A continuous high voltage electrostatic field system for thawing food materials

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Abstract

A laboratory continuous HVEF thawing system was designed and constructed in accordance with standards for food machinery. Corona discharge in wire-plate electrodes was considered for the system and a stainless-steel sheet was utilized as the conveyor belt. Corona flow was created by applying high voltages of 15, 20, and 25 kV and electrode gaps of 6, 8, and 10 cm. To evaluate the system, frozen tylose MH4000 gel with a moisture content of 77% w.b. as a meat analog was thawed from −10 to 0 °C. The thawing duration which was mostly devoted to increase the temperature of control sample (no electrostatic field), considerably decreased when thawing the gel in the presence of the high voltage. High voltage and EG indicated significant effect on both thawing duration and specific energy consumption (p<0.0001). The thawing duration decreased significantly by decreasing the electrode gap and increasing the applied voltage. In terms of energy consumption, the best condition (minimum specific energy consumption of 10.33 kJ kg⁻¹) was obtained for the voltage of 15 kV, and the electrode gap of 10 cm.

Introduction

Freezing is one of the most important processes for preserving vegetables, meats, and some fruits. Most of frozen foods should be firstly thawed. The conventional methods for thawing are exposing the frozen material to air, dipping it in cold water, tap water, hot water, as well as keeping in refrigerator (Eastridge and Bowker, 2011). These methods are however time-consuming and may deteriorate the food quality, especially for meat thawing. On the other hand, there are some limitations in other methods such as microwave thawing. This method usually act non-uniformly and some regions of the thawed food may be cooked (Taher and Farid, 2001).

In most thawing methods, the process is performed in batch mode in which the food is placed in a container and is thawed. While for thawing the great amount of materials, the movement of the product is carried out continuously in the system, which is more suitable regarding its health and better efficiency over the batch mode. Hence, many studies have been conducted on the development
of new efficient methods to improve the freezing and thawing processes (Ould Ahmedou and Havet, 2009).

Using the conventional methods like passing airflow at low speed over the frozen food on a large scale, such as large pieces of meat or fish, is time consuming. Because in this method, thawing is accomplished by convective heat transfer to the product on its surface, while the frozen layers have low thermal conductivity. To overcome this issue, the airflow rate can be increased to enhance the heat transfer rate, but the energy consumption is increased significantly. Hence, new methods including ultrasound-assisted, ohmic, high-pressure, pulsed electric field, magnetic nanoparticles plus heating, radio frequency and high voltage electrostatic field (HVEF) thawing are used in recent studies. Except HVEF thawing, these methods are time consuming and energy intensive (Cai et al., 2019). Therefore, there is a basic requirement to develop methods that could reduce the energy consumption and thawing duration without damaging and microbial growth, as well as other disadvantages associated with physical and chemical changes occurred in the product (Yar et al., 2015).

HVEF thawing has been applied in a few studies in laboratory scale. In a study the energy for the HVEF thawing was 0 to 190 kJ kg⁻¹, which was less than 1100 kJ kg⁻¹ needed for microwave thawing (He et al., 2014). The HVEF had fewer effects on the physicochemical and structural changes of myofibrillar proteins, the total microbial counts, the volatile basic nitrogen, and other parameters of livestock meat compared with traditional thawing methods. Jia et al. (2017) confirmed that with the HVEF thawing (voltage range: −25 to 0 kV), protein oxidation did not occur and the dynamic rheological analysis, protein aggregation, and gel texture analyses showed better results compared with air thawing of frozen rabbit meat. In addition, there was no significant change in the structure of myofibrillar proteins. He et al. (2013) also reported that the HVEF treatment could reduce the total microbial counts in thawed pork tenderloin meat by 0.5 to 1 log CFU/g in the temperature range of −5 to 0 °C. From the above, the HVEF is a suitable thawing technology for thawing meats once parameters are optimized. So, the advantages of the HVEF thawing are low energy consumption,
generation of ozone that prevents the microbial load during the process, non-thermal thawing, and utilizing simple equipment (Shivashankara et al., 2004). The systems used in the previous HVEF studies include a plate electrode and needle or wire electrodes located on a distinct air distance, and the frozen material is placed between two conductive electrodes on the plate. The electrodes are then connected to a high voltage source, and the voltage level is increased to a certain extent to prevent an electrical discharge (Xiangli et al., 2013). In such systems, when the voltage is applied to the needle or wire electrodes, the air is ionized in the vicinity of them and the ions move toward the plate electrode connected to the other pole. During the movement of the ions towards the plate electrode, due to their collision with air molecules, the momentum of the ions is transferred to the air molecules. As a result of this collision, a mass of ionized air flows which is called corona wind or secondary flow. The needle or wire electrode is called the corona electrode. Choosing the type of the corona electrodes is most influenced by the geometry of the chamber and operation of the system. The HVEF thawing can be done using AC or DC voltages, and the systems with some needles and plate electrodes have convenient efficiency at thawing the frozen material (Xie and Hua, 2001; Yaxiang et al., 2009).

Thawing of some foods such as tuna, beef, and eggs has been studied via the HVEF at low ambient temperature in the range of −3 to 3 °C in the batch mode (Ohtsuki, 1991). The results showed that the thawing duration was reduced by one-quarter to one-third, compared to non-field conditions. Thawing of chicken thigh by the HVEF showed that the method could significantly reduce the thawing duration at −3 °C and keep the product fresh compared to the conventional storage method in the refrigerator (Hsieh et al., 2010). Another study on the frozen pork tenderloin revealed that the use of the HVEF at an electrode gap (EG) of 5 cm with the applied voltages of 6, 8, and 10 kV significantly increased the rate of thawing (Xiangli et al., 2013). Also, in investigating the thawing characteristic of frozen tofu under high-voltage alternating electric field it was reported that as voltage increased, the thawing duration decreased (Deng et al., 2017). Ding et al. (2018) obtained similar results on the frozen tofu under HVEF assisted thawing. They showed that the thawing duration of
frozen tofu decreased with the increase of voltage and it had a great relevance with the configuration and distance of the electrodes. Also, the electric parameters had a remarkable effect on thawing loss and thawing duration when center temperatures of frozen tofu decreased from −2 to 0 °C.

Yaxiang et al. (2011) studied the effects of different high voltages, EGs and distances between the adjacent needle electrodes on the thawing rate of ice and the energy consumption of the process in the batch mode. Based on the thawing rate curve of the ice versus the distance between two needle electrodes, the thawing rate reached its maximum amount when the distance between the two adjacent electrodes was in the range of 6 cm.

Despite the promising studies on the thawing of the food materials in the batch mode, in the literature, to the best of the authors’ knowledge, no study was available on the HVEF thawing in the continuous mode. This study was aimed to design and construct a continuous system for feasibility investigation of the HVEF thawing of meat in laboratory scale. Some advantages of this type of HVEF thawing system could be thawing of frozen materials continuously, which causes time and cost saving for high volume thawing of food materials.

**Materials and methods**

In this study, a laboratory continuous HVEF thawing system was designed in CATIA software (Dassault system, CATIA V5R20), and then it was constructed as type of a tunnel according to the food machinery standards. By passing the frozen material through this system, the thawing process is carried out under HVEF. Fig. 1 shows the schematic of the system and its different parts.

It should be noted that the phenomenon of thawing under the HVEF is complex. The effect of corona wind flow on such a system is affected by the geometry of the positive and negative electrodes (corona electrodes and ground electrode), the type of voltage (AC or DC), the voltage value, the distances between the two adjacent electrodes, and the EG and presence of the initial wind flow in the system (Akishev et al., 2003; Lin and Adamiak, 2008). Due to the fact that the applied voltage to the electrodes of the system is of the order of kilovolts, it was necessary to insulate all electrical
conductive parts for the user safety when contacting with the high voltage electrodes. Therefore, considering the optimal mechanism for the system, the insulation material was polyamide, glass, and compact plastic. The conductive components such as pole electrodes were also selected in accordance with the standards of food industry machines made of stainless steel 304. The structure of the device and the geometry of its components along with their design details are described below thoroughly.

**Corona electrodes**

Regarding the physics of the system, the frozen food moves inside a tunnel and it is thawed. In order to facilitate adjusting the electrodes distances, and their distribution over the channel and convenience of construction, all the corona electrodes were considered as 0.5 mm diameter stainless steel wires (Lin and Adamiak, 2008). All the electrodes were mounted along the tunnel in specific intervals and transversally attached to the top of the tunnel in the form of a ladder (Fig. 1). In order to change the EG, the height of the two rails can be adjusted from the ground electrode. The electric field created between the corona electrodes and the ground electrode was calculated by Eq. (1):

\[
E = \frac{V}{d}
\]

(1)

where, \(V\) is the voltage, and \(d\) is the electrode gap.

In the system, the values of the applied voltage and the electrode gap are adjustable in the range of 0 to 70 kV and 1 to 20 cm, respectively. For conducting the experiments, the applied voltage was considered in the range of 15 to 25 kV and the EG in the range of 6 to 10 cm (Yaxiang et al., 2011; Deng et al., 2017c). Since the electric field created between the two poles is inversely proportional to the distance between them according to Eq. (1), it was necessary that the wire electrodes be transverse, smooth and straight and have no deflection. The electrode also should be able to move on the rail so that the distance between the two adjacent wires could be adjusted. Eventually, one of the rails of the formed ladder was connected to the positive pole of the high voltage power supply. The ionization
region around each wire after applying the voltage known as corona crescent radius, was calculated from Eq. (2) (Guo et al., 2014):

\[ r_i = r + 0.03\sqrt{r} \]  

(2)

where, \( r \) is the wire radius and \( r_i \) is the ionization radius.

The ionization radius increases as the applied voltage increases. Given the small radius of ionization, this area can be ignored. Therefore, the distance between two adjacent electrodes in the system was approximately selected to be 100 times more than the radius of the corona electrode and was in the range of 5 to 10 cm (Lin and Adamiak, 2008). Altogether, 28 wired electrodes were installed at 7 cm intervals.

**Ground electrode and material motion mechanism**

Since the wire and plate electrodes were considered for the system, the plate electrode distance from the corona electrodes should be constant. Moreover, a 2.5 m long conveyor was designed and constructed in order to move the frozen material continuously in the system.

The surface of the conveyor belt was considered as the ground electrode, which moves along the ladder-shaped electrodes underneath the wire electrodes. Due to the presence of food on the conveyor belt, its material should be hygienic and in agreement with the standards for food industry machines (BS EN ISO, 2005). It should also be electrically conductive, flexible, and should have sufficient tensile strength. Considering these criteria, a 304 stainless steel spring sheet with 0.1 mm thickness was used as the conveyor belt.

The approximate duration for thawing of the food materials is between 45 to 60 min (Guo et al., 2014). Considering the effective length of the conveyor belt (240 cm), the remaining duration of the material on the belt could be controlled by adjustment of the belt velocity. The maximum velocity was considered to determine the required power. The velocity was calculated to be 3.5 cm min\(^{-1}\) by
considering the minimum thawing duration (45 min). A 375 W three phase AC electromotor and gearbox (Ratio of 1:100) with a speed controller was used to drive the belt.

**High voltage connections**

Regarding the high voltage connections, the driver roller was used to transfer the electric current to the metal belt. The driver roller was constructed from 304 stainless steel which is conductive and in contact with the conveyor belt. In order to insulate the surface of the roller from its axis and prevent transferring the electric current to the bearings, a polyamide cylinder was inserted inside the tube. The driven roller was made of polyamide, which is an electric insulator. To transfer the electric current to the conveyor belt, as shown in Fig. 1, a fixed carbon electrode was mounted on the device chassis which was in sliding contact with the driver roller. To supply the voltage, a DC power supply (Model HV50N OC, FNM co., ltd, Tehran, Iran) with voltage adjusting capability in the range of 0 to 70 ± 1 kV and a maximum current of 2000 ± 1 μA was utilized. By connecting the poles of the power supply to the carbon electrode and the rails, the electric field between the two poles was created.

By applying the voltage and measuring the current in the system, the specific energy consumption (SEC) of the process was calculated by Eq. (3):

$$SEC = \frac{V . I . t}{m}$$

(3)

where, $V$ is the applied voltage, $I$ is the electric current, $t$ is the thawing duration, and $m$ is the mass of the frozen material.

**Device chamber**

In order to prevent the air flow into the corona wind zone, control temperature, as well as protect the user from the risk of electric shock, the whole conveyor and its components were placed in an
insulated chamber. The chamber was made of pressed plastics sheet in the form of a tunnel with dimensions of 50×50×270 cm (Fig. 1).

In order to entry and exit the materials, the first and end of the tunnel are open and covered by two thick pads. On the top of the tunnel, two windows were installed longitudinally to facilitate user access to the conveyor. The glass was mounted at the lateral and top sides of the tunnel to see the movement of the material inside the system. To control the ambient temperature, the entire setup was placed in a room, which was kept at a constant temperature by a temperature control system. As illustrated in Fig. 2, the room was constructed from nylon and iron rods. The inlet and outlet of the airflow into and out of the room were placed in its floor in order to prevent the flow of the air into the device chamber and its interference with the corona wind. The temperature control sensor was mounted on the interior wall of the room at the same level with the device conveyor. The room temperature was set to be 25 ± 1 °C during the experiments.

Experiments

To conduct the experiments, tylose gel MH4000 sample was used with a moisture content of 77% w.b. since its thermo-physical properties is similar to red meat (Icier and Ilicali, 2005). The tylose gel sample was frozen within the range of −8 to −10 °C with a dimension of 1.5×4×6 cm and mass of 21.6 ± 0.2 g. The criterion of the thawing process was to increase the temperature of the sample center to 0 °C. A 4 channels fiber optic thermometer (Model FOB100, Canada) comprising multipurpose fiber optic temperature sensors with the accuracy of ± 0.8 °C was used to measure the temperature of the frozen sample center and record it at 2 s intervals during the thawing process. For this purpose, the frozen gel was drilled with a 2 mm drill and the sample was placed on the conveyor belt after inserting the optical fiber inside it. The experiments were conducted in the presence of the field and without the field as the control. Thawing experiments were independently performed three times in this study and the average was taken. In each HVEF treatment, the sample was placed at the same position on the grounded electrode to keep the consistency of the experiment.
It has been reported that both the center and surface temperatures of sample increase rapidly with increase in the applied voltages and have some similar characteristics (He et al., 2014). Therefore, we only measured the center temperature of the tylose gel to investigate the effect of process parameters and electrode configuration. Considering the thawing duration, the speed of the conveyor was adjusted to pass the frozen material along the conveyor. The thawing duration was determined at the voltages of 15, 20, and 25 kV, and the EGs of 6, 8 and 10 cm. The distance between the adjacent wire electrodes was also 7 cm.

**Statistical analysis**

The experiments were performed in three replications based on completely randomized design. The treatments were high voltages and EGs. The averages were compared according to the LSD test at the 5% probability level.

**Results and discussion**

To evaluate the designed and constructed system at aforementioned conditions, the threshold value for the current in the power supply was set to be 1000 μA. It should be noted that by applying the voltage to the electrodes, the current value should not exceed the threshold value. Moreover, by applying the higher voltages for the EG of 6 cm or adjusting the current threshold value to values greater than 1000 μA, there may be an electrical discharge between the two poles which causes not creating the corona wind.

Fig. 3 shows variations in the temperature of the tylose gel sample with time in the presence of the electric field and without that (control). It could be observed that there was differences between thawing duration under control and HVEF states. The HVEF conditions for thawing were the voltages of 15, 20, and 25 kV, the distance between the adjacent wire electrodes of 7 cm, and the EG of 6, 8, and 10 cm. As depicted, under the control condition, the thawing duration was mostly devoted to increase the temperature, which considerably decreased when thawing the sample in the presence of
the high voltage. It is seen that the thawing rate changed at three stages: before −6 °C, from −6 to −3 °C, and from −3 to 0 °C at all EGs and applied voltages. It is obviously around −3 to −2.8 °C is the freezing point of the water solution in the food material. The second stage that is near to the temperature of −3 °C is time consuming as it is approximately close to the thawing point of the tylose sample because of the latent heating requirement.

The values of the electric current, electric field, thawing duration and specific energy consumption at different applied voltages and distances between the two poles are given in Table 1. As presented, the electric current increased with the applied voltage at a constant EG, and it decreased as the EG increased when the voltage is fixed. It is observed that there was a remarkable difference between control sample and thawing process under the HVEF. In addition, the thawing duration significantly influenced by the high voltage and EG (p<0.0001). Among all the HVEF treatments, the highest thawing duration was occurred at the voltage of 15 kV and the EG of 10 cm. The lowest thawing duration was also belonged to the voltage of 25 kV and the EG of 6 cm. These values approximately decreased by 33.5%, and 76.3% in comparison with the corresponding value for the control, respectively.

The thawing duration decreased by decreasing the EG and increasing the applied voltage significantly (Table 1). Xiangli et al. (2013) studied the thawing of pork tenderloin meat under HVEF and reported that as voltage increased, the thawing duration decreased. This result was also stated in another research (Xie and Hua, 2001). Yaxiang et al. (2009), and Yaxiang et al. (2011) showed that when the distance between the two adjacent electrodes was fixed, the ice thawing rate changed with the EG inversely.

Similar to the thawing duration, the effect of high voltage and EG on the SEC was significant (p<0.0001). The SEC increased by decreasing the EG and increasing the applied voltage significantly (Table 1). This finding has been also reported in previous researches (Yaxiang et al., 2009; Yaxiang et al., 2011).
According to Eq. (3) and as expected, the specific energy consumption is proportional to the thawing duration. However, the opposite trend for the thawing duration and SEC is due to the predominant effect of reduction in the electric current when the EG increases at a constant voltage. Hence, in contrary to the thawing duration, the highest value of the SEC was belonged to the voltage of 25 kV and the EG of 6 cm, and its lowest value was related to the voltage of 15 kV and the EG of 10 cm.

Conclusions
In this study, a high voltage electrostatic field (HVEF) continuous thawing system in wire-plate electrode arrangements was designed and constructed for thawing foodstuffs according to the standards of food industry machines. The device was evaluated by the frozen tylose MH4000 which is a meat analog in order to investigate the feasibility of foodstuff thawing by the device. The high voltages of 10, 15, and 25 kV and the EGs of 6, 8, and 10 cm were considered for the device assessment. Based on the findings, the HVEF continuous system could be a feasible rapid method for thawing of food materials such as meat. As the system is a laboratory-scale type, it can be studied more in the future for energy consumption in comparison with the other thawing systems and from economic point of view to be used in the food industries.

References
Akishev, Y.S., Dem’yanov, A.V., Karal’nik, V.B., Monich, A.E., and Trushkin, N.I. (2003). Comparison of the AC barrier corona with DC positive and negative coronas and barrier discharge. Plasma Phys. Rep., 29 (1), 82-91.

BS EN ISO 1672-2, (2005). Food Processing Machinery. Dough Mixers. Safety and Hygiene Requirements.

Cai, L., Cao, M., Regenstein, J., and Cao, A. (2019). Recent Advances in Food Thawing Technologies. J. Compr. Rev. Food Sci. Food Saf., 18, 953-970.
Deng, S., Gao, Z., Xu, J., Wang, G., Bai, Y., and Ding, C. (2017). The thawing characteristic of frozen tofu under high-voltage alternating electric field. J. Food Qual., 2017, 1-6.

Ding, S., Ni, J., Song, Z., Gao, Z., Deng, S., Xu, J., Wang, G., and Bai, Y. (2018). High Voltage Electric Field-Assisted Thawing of Frozen Tofu: Effect of Process Parameters and Electrode Configuration. J. Food Qual., 2018, 1-8.

Eastridge, J.S., and Bowker, B.C. (2011). Effect of rapid thawing on the meat quality attributes of USDA select beef strip loin steaks. J. Food Sci., 76 (2), 156-162.

Guo, B.Y., Guo, J., and Yu, A.B. (2014). Simulation of the electric field in wire-plate type electrostatic precipitators. J. Electrostat., 72, 301-310.

He, X., Liu, R., Nirasawa, S., Zheng, D., and Liu, H. (2013). Effect of high voltage electrostatic field treatment on thawing characteristics and post-thawing quality of frozen pork tenderloin meat. J. Food Eng., 115(2), 245–250.

He, X., Liu, R., Tatsumi, E., Nirasawa, S., and Liu, H. (2014). Factors affecting the thawing characteristics and energy consumption of frozen pork tenderloin meat using high-voltage electrostatic field. Innov. Food Sci. Emerg. Technol., 22, 110–115.

Hsieh, C.W., Lai, C.H., Ho, W.J., Huang, S.C., and Ko, W.C. (2010). Effect of thawing and cold storage on frozen chicken thigh meat quality by high-voltage electrostatic field. J. Food Sci., 75(4), 193-197.

Icier, F., and Ilicali, C. (2005). The use of tylose as a food analog in ohmic heating studies. J. Food Eng., 69, 67-77.

Jia, G., Nirasawa, S., Ji, X., Luo, Y., and Liu, H. (2017). Physicochemical changes in myofibrillar proteins extracted from pork tenderloin thawed by a high-voltage electrostatic field. Food Chem., 240, 910–916.

Lin, Z., and Adamiak, K. (2008). Numerical simulation of the electrohydrodynamic flow in a single wire-plate electrostatic precipitator. IEEE. Trans. Ind. Appl., 44 (3), 683-691.

Ohtsuki, T. (1991) Process for thawing foodstuffs. US Patent 5034236.
Ould Ahmedou, S.A., and Havet, M. (2009). Effect of process parameters on the EHD airflow. J. Electrostat., 67, 222-227.

Shivashankara, K.S., Isobe, S., Al-Haq, M.I., Takenaka, M., and Shiina, T. (2004). Fruit antioxidant activity, ascorbic acid, total phenol, quercetin, and carotene of Irwin mango fruits stored at low temperature after high electric field pretreatment. J. Agric. Food Chem., 52 (5), 1281-1286.

Taher, B.J., and Farid, M.M. (2001). Cyclic microwave thawing of frozen meat: experimental and theoretical investigation. Chem. Eng. Process., 40, 379-389.

Xiangli, H., Rui, L., Nirasawa, S., Zheng, D., and Liu, H. (2013). Effect of high voltage electrostatic field treatment on thawing characteristics and post-thawing quality of frozen pork tenderloin meat. J. Food Eng., 115, 245-250.

Xie, J., and Hua, Z.Z. (2001). The experimental research on the thawing process of quickly frozen potato in the high static-electric voltage fields. J. Refr., 2, 1-5. (In Chinese)

Yar, R., Faye Bedane, T., Erdogduc, F., Koray Palazoglu, T., Farag, K.W., and Marra, F. (2015). Radio-frequency thawing of food products - A computational study. J. Food Eng., 146, 163-171.

Yaxiang, B., Luan, Z.Q., Li, X.J., and Xu, J.P. (2009). Study on the thawing mechanism of high voltage electrostatic field. Trans. CSAE., 26, 347-350.

Yaxiang, B., Sun, Y., Li, Z., and Kang, D., (2011). Study the optimum parameters of high voltage electrostatic field thawing. Procedia Eng., 16, 679-684.
Fig. 1. Schematic of continuous HVEF thawing system: 1) whole device, 2) driver roller, 3) stainless steel conveyor belt, 4) aluminum rail, 5) wire electrode, 6) glass holder plate, 7) high voltage power supply, 8 and 9) connections of power supply wires to the poles, 10) carbon electrode in contact with conveyor roller, and 11) temperature sensor.

Fig. 2. Continuous HVEF thawing system inside the nylon room.
Fig. 3. Variations in temperature of tylose gel center with thawing duration under control condition and HVEF at different voltages (15, 20, and 25 kV) and EGs (6, 8, and 10 cm).

Table 1. Measured and calculated values of electric current, electric field, thawing duration and specific energy consumption for HVEF thawing of tylose gel at different voltages and electrode gaps.

| Voltage (kV) | The electrode gap (cm) | Electric field (kV m⁻¹) | Electric current (μA) | Thawing duration (min) | SEC (kJ kg⁻¹) |
|-------------|------------------------|-------------------------|-----------------------|------------------------|---------------|
| 15          | 6                      | 250                     | 24                    | 22.13±0.12³            | 22.13±0.12³   |
|             | 8                      | 187.5                   | 13                    | 31.30±0.32³             | 16.97±0.18⁶   |
|             | 10                     | 150                     | 6                     | 41.23±0.15⁶             | 10.33±0.03³   |
| 20          | 6                      | 333.3                   | 166                   | 17.50±0.26³             | 161.40±2.44³  |
|             | 8                      | 250                     | 30                    | 23.43±0.20³             | 39.07±0.35³   |
|             | 10                     | 200                     | 12                    | 33.40±0.17³             | 22.30±0.12³   |
| 25          | 6                      | 416.6                   | 357                   | 14.67±0.24³             | 363.60±5.98³  |
|             | 8                      | 312.5                   | 178                   | 22.60±0.31³             | 279.33±3.79³  |
|             | 10                     | 250                     | 85                    | 25.50±0.26³             | 150.53±1.56³  |
| Control     | -                      | 0                       | 0                     | 62.08±0.57             | -             |

The values for thawing duration and SEC present mean ± one standard error. In each column, the means followed by the same common lowercase letter do not differ statistically based on LSD test at 5% probability level.