 S/m. Currently, there is a wide use of ohmic heating potential in the food industry. Ohmic heating is most widely used in the food industry, including the inactivation of pathogens, enzymes, and the removal of some inappropriate compounds in food.

INTRODUCTION

Due to the increasing population growth today, the need for new technologies for better food processing is felt more and more. Various studies predict a strong population growth in the next 30 years (Hofstra and Vermeulen, 2016).The world population will be approximately 9 to 11 billion people by 2050 (Röös *et al.*, 2017). The distribution of this number is disproportionate in terms of territory and is mostly based on urban environments (Kummu *et al.*, 2016). The concern about food security is not unfounded, and in this context, there is a need for scientific innovations and new technologies in order to produce and process of food (Fróna *et al.*, 2019).A century ago, agricultural products were often available to the consumer in an unprocessed form to prepare food at home. But today, most of the food products that purchased by consumers are processed foods. Heating is one of the methods of food processing that is used to eliminate pathogens, bacteria, improve food texture, digestibility and detoxification of different types of food products (Vanga *et al.*, 2017). Despite the effectiveness of traditional technologies in terms of microbial safety, these methods lead to deterioration of sensory and nutritional properties of food. Although food fortification can overcome some food spoilage, it is difficult to maintain sensory characteristics such as aroma, taste, texture and appearance in conventional heat processing. Also, the common methods of heating food need to generate heat energy from outside the environment and then transfer it to the food. This heat transfer takes place by conduction, convection or radiation. For products containing particles, especially when the particles are very large, conventional heating methods require excessive heat processing, in which case destruction of the outer part of the particles occurs (Varghese *et al.*, 2014). In addition, conventional methods consume more energy. Considering that uninterrupted supply of energy in industrialized countries is needed to maintain life, it is possible to help save energy by using new technologies (Sprunt, 2016). New thermal and non-thermal technologies based on physical techniques for food preservation have the ability to meet consumer demands and deliver processed foods with high quality and long shelf life, without additives (Varghese *et al.*, 2014). Among these heating and food processing methods are Pushed Electric Fields (PDE), High Voltage Electric Fields (HVED), Moderate Electric Fields (MEF), Ohmic Heating (OH), Pulsed Ohmic Heating (POH), (Rocha *et al.*, 2018) Sonography, Microwave and (Lee and Jun, 2011). Meanwhile, one of the great alternative methods for heating is ohmic heating.

Ohmic heating is a fast heating method and has a large number of the applications and potential for food industry, water distillation, waste treatment, chemical processing, etc. (Sakr and Liu, 2014). Ohmic heating is the greenest technology for extraction and its use generally reduces extraction time and energy consumption (Rocha *et al.*, 2018). In ohmic heating, pasteurization and sterilization processes take place with high efficiency (Varghese *et al.*, 2014). Ohmic heating produces heat directly from inside the material and there are no limitations such as low heat transfer coefficient and also the difficulty of heat penetration to the wall of another surface (Alamprese *et al.*, 2019).Considering the progress made and the need for continuous heat

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treatment at high temperature and short time, a bright future is predicted for this method, especially in food industry processing.

Background

The ohmic heating is an old subject. In the 19th century several processes were patented that used electric flow to heat certain materials. At the beginning of the 20th century, electric pasteurization of milk was achieved by passing the milk through parallel plates with a voltage difference between them. Commercial electric pasteurizers have been used in six steps in the United States (Sastry and Palaniappan, 1992). In McConnell and Olsson's invention in 1938, Frankfurt sandwiches were cooked by passing an electric flow for a predetermined time (Verner and Oisson, 1938). In 1951, Schade introduced potato blanching method using ohmic heating to prevent enzymatic color change. At that time, due to the lethal effects of electricity, as well as the lack of insulating materials and suitable electrodes, this technology was practically abandoned. Since then, little attention has been paid to this technology except in electric smelting (De Alwis and Fryer, 1990).Over the past few decades, designs for ohmic heating have become available due to material improvements and developments. The British Electricity Council has registered and licensed a DC ohmic heating system to APV Baker (Ruan *et al.*, 2001).The special interest in this technology is due to the continuous need of food industry for heating and disinfection methods.

Conventional heating vs volumetric heating

In conventional heating, a heat source is created outside and applied to the material, and thermal energy is transferred through conduction or convection by moving the material from a high temperature region to a low temperature region. An example of a typical heating device is a kitchen stove, and heat transfer is caused by a temperature gradient between the source and the material. A common heating defect is non-uniform heating throughout the material, which occurs due to thermal conductivity gradients and low heat transfer rates. The second method of volumetric heating (microwave and ohmic heating), heating directly interacts with the molecules in the material and increases the kinetic energy of the molecules of matter. Electromagnetic waves spread at a very high speed and the electric field penetrates through it. It is called volumetric heating. The main drawback of volumetric heating is that its efficiency depends significantly on the properties of the material. Typical temperature profiles for conventional and volumetric heating processes are shown in Fig. 1.

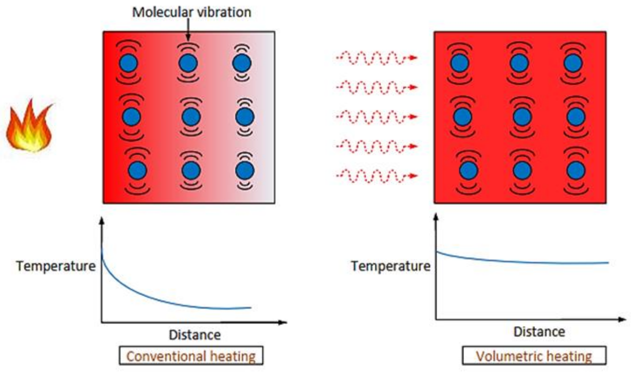

Fig 1. Typical and volumetric heating temperature profiles throughout the heating process

Ohmic heating

As electrons or ions pass through materials in the presence of an electric field, Collision with atoms and molecules produces heat. The amount of energy released depends on the mobility of charge carriers and the intensity of the electric field. The heat produced by conductive, electronic or ionic flow is called ohmic heating. An image of ohmic and ionic heating is shown in Fig. 2.

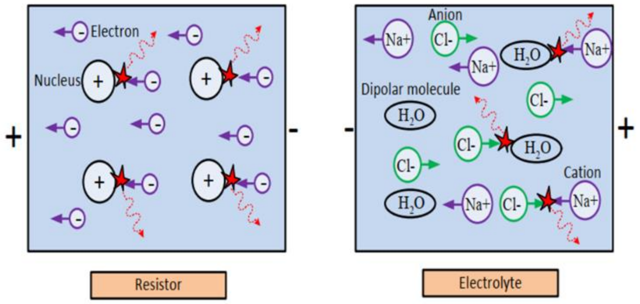

Fig 2. Ohmic heating from conduction flow (left) and ion flow (right)

The principles of ohmic heating are very simple. As shown in Fig. 3, ohmic heating works based on the passage of AC alternating flow (Ruan *et al.*, 2001). In ohmic heating, materials between two electrodes act as electrical conductors with resistance. Liquids and food solids are simultaneously heated by passing electric flow through them (Marra *et al.*, 2009).

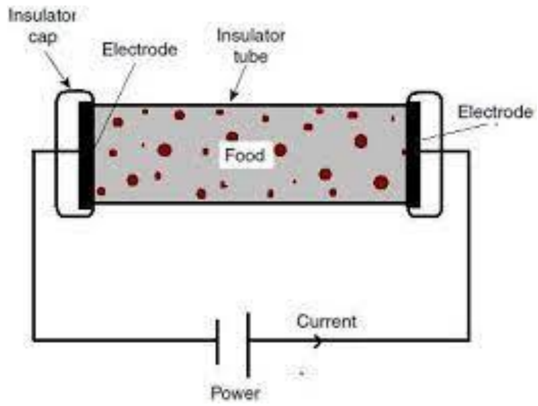

Fig 3. Schematic diagram of ohmic heating process (http://www.steemit.com)

Heating techniques commonly used for food rely on the transfer of heat from a heated surface. This heat can be produced through an electric heating element directly or indirectly from a hot environment (for example steam), through a heat exchanger (for example shell and plate tube). These methods require a temperature gradient (temperature difference) for the heat transfer process to the material, so the surface is at a higher temperature than the product. A hot surface can cause deposits and burns on surfaces for certain products. This causes the speed of heat transfer to decrease, thus having a negative effect on the product. Heating and heat transfer of highly viscous liquids or with particles is difficult. Ohmic heating does not have the mentioned problems by removing hot surfaces resulting from heating materials (Sakr and Liu, 2014). The success of ohmic heating depends on the amount of heat generation in the system, the electrical conductivity of the material, the amount of electric field, the residence time of the material, and the way the material flows through it (Takhistov, 2007).

To understand the process of ohmic heating, it is necessary to study the electrical conductivity of food and predict the resulting heating patterns. Understanding the effect of ohmic heating on sensory and microbiological quality of food is an important issue. The essential distinction between ohmic heating methods and other heating methods is the use of electrodes that are in direct contact with the material. Electrodes in ohmic heating cause connection and uniform distribution of electric flow in heated materials (Silva *et al.*, 2017).

IMPORTANT TERMS AND DEFINITIONS

Ohmic heating is a heat-based process. Therefore, the electric field strength, residence time and electrical conductivity of a food product are the most important process factors that strongly affect the temperature production and the effectiveness of ohmic heating. The applied voltage and the temperature at which the sample is heated are among the parameters used when using alternating flow frequency ohmic heating. The main property that affects ohmic heating is the electrical conductivity of food (Varghese *et al.*, 2014).

Electrical conductivity

The internal resistance of food compounds to the passage of electricity leads to the creation of heat inside the food. In other words, electrical energy is converted into heat energy. The effect of electrical conductivity in the conversion of this energy and governing equations can be seen well. Electrical conductivity is represented by σ and is a factor that shows the quality of electric flow passing through food. In fact, electrical conductivity is the ratio of flow density to electric field strength. Its SI unit is siemens per meter S/m. The amount of electrical conductivity for all materials is calculated from Equation (1) (Hoseini and Fadavi, 2017).

$$\sigma = \frac{L}{A} \times \frac{I}{V} \tag{1}$$

Where, L is the length (m), A is Area (m^2), I is electricity current (A) and V is Electric potential difference (v).

$$\sigma\tau = \sigma i + M \tag{2}$$

Electrical conductivity is a very important factor in ohmic heating. Many researchers reported the electrical conductivity of various foods including fresh fruits heated with ohmic heating. Electrical conductivity for apple, pineapple, and pear, strawberry and peach fruits is 0.05-1.2 S/m. Compared to fruit juice, the electrical conductivity of pure water is very low and is about 0.055 µS/cm. The electrical conductivity of some foods is given in Table 1.

Table 1- Electrical conductivity values of some foods heated by ohmic heating (Hoseini and Fadavi, 2017)

Matter	Electrical conductivity at 25ºC (S/m)
Black coffee	0.182
Coffee with milk	0.357
Apple juice	0.239
Cocoa milk with 3% fat	0.433
pork meat	0.64-0.86
Tomato juice	1.697
Sea water (TDS=44 mg/L)	5.8
Sea water (TDS=58.26 mg/L)	6.78
Sea water (TDS=57.78 mg/L)	6.75
Sea water (TDS=62.82 mg/L)	7.2

The voltage distribution inside the ohmic heater can be obtained from Maxwell's equation. Another method is to combine Ohm's law and continuity relationship for electric flow.

$$\nabla(\sigma\nabla V) + \frac{\partial \rho c}{\partial t} = 0 \tag{3}$$

For steady heat transfer conditions, the equation changes as follows.

$$\nabla(\sigma\nabla\nabla) = 0 \tag{4}$$

Where, σ is electrical conductivity of food (S/m), ρc: flow density (A/m³) and t is time (s)

In a constant voltage process, the volumetric heat generation rate ($\dot{u}$, W/m³) is obtained from the following equation.

$$\dot{u} = |\nabla V|^2 \tag{5}$$

During ohmic heating, the rate of heat transfer in a single-phase liquid food is expressed by the unsteady heat conduction equation with internal heat generation by the following equation.

$$\nabla(k\nabla T) + \dot{u} = \rho C_P \frac{\partial T}{\partial t} \tag{6}$$

In this equation, k, ρ and Cp are thermophysical properties that depend on the temperature of the food.

Where, k is thermal conductivity (W/mK), ρ is density (kg/m³), Cp is specific heat capacity (J/kg K).

By adding the displacement heat transfer component in relation number 6, the amount of displacement heat transfer in the food fluid can be obtained. Uniform production of heat ($\dot{u}$) leads to relatively uniform and fast heating compared to other heating methods, especially in liquid foods. As a result, this technique is suitable for continuous processing of food fluids.

In general, an ohmic heating system includes a power supply to supply system power, a variable power supply (variac) to regulate voltage, flow and voltage measurement units, an ohmic heating cell with electrodes, a temperature measurement system, and a microcomputer. It is for recording data (Hoseini and Fadavi, 2017).

Heating rate

Due to the passage of electric flow through the sample, a sensible heat is generated and the temperature increases from t_i to t_f. The amount of heat given to the system can be calculated from the following equation (Sakr and Liu, 2014).

$$Q = m\, C_P(t_f - t_i) \tag{7}$$

Heating power

The power of ohmic heating system is calculated from equation 8.

$$P = \sum VI\Delta t \tag{8}$$

Where, Δt is the period of time

Frequency and waveform

The frequency used for ohmic heating in food processing is usually 50-60 Hz and is classified as a low frequency (Knirsch *et al.*, 2010). Electroporation is the creation of pores in the cell membrane due to the existence of an electric flow, which leads to an increase in the permeability of the membrane, and finally, the diffusion of substances across the membrane is obtained. Rapid cell membrane perforation is obtained from a very low frequency. As a result, the electrical conductivity suddenly increases and affects the texture of the final product. Using high frequencies can reduce cell membrane electroporation. But it significantly increases the time to reach the required temperature (Indiarto and Rezaharsamto, 2020).

Size, specific heat capacity, and viscosity of the material

As the particle size of the material increases, the electrical conductivity decreases (Indiarto and Rezaharsamto, 2020). Materials with a particle size of less than 5 mm can affect conductivity. Large particles 15-25 mm have a significant effect on electrical conductivity and heating speed (Indiarto and Rezaharsamto, 2020).When solid particles are suspended in a liquid medium with the same electrical conductivity, the material with low specific heat capacity heats up faster (Varghese *et al.*, 2014). Materials with higher specific weight and specific heat capacity need more time to reach the desired temperature. Low-viscosity liquid materials heat up faster than high-viscosity materials (Marcotte *et al.*, 2000). Materials with higher solid particle concentrations usually heat faster (Varghese *et al.*, 2014).

Flow density

Flow density is the ratio between the amount of flow and the surface area of the electrode and is important for calculating the critical flow density used in electrode design. The voltage gradient used affects the ohmic heating time (Sakr and Liu, 2014).

Emperatures

The electrical conductivity of the sample depends on the temperature of the material. In ohmic heating, the temperature of the material changes very quickly. The amount of power is directly related to the amount of electrical conductivity. Feedback control should be used to adjust the power consumption during warm-up.

Zell et al. (2009) made a new thermocouple to monitor temperature changes during ohmic heating. They found that a triple probe was more satisfactory than a thermocouple for ohmic heating applications (Zell *et al.*, 2009). Ye et al. (2004) and Marra et al. (2009) have developed mathematical models to analyze and estimate heat transfer and temperature distribution during ohmic heating. The designed models can be used to optimize the cell shape and electrode configuration (Marra *et al.*, 2009; Ye *et al.*, 2004).

Ohmic heating designs

Ohmic heating systems have different designs, but several key elements are present in all designs (Varghese *et al.*, 2014). These elements include a heating chamber, a pair of electrodes, and an alternating flow generator that supplies the electrical energy of the system (Indiarto and Rezaharsamto, 2020). The used electrodes should be made of highly conductive, low-cost, and non-corrosive materials to prevent the release of metal ions such as Mn, Ni, Fe, Cr, and Mo into food (Zandi *et al.*, 2015). The electrodes connected to the power source must be in direct contact with the material for the electrical flow to be connected. The distance between the electrodes may vary depending on the size of the system used. The number of rows of electrodes changes the number of electric fields formed (Varghese *et al.*, 2014). Comparison of ohmic heating with other heating methods (Sakr and Liu, 2014) is shown in Table 2

Configuration types

Batch

In the batch configuration, the flow is ignored so that the material is stationary. This model facilitates the calculation of basic parameters such as electrical conductivity, heating time, and process homogeneity. This model can be used to identify an initial composition and monitor the effect of processing on the final product quality. This plan is ideal for use in the laboratory because it is a practical and useful program for the development of new methods (Indiarto and Rezaharsamto, 2020).

Parallel bar

Usually, it is used in cases where the cost of processing is more important than the material. The construction of this design is much cheaper than parallel plates, but it does not provide uniform heat in the material. As a result, liquids often have to be mixed after heating to make the temperature uniform, and it is not suitable in cases where it is necessary to be processed the material without damaging it (Sakr and Liu, 2014).

Linear

In this configuration, the product is flowing from one electrode to the other with the fluid flowing parallel to the electric field. Compared to the previous two designs, the arrangement of the two electrodes is relatively far apart (Indiarto and Rezaharsamto, 2020).

Bar arrangement

It is a low-cost option, but it can heat more than others.

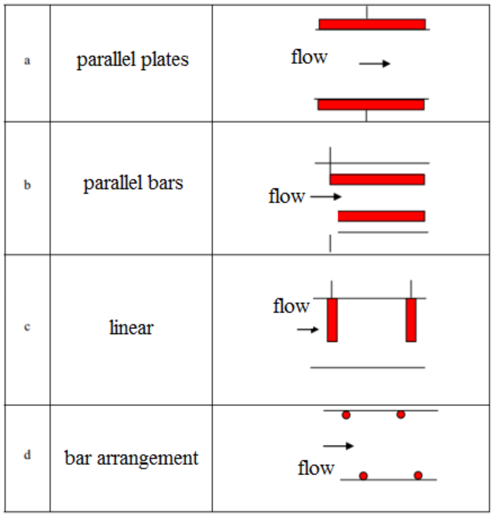

Figure 4- Typical arrangements of electrodes in ohmic heating flow (Sakr and Liu, 2014)

In the use of ohmic heating, the choice of the electrode is an important parameter (Kumar, 2018).

In previous designs, various conductive electrode materials such as titanium, stainless steel, titanium platinum, aluminum, and graphite have been used. Electrodes are usually selected based on price and corrosion resistance, which may affect ohmic heating efficiency. In cases where product quality is not important, such as waste taps, low-carbon electrodes are often used. For high-quality applications, metals such as stainless steel are preferred. Also, the frequency of the power supply should be increased significantly to avoid corrosion and apparent dissolution of the metal (Stancl and Zitny, 2010). Summary of ohmic heating applications in the industry(Sakr and Liu, 2014) is shown in Table 3.

Table 2 - Comparison of ohmic heating with other heating methods (Sakr and Liu, 2014)

	Source	Returns	Materials used for heating	Operating parameters
Ohmic heating	Electric flow is passed through the heated sample and as a result, the temperature increases due to the conversion of electrical energy into heat	82-97% energy saving and at the same time reducing the heating time by 90-95% compared to conventional heating, energy efficiency close to 100%, and uniform temperature distribution.	Liquid and solid	pH, the electrical conductivity of the heated sample, voltage gradient
Heating resistance	An electric flow flowing through a resistor converts, electrical energy into heat energy	Converts almost 100% of electrical energy into heat	Liquid, solid, and gas	It depends on the coefficients of conductive, convective, and radiant heat transfer
Microwave heating	Energy is directly transferred to materials through molecular interaction with the electromagnetic field	max 65% at 2.45 GHz	liquid and solid	It depends on the internal dielectric properties, distribution of the electromagnetic field, and the shape of the heating element
Heat pump	An electrically powered vapor compression cycle stores energy from the surrounding air into water in a tank	Depending on the operating conditions, the COP is about 1/2	Liquid, solid, and gas	Condenser inlet temperature, condenser outlet temperature, dryness fraction at the evaporator inlet, evaporator outlet temperature

Application of ohmic heating in the food industry

Ohmic heating has great potential for use in the food industry. Ohmic heating of food is used for microbial inactivation, pasteurization, extraction, blanching, melting, gelatinization and evaporation. This method can be used for different food products. In some food products for better conductivity, primary processing (to improve the ionic content and conductivity of the solid phase) should be done (Indiarto and Rezaharsamto, 2020). The smaller the difference in the conductivity of materials in the liquid and solid phases, the more uniform the electric flow is distributed so that the generated heat is evenly distributed (Samprovalaki *et al.*, 2007). Before the ohmic heating process, other pre-treatments can be made to homogenize the texture and equalize the electrical conductivity in the material to achieve uniform heating in all process steps within the material (Indiarto and Rezaharsamto, 2020).

Table 3- Summary of ohmic heating applications in the industry (Sakr and Liu, 2014)

Process	Application	Equipment	Industry
Heating liquids	Food preparation, chemical production, refining, distillation, cracking, water treatment	Different types of furnaces, reactors, and heaters	Agricultural and food products, production of chemicals, oil
Heat treatment	Food production (including baking, roasting, and frying)	Different types of ovens	Primary metals, metal products, glass, ceramics
Other heat treatment	Food production (including baking, roasting, and frying), sterilization, chemical production	Different types of furnaces, reactors, and heaters	Agricultural and food products, glass, ceramics, plastic, and rubber, chemical production

Advantages and Disadvantages

Advantages

The advantages of ohmic heating include better product quality, less cooking time, lower capital cost, higher energy efficiency, and an environmentally friendly process. Compared to other electric heating methods, it requires a less initial investment. It is also possible to make processed foods containing large particles (up to one inch) that are difficult to process using conventional heat exchangers. Additionally, due to reduced product deposition on the food contact surface, ohmic heating cleaner requirements are relatively lower than traditional heat exchangers. In general, ohmic heating systems are beneficial due to investment optimization, increased efficiency, the immediate shutdown of the system, and reduced maintenance costs due to the lack of moving parts. It can also heat food containing particles and mixtures of liquid and particles. With ohmic heating, high temperatures can be reached quickly and since there is no hot surface to transfer heat, the risk of product damage due to burning is low (Varghese *et al.*, 2014).

Disadvantages

Marcotte et al. (Marcotte *et al.*, 2000) compared the cost of installation and operation of ohmic food processing systems with conventional freezing and heating systems. It was found that the ohmic heating method is more expensive. Another problem is that foods containing fat globules are not heated effectively during the ohmic heating process because they are non-conductive due to the lack of water and salt. If these globules are present in a highly conductive area where flows can flow away from them, they may heat up slowly due to a lack of electrical conductivity. Any pathogenic bacteria that may be present in these globules may receive less heat treatment than the rest of the (Hosahalli and Marcotte, 2016). Summary of advantages and disadvantages of ohmic heating (Sakr and Liu, 2014) is shown in Table 4.

Table 4- Summary of advantages and disadvantages of ohmic heating (Sakr and Liu, 2014)

Advantages	Disadvantages	Suggestion for improvement
1. The required temperature is reached very quickly	1. Lack of information	1. Lack of information
2. Fast and uniform heating of liquid with a higher heating speed	2. Narrow frequency band	2. Narrow frequency band
3. Reducing surface sedimentation problems	3. It is difficult to monitor and control	3. Difficult monitoring and control
4. Non-transfer of residual heat after cutting off the flow	4. The complex connection between temperature and power distribution	5. The complex connection between temperature and power distribution
5. Low maintenance costs and high energy conversion efficiency		
6. The immediate shutdown of the system		
7. Reduction of maintenance costs due to lack of moving parts		
8. A silent and environmentally friendly system		
9. Reducing the risk of sedimentation on the heat transfer surface		

CONCLUSION

The ohmic heating process is an alternative method that uses electrodes to convert electrical energy into heat. The electrode is in direct contact with the heated material. The ohmic heating process provides higher-quality final products, faster cooking time, and optimal energy use. The electrical conductivity of heating materials is one of the factors that determine the effectiveness of an ohmic heating system. Ohmic heat can be produced effectively and efficiently from materials with electrical conductivity between 0.01 and 10 S/m. Currently, there is wide use of ohmic heating potential in the food industry. Ohmic heating is most widely used in the food industry, including the inactivation of pathogens, enzymes, and the removal of some inappropriate compounds in food.

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