Innovative Food Science and Emerging Technologies 22 (2014) 110–115

Contents lists available at ScienceDirect

Innovative Food Science and Emerging Technologies

journal homepage: www.elsevier.com/locate/ifset

Factors affecting the thawing characteristics and energy consumption of frozen pork tenderloin meat using high-voltage electrostatic field

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ARTICLE INFO

Article history:
Received 31 August 2013
Accepted 21 December 2013
Available online 4 January 2014

Editor Proof Receive Date 24 January 2014

Keywords:
High-voltage electrostatic field (HVEF)
Thawing
Pork tenderloin meat
Electric field strength
Energy consumption

ABSTRACT

We investigated the thawing characteristics of frozen pork tenderloin meat by high-voltage electrostatic field (HVEF) considered to be the corona discharge treatment in the research. At the electrode distance of 6 cm, the thawing time was shortened by increasing voltages from 4 to 14 kV, but the shortening was not significant from 10 to 14 kV. As the discharge gap increased from 3 to 10 cm, the thawing time similarly increased accordingly under 8, 10, 12 and 14 kV. We developed regression models to describe the thawing times and energy consumption under different electric field strengths. The specific energy consumption for microwave, hot-water and cold-water thawing was about 1104, 248 and 184 kJ/kg respectively, while that for HVEF thawing was very small at about 0–190 kJ/kg. The difference between center and surface temperatures was about 0.3–1.2 °C. This proved HVEF could achieve energy-efficient uniform thawing in significantly less time.

Industrial relevance: With the increasing demand in thawing a large amount of frozen meat in a short period of time, high-voltage electrostatic field thawing treatment deserved a comprehensive and systematic in-depth study because of its advantages of shortening time, saving energy and keeping quality. At present, the problems in industrial application were the thawing characteristics, parameters of the electric field and energy consumption under different technologies. These would be discussed in this article.

1. Introduction

High-voltage electrostatic field (HVEF) treatment is very popular in electrostatics and has been extensively studied in recent years. A strong electrostatic field that affected the characteristics of various samples was generated with two non-contact electrodes connected with a certain high voltage. Wang et al. (2009) studied the effect of a high-voltage electrostatic field on plant seeds. One active heat-transfer enhancement technique is electrohydrodynamic drying of different materials like wheat, rapeseed and tomato slices using high-voltage electrostatics (Basiry & Esehaghbeygi, 2010; Cao, Nishiyama, & Koide, 2004; Esehaghbeygi & Basiry, 2011). HVEF treatment can also preserve the freshness of products to improve shelf life (Hsieh & Ko, 2008; Palanimuthu, Rajkumar, Orsat, Gariépy, & Raghavan, 2009).

HVEF thawing has developed recently in HVEF application and drawn increasing attention. Asakawa (1976) first reported that the vaporization of water was enhanced remarkably in an electric field. Ohtsuki (1991) invented a process to thaw food rapidly at a low surrounding temperature in the range from −3 to 3 °C. As a result, the thawing time could be shortened to 1/4–1/3 of the original time under the same temperature condition. Hsieh, Lai, Ho, Huang, and Ko (2010) researched HVEF thawing and cold storage of frozen chicken thigh meat compared with samples stored in a common refrigerator. The results showed that the HVEF can significantly shorten thawing time for frozen chicken thigh meat at −3 °C and can keep products fresh. In our previous study, it was also reported that HVEF treatment at the fixed electrode distance of 5 cm by applied voltages of 6, 8 and 10 kV significantly increased the thawing rates of frozen pork tenderloin meat and did not affect the post-thawing quality of the meat (He, Liu, Nirasawa, Zheng, & Liu, 2013). Meanwhile, HVEF treatment can inhibit microbial growth by 0.5–1 log CFU/g and reduce volatile basic nitrogen production during storage. However, limited work has been done in the influencing factors and energy consumption of thawing frozen pork tenderloin meat using an HVEF. Thus, it is necessary to explore how voltages, electrode distances and electric field strengths influence HVEF thawing, and the energy consumption of HVEF treatment.

In our research, the high voltage electrostatic field could be considered to be the corona discharge treatment, which was the non-uniform electric field contributed by the unequal charge distribution on the needle electrodes. The corona discharge treatment could produce a corona wind from the needle electrodes to the grounded electrode. The highly charged corona wind was responsible for the HVEF thawing. The use of air ions in a strong electric field to increase heat or mass transfer is known as electrohydrodynamics (Chen & Barthakur, 1991). Therefore, the HVEF thawing in the study was similar to the principle of electrohydrodynamics. The objectives of the present study were to investigate how the voltages, discharge gaps and electric field strengths

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http://dx.doi.org/10.1016/j.ifset.2013.12.019

affect HVEF thawing, including the thawing time, temperature variation and energy consumption, and to develop regression models to predict the thawing condition with different HVEF physical parameters. Meanwhile, we compared the specific energy consumption for HVEF, microwave, hot-water and cold-water thawing.

2. Materials and methods

2.1. Materials

The fresh pork tenderloin meat was purchased from a local supermarket and stored in a cooler bag prior to sample preparation. The meat (purchased from a supermarket) originated from a stable pig slaughterhouse, which processed a single species across a limited range of ages and weights. The post-slaughter carcass was chilled for 24 h in a 0–4 °C refrigerator prior to transportation and cutting.

This particular meat was studied because the meat was almost purely lean without fat, which ensured that samples had good consistency in material components, easily cut into definite shapes. In addition, pork tenderloin meat was a typical red meat consumed in large amounts every year.

2.2. Sample preparation

Using a knife, fresh pork tenderloin meat was cut into rectangular prisms ($2 \times 5 \times 5$ cm^3) each weighing approximately 50 g. The pieces were stored for 48 h in an air-blasted refrigerator (Samsung BCD-285WNMVS) controlled at −20 °C.

2.3. Experimental apparatus

As shown in Fig. 1, the main HVEF experimental apparatus comprised a high-voltage power generator (DW-N303-1AC, Dongwen High Voltage Power, Tianjin, China), a high-voltage electrostatic treatment chamber, and a multiple points-to-plate electrode. The high-voltage electric field apparatus was adjusted with a high-voltage controller to output a negative high voltage from 0 to 30 kV. A voltmeter and amperemeter measured the voltage across and the current through the circuit, respectively. The multiple points-to-plate electrode consisted of a corona discharge electrode (stainless-steel needles with copper wires) and grounded plane electrode (a 40×40 cm stainless steel plate). The corona discharge electrode was formed by a 9×9 cm^2 integrated circuit plate embedded with 16 sharp-point needles (0.001 mm diameter; 3 cm between any two needles). This electrode was connected to the negative pole of the high-voltage power generator. The electric field strength was varied by adjusting the distance between the two electrodes.

The “meat” in Fig. 1 referred to one piece of meat cut into rectangular prisms ($2 \times 5 \times 5$ cm^3) each weighing approximately 50 g. There were two other parallel multiple points-to-plate electrodes connected to the high-voltage power generator to form three identical HVEF systems.

2.4. Thawing experiment

The frozen pork tenderloin meat was thawed at 12 °C under an electric field generated by high voltages of 8, 10, 12 and 14 kV. The discharge gap was adjusted to 3, 4, 5, 6, 8 and 10 cm. When the electrode distance was 6 cm, thawing experiments were performed with different voltages of 4, 6, 8, 10, 12 and 14 kV. The control samples were placed on the same kind of stainless steel plate without the electric field in the treatment room. Negligible air movement in the treatment room ensured that air velocity was near-zero. The relative humidity (RH) of the air was 80 ± 0.1% (SATO, SK-L200TH). Three pieces of frozen meat were selected randomly for each HVEF treatment and for the control treatment (thawing in the air). Three temperature sensors were separately inserted into the geometric center of the three parallel meat samples to record the center temperature. The surface temperature of the sample was measured by inserting the temperature sensor to the center point about 5 mm from the surface. All measurements were repeated three times. Thawing was considered complete when the center temperature reached 0 °C, as determined by the temperature sensor with high accuracy of 0.5 °C in the range from −20 to 100 °C (Testo 826-T4, Germany). A regression model was developed to describe thawing times under different electric field strengths providing physical parameters for industrial application.

Microwave thawing was carried out with a domestic microwave oven (Galanz) having a 1180 W magnetron power input. The microwave oven had five power levels: 20%, 40%, 60%, 80% and 100% of the total input power. The minimum of 20% was set as the microwave thawing power to avoid overheating the corners of the frozen meat. The center temperature of 0 °C was set as the thawing end point, and the thawing time was recorded.

For hot-water thawing, the experiment was performed by submerging frozen meat wrapped with a zip-lock bag in 300 ml hot water (60 °C), an approximate temperature setting for foodservice hot-holding equipment (Shrestha, Schaffner, & Nummer, 2009). Cold-water thawing was by submersion in 300 ml water (20 °C), and the control was set as 300 ml water without submersion of frozen meat. The temperature sensor was inserted into the geometric center of the meat to record the center temperature changes, and the center temperature of 0 °C was set as the thawing end point. At the same time, temperature sensors were also inserted into the water of the treatment and the control to record the temperature changes until the end of thawing.

2.5. Energy consumption and specific energy consumption calculation

The energy consumption is determined by the work done by electricity, calculated with the equation

$$W = UIt, \qquad (1)$$

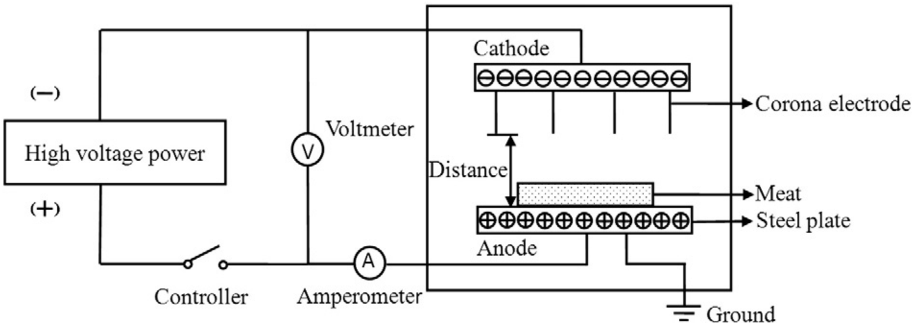

Fig. 1. Schematic diagram of the HVEF treatment system used in this experiment (see text for details).