NUEJ
Naresuan University
Engineering Journal

Suitable Voltage Determination of Ohmic Heating Process for Household Pork Steak Preparation Machine

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(Received: 13 September 2022, Revised: 12 January 2023, Accepted: 8 February 2023)

Abstract

This paper presents the procedure to determine the suitable applied voltage in the ohmic heating process for pork steak preparation combined with conventional grilling. The electrical, physical, and chemical properties parameters that are investigated. During the ohmic heating process, not only the temperature rises and duration time for each cooking level examined, but also the ampacity required of the equipment in the process is considered. In the experiment, meat samples with cross-section areas: 4 × 2, 4 × 3, and 4 × 4 inch^2 with a thickness of 0.5 inches were tested by an alternating current (AC) voltage source: 20, 25, and 30 V at a frequency of 50 Hz within 300 seconds. The criteria for selecting the suitable voltage were the rate of temperature rise of the meat sample must increase linearly for all 3 sizes of meat before the pre-boiling temperature, the maximum load current did not exceed the copper wire ampacity, and the duration time used between each adjacent stage of meat cooking was chosen to be longer. From the experiment results, the appropriate voltage for the steak cooker's default setting was 20 V for the following reasons: 1) The rates of temperature increase were linearly proportional for all 3 sizes of meat samples as well-done or internal meat temperature reached 71 ^{o}C and within 300 seconds. 2) The maximum load current of the applied voltages at AC 20 V was the lowest current (7.43 A). 3) The duration time used between each adjacent stage of meat cooking of AC 20 V was the longest time compared to others. Thus, the steak's cooking level can be easily managed. After the ohmic heating process, the steaks' physicochemical properties (pH, moisture, drip loss, cooking loss, water holding capacity (WHC), shear force, and color) were evaluated. The steaks did not approach the dangerous toxicity level, and the cooking time was nearly half that of conventional grilling.

Keywords: Alternating Current (AC), Suitable Voltage, Ohmic Heating, Steak Preparation Machine, Physicochemical Properties, Cooking level, Cooking time

1. INTRODUCTION

At present, ohmic heating is widely used in food processing and quality improvement. Preheating, cooking, pasteurization, and sterilization are all examples of these processes (Yildiz-Turp et al., 2013). Compared to other heating systems, ohmic heating allows for a quick temperature rise while saving energy. Ohmic heating is a process that results from the dissipation of heat caused by the passage of electric current through the food's resistance. To achieve a rapid temperature increase, the ohmic heating methods must account for the kind of food with low electrical resistance (Richa et al., 2017).

Generally, the ohmic heating is employed in muscle food to increase meat quality, accelerate the cooking process, and extend shelf life. However, due to the heterogeneous structure of the meat and the varying electrical conductivity of each piece of meat, a wholesale cut of meat was inappropriate for ohmic heating on an industrial scale. Consequently, the heat generated in each component differs (Shirsat et al., 2004). Nevertheless, in steak production, meat samples were categorized based on type, size, and shape. Therefore, the electrical conductivity of meat should be homogenous. The quantity of electrical current that flows through food is determined by the electrical resistance of the whole piece of meat. The electrical resistance varies with meat size, shape, and overall electrical conductivity. The electrical conductivity in meat consists of (1) muscle and the structure of the junction between connective tissues and muscle stripes, (2) Fat content retards temperature rises and results in unequal heat distribution between fat and muscle tissues (Shirsat et al., 2004a; Mahapatra et al., 2007; Damez and Clerjon, 2013), and (3) Moisture content and the concentrations of other intrinsic chemicals like salt and acid have a role in ohmic heating. The amount of salt or acid acts as a catalyst for ionization, with additional ions greatly increasing the electrical conductivity of the meat (Chen et al., 2022). When acid or salt are introduced, the rate of temperature change is increased (Marcotte and Trigui, 2000). Additionally, the inner water content influences the overall electrical conductivity by approximately 70%. As the temperature of the meat increases, the electrical conductivity of the meat also trends to increase (Shirsat et al., 2004).

Following the ohmic heating process in meat, softness, color, and toxicity are important factors to consider. The softness of the food can be measured by shear force or juiciness measurements. Zell et al. (2010) found that in the case of ohmic heating by applying a voltage to a high temperature for a short time (HTST), it will be very tough and less juicy than in the case of a low temperature that takes a long time (LTLT). But it was also found (Jung et al., 2022) that LTLT was softer than conventional heating methods because of large cooking losses. Bozkurt and Icier (2010) found that the fat content of the meat did not affect the color values. Nonetheless, ohmic heating provides brighter colors and a more homogeneous appearance of the color than conventional heating, which provides a stepped appearance of the color depending on the amount of heat radiated. The last part deals with food toxicity, which is induced by corrosion from metal to food contaminants, with the amount of corrosion varying depending on the type of metal utilized. Platinum, titanium, or food-grade metal coatings are recommended (Jun et al., 2007; Wang and Farid, 2015).

Generally, the electrical power sources in the ohmic heating process consist of alternating current (AC) and direct current (DC) sources. For both electrical power sources, the increase in temperature followed the same trend. In the case of DC ohmic heating, an oxidation reaction occurred in the anode electrode region. Consequently, the anode side of the meat has a higher internal temperature than the other side. In addition, residual metal and gel formation occurred at both electrodes during the DC ohmic heating process (Sriruwat et al., 2019). Therefore, AC ohmic heating is a better choice than DC ohmic heating. Sriruwat et al. (2020) studied the relationship between the input voltage and heat generated in pork meat by an AC ohmic heating process at voltage levels of 20, 25, and 30 V; cross-section areas of 4×2, 4×3, and 4×4 inch^2 with 0.5 inch thickness. The result shows that the rate of temperature change was linear within 3 minutes, but the temperature could not be increased to 71 ºC (well-done) except at 30 V (4×2 inch^2) before becoming a quadratic curve.

Based on the aforementioned above, AC ohmic heating with a voltage between 20 and 30 V can be used to enhance the internal temperature of a steak in less time and that was softer meat than conventional grilling. To maintain a linear rate of temperature rise while controlling the input voltage in order to cook all sizes of meat to a well-done. The leanest meat, the simplest control, the duration time, and the electrical effect must be considered.

Therefore, this paper aims to investigate the suitable voltage for the ohmic heating process determined by the temperature rise, the duration time between each adjacent stage of meat cooking, and the maximum current. The pork samples have a cross-section area of 4×2, 4×3, and 4×4 inch^2 with 0.5 inch thickness. The applied AC voltage level is 20, 25, and 30 V at a frequency of 50 Hz within 300 seconds. Furthermore, after the heating process, the experiments are shown their cooking time and quality of ohmic heating including pH, moisture content, drip loss, cooking loss, water holding capacity (WHC), shear force, and color.

2. The effect of physical and electrical factors in temperature rise

The increase in temperature during the ohmic heating process is generated by the input of electrical energy (W_e) into the meat, which is transformed into heat energy (W_h) and heat loss to the surrounding (ε), as represented by Equation (1). In addition, the electrical power is proportional to the current passing through it and the overall electrical resistance of the meat. Therefore, as the voltage rises, the temperature rises as well, changing the structure of the meat and, as the muscle structure changes, altering the rate at which the temperature rises.

$$W_e = W_h + \varepsilon$$
$$I^2 Rt = mC_p \Delta T + \varepsilon \quad (1)$$

where W_e is electrical energy (J), W_h is thermal energy (J), I is electrical current (A), R is electrical resistance (Ω), t is the duration of time for the ohmic heating process (s), m is mass (kg), C_p is the specific heat capacity of a substance (J / kg^oC), and ε is heat energy loss (J).

The electrical resistance is proportional to the electrical conductivity, cross-sectional area, and distance through which the current passes, as represented by Equation (2).

$$R = \frac{1}{\sigma} \cdot \frac{l}{A} \quad (2)$$

where A is the cross-sectional area (m^2), l is the thickness (m), and σ is the electrical conductivity (S / m).

As the temperature of a protein increases, its structure changes, resulting in a change in its overall electrical conductivity. When the temperature rises, connective tissue and muscle fibers contract more, resulting in water loss. It has been found that the meat's water is extracted from the intercellular gaps of the muscle fibers, resulting in a rise in the meat's overall electrical conductivity (Cross H.R. et al. 1986). Furthermore, Equation 1 shows that the thermal energy is mass dependent. Therefore, the increase in weight due to water has a significant effect on the rate of temperature rise.

3. MATERIALS AND METHODS

3.1 AC ohmic heating system

Figure 1(a) shows an ohmic heating system that includes a variable transformer ranging from 0 to 230 V, an ohmic cell, and measurement equipment. The ohmic cell is composed of parallel pads made of stainless steel 316L with 4.50 × 4.50 inch^2 and a thickness of 0.04 inch that is enclosed in a plastic box 4.72 × 4.72 × 1.18 inch^3.

A digital multimeter, Fluke model: Fluke-115 was used to measure the voltage drop and current, and temperature using a digital clamp meter, HT model: HT9015 by placing K-type temperature probes at places T1 and T2, each measuring 0.5 inch from the edge of the meat, as seen in Figure 1 (b).

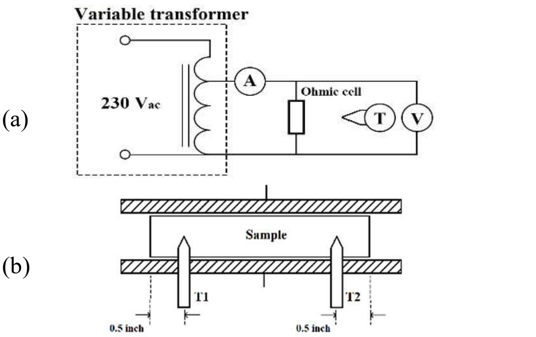

Figure 1 (a) AC ohmic heating system including variable transformer and (b) ohmic cell with temperature probe installed

3.2 Pork meat samples

Generally, the conductivity of pork meat after the slaughter at 90 minutes was in the range of 3.50 – 5.00 mS/cm, and at 24 hours after the slaughter, it was in the range of 5.00 – 8.00 mS/cm (Runowska et al., 2010). Pork meat typically contains 53% water, 26% protein, 21% fat, and less than 1% carbohydrates. where the sirloin portions are low fat (4%).

Pork meat (sirloin) from municipal slaughterhouses in Phitsanulok Province has been butchered within the last 24 hours. The muscle line was cut into a cross-section with 4 × 2, 4 × 3, and 4 × 4 inch^2, thickness 0.5 inch, and average weight (80, 115, and 150 g). The storage temperature was around 25 ºC, with an initial pH of 5.5 to 5.7.

3.3 The experiment procedure

In order to find the suitable voltage, AC voltages of 20, 25, and 30 V were compared on all 3 sizes of meat within 300 seconds. The experiment was repeated 5 times and the mean was calculated. The electrical and temperature results were analyzed according to the following steps:

1. Collect the data and plot the rate of temperature change with respect to time, the maximum current used at each voltage level, and measure the duration time at the adjacent cooking level.
2. Analyze the temperature change of each voltage level by choosing the voltage level that maintains a linear rate of temperature rise, which provides the longest duration time and appropriate current for the design of the equipment in ohmic heating.

After obtaining the suitable voltage, an examination of ohmic heating with grilling was conducted utilizing the Association of Official Analytical Chemists (AOAC) method in order to evaluate various chemical and physical properties such as pH, moisture content, drip loss, cooking loss, WHC, shear force, and color. The AOAC is a widely recognized and respected source that provides reliable chemical and microbiological methods and consensus standards, which are adopted by various international organizations as harmonized reference methods. Subsequently, the data were analyzed utilizing the Statistical Package for the Social Science (SPSS), and mean values were compared utilizing Duncan's new multiple-range tests. Additionally, a comparison of the cooking times of ohmic heating with grilling to conventional grilling was conducted at five different cooking levels, while maintaining the same temperature, and residual metal was measured using an Atomic Absorption Spectrophotometer (Thai Industrial Standards Institute 1378-2559).

4. RESULTS

4.1 Procedure for determining the suitable voltage level

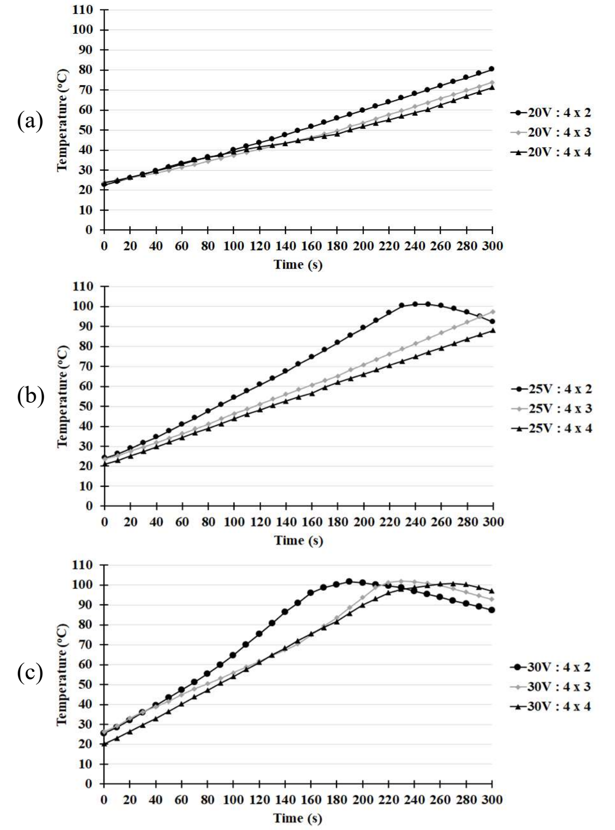

Figure 2 Relationship between temperature (ºC) and time (s) of all meat sizes when applying (a) 20 V, (b) 25 V, and (c) 30 V

The relationship between temperature and time of all meat sizes during ohmic heating at different voltages was presented in Figure 2. The rate of temperature rise prior to 71 ºC was found to be constant at all voltages, except AC 30 V 4 × 2 inch^2 as shown in Figure 2(c). The increase in conductivity and the nonlinear rate of temperature rise during the pre-boiling period were caused by the impact of water leaking from the cell membrane due to the high voltage drop. As water began to evaporate, the electrical conductivity gradually decreased. After the temperature rises to 100 ºC, the temperature remained constant and gradually decreased.

Table 1 presents the rate of temperature rise and maximum operating current for consideration of the ohmic cooking time. At AC 20 V, the temperature rise rate was between 0.16 and 0.19 °C/s, and the maximum operating current was 7.43 A. This was lower than at AC 25 V and 30 V, where the temperature increase rate was between 0.22 and 0.34, and 0.34 and 0.45 °C/s, respectively, at maximum currents of 10.42 and 12.49 A.

In addition, the duration time between each adjacent stage of meat cooking was compared in Table 2. At AC 20 V, the cooking time was the longest of all voltage levels. Comparing each size of the meat, it was found that the largest size had the longest temperature rise time. This is because the specific heat capacity of water is greater than that of muscle (Muthukumarappan et al., 2019). The specific heat capacity is the amount of heat absorbed per unit mass of a material when its temperature increases by 1 K or 1 °C. Therefore, at the same voltage level, the overall specific heat capacity of large meat is higher than that of small meat. When the duration time between each adjacent stage of meat cooking was obtained from the fitting curve in the initial to well-done temperature.

The results of the experiment indicate that at AC 20 V, the temperature can be increased to 71 °C, a well-done state, providing a consistent temperature increase for all 3 sizes of meat. This voltage level also has the longest cooking time and the lowest maximum current. Therefore, we selected 20 V as the suitable voltage for the pork steak preparation machine. Figure 3 shows a comparison of cooking time between ohmic heating with grilling and conventional grilling, demonstrating that ohmic heating with grilling requires less time than conventional grilling. Additionally, the cooking time at the well-done was approximately half that of a conventional grilling.

4.2 Chemical, physical, and residual metal on the ohmic heating process in combination with grilling

Table 3 shows the chemical changes during ohmic heating combined with grilling. The pH of the meat tended to become slightly acidic after ohmic heating, which occurs as a result of the breakdown of muscle cells that releases intracellular fluid. In cases that involve a great deal of damage (well-done), the pH is significantly different from other cooking levels ($p<0.05$).

In addition, the cooking loss was low at the medium and medium well levels, since there was substantial water loss prior to heat storage. This resulted in a low residual water value in the meat for low-temperature storage. In terms of water holding capacity, the well-done level was found to be lower than the other levels, due to the large volume of water discharged at the start. Consequently, each value was substantially different from the others ($p<0.05$).

Table 4 shows the shear force and color values during cooking. The shear forces of the medium well and well-done meats were observed to be significantly low as pork meat becomes tender at a higher temperature. In terms of color values, rare meat was the brightest because the surface browns as the temperature rises, while medium rare and medium meat had the highest redness values among the different cooking levels. As a result, each value was substantially different from the others ($p<0.05$). L* represents lightness, a* represents relative to the green (-a*) – red (+a*) opponent colors, and b* represents relative to the blue (-b*) – yellow (+b*) opponent colors.

Table 5 shows the metal residues on pork steaks treated with ohmic heating and grilling. Manganese, chromium, and iron were analyzed using an Atomic Absorption Spectrophotometer (Thai Industrial Standards Institute 1378-2559). The findings indicate that permissible levels of heavy metals had no adverse effect on the health or appearance of the steak product.

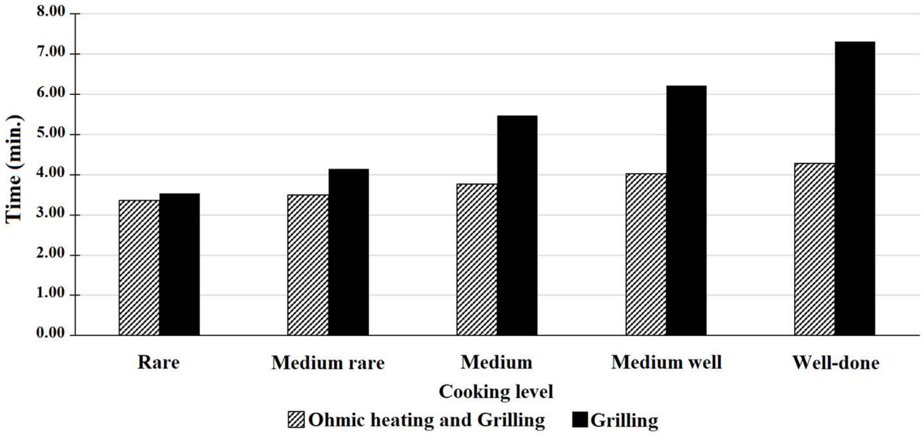

Figure 3 The relationship of cooking time (min) at different cooking levels of two heating processes.

Table 1 The rate of temperature rise and the maximum current during the ohmic heating process

Voltage level (V)	dT/dt (°C/s)			I_{max}(A)		
	(4 × 2)	(4 × 3)	(4 × 4)	(4 × 2)	(4 × 3)	(4 × 4)
20	0.19	0.17	0.16	6.96	7.43	7.24
25	0.34	0.25	0.22	9.53	10.40	10.42
30	0.45	0.35	0.34	10.47	10.49	12.49

Table 2 Duration time between each adjacent stage of meat cooking

Cooking level	Temperature (°C)	Duration time between each adjacent stage of meat cooking (seconds)								
		20V			25V			30V		
		(4 × 2)	(4 × 3)	(4 × 4)	(4 × 2)	(4 × 3)	(4 × 4)	(4 × 2)	(4 × 3)	(4 × 4)
R – MR	60-62	11	12	13	6	8	9	4	6	6
MR – M	62-65	16	18	19	9	12	14	7	9	9
M – MW	65-68	16	18	19	9	12	14	7	9	9
MW - WD	68-71	16	18	19	9	12	14	7	9	9

Note: R is rare, MR is medium rare, M is medium, MW is medium well and WD is well-done.

Table 3 Chemical properties of pork steaks treated with ohmic heating and grilling (initial pH 5.68, oil temperature 180 °C, furnace temperature 240 °C)

Cooking level	pH (after trial)	Moisture content (%)	Drip loss (%)	Cooking loss (%)	WHC (%)
Rare	5.99±0.06^{ab}	68.24±0.88	11.09±2.45^{a}	14.83±0.89^{a}	75.35±4.87^{a}
Medium rare	6.10±0.18^{a}	66.42±4.20	9.10±1.46^{a}	12.62±1.20^{b}	43.51±1.50^{b}
Medium	5.99±0.01^{ab}	67.03±0.42	7.90±0.34^{ab}	10.47±0.79^{c}	28.42±1.13^{d}
Medium well	5.93±0.06^{ab}	66.65±0.61	10.21±2.35^{a}	6.31±0.85^{d}	42.10±1.02^{b}
Well-done	5.87±0.05^{b}	68.06±1.34	5.27±0.96^{b}	4.90±0.97^{d}	34.89±0.20^{c}

Note: Vertically different characters showed a statistically significant difference at ($p< 0.05$)

Table 4 Physical properties of pork steaks treated with ohmic heating and grilling (initial pH 5.68, oil temperature 180 °C, furnace temperature 240 °C)

Cooking level	Shear force (kgF)	Color value		
		L*	a*	b*
Rare	7.32±0.39^{a}	68.85±0.55^{a}	7.26±0.31^{b}	21.52±2.00^{b}
Medium rare	7.68±0.63^{a}	61.54±0.36^{c}	8.36±0.33^{a}	23.23±1.69^{b}
Medium	4.97±0.70^{b}	59.60±0.25^{d}	8.60±0.16^{a}	25.96±0.83^{a}
Medium well	4.51±0.26^{b}	62.35±0.26^{b}	7.18±0.50^{b}	21.99±0.71^{b}
Well-done	4.38±0.31^{b}	62.76±0.13^{b}	6.30±0.26^{c}	26.63±0.44^{a}

Note: Vertically different characters showed a statistically significant difference at ($p< 0.05$).

Table 5 Metal residues on pork steaks treated with ohmic heating and grilling

Cooking level	Residual metal type (ppm)		
	Mn	Cr	Fe
Rare	0.06±0.08	0.03±0.05	0.07±0.00
Medium rare	0.00	0.07±0.02	0.08±0.06
Medium	0.11±0.03	0.04±0.02	0.13±0.01
Medium well	0.02±0.03	0.03±0.03	0.14±0.06
Well-done	0.10±0.08	0.06±0.04	0.24±0.10

5. Conclusion

This paper presents a procedure for selecting the suitable voltage of power supply in ohmic heating processes for household pork steak preparation machines at different cooking levels. This paper also considers the tenderness, color, and residual metal when used in the cooking process. Based on the proposed selection procedure in material and methods, it was determined that AC 20 V is the suitable voltage for a pork steak preparation machine, as the temperature can be raised to 71 ºC (well-done) for all 3 sizes of meat while maintaining a constant rate of temperature rise throughout 300 seconds. the maximum current did not exceed the copper wire ampacity, and the duration time between each stage of meat cooking was the longest. According to the chemical and physical experimental results, the shear forces of medium well and well-done meats were observed to be significantly low. In terms of color values, rare meat was the brightest color, while medium rare and medium meat had the highest redness values among the different cooking levels. The cooking time for well-done steak was half that of a conventional grill, and the amount of heavy metal contained in pork meat was within permissible limits and has no negative impact on the health or appearance of the steak product. In addition, the suitable voltage-selecting procedure of ohmic heating combined with grilling can be used in the design of electrical power supplies for other sizes and types of meat.

6. Acknowledgment

This study is funded by research funding from the Faculty of Engineering. We also appreciate the cooperation of the Department of Argo-Industry at Naresuan University's Faculty of Agriculture, Natural Resources, and Environment for this research.

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