Korean J. Food Sci. Ani. Resour.
Vol. 29, No. 3, pp. 302~309(2009)

Effects of Air Blast Thawing Combined with Infrared Radiation on Physical Properties of Pork

Geun-Pyo Hong[1,2], Kook-Bo Shim[2], Mi-Jung Choi[3], and Sang-Gi Min[2,*]
[1]*Department of Animal Science and Biotechnology Research Institute, Chonnam National University, Gwangju 500-757, Korea*
[2]*Department of Food Science and Biotechnology of Animal Resources, Konkuk University, Seoul 143-701, Korea*
[3]*National Nanotechnology Center, National Science and Technology Development Agency, Bangkok 12120, Thailand*

Abstract

This study investigated the effects of infrared (IR) radiation combined with air blast thawing on the physical properties of pork. Regardless of air velocity, increasing IR dosage produced an exponential increase in the thawing rate of pork. This rate increased further when air blast velocity was increased. IR treatments showed significantly lower thawing loss than that of 0 Watt treatment, while increasing air velocity significantly increased thawing loss of pork ($p<0.05$). Increasing both IR power and air velocity tended to decrease the cooking loss of pork. Moreover, increased IR power tended to decrease the water holding capacity and shear force of pork. The shear force changes were not significant ($p>0.05$). Shear force also increased with increasing air velocity. In addition, the higher the air velocity the higher the shear force of pork. In Commission Internationale de l'Eclairage (CIE) colour determination, control of temperature prevented discolouration from overheating of sample surface. The results suggest that IR dosage combined with air blast has potential in thawed meat quality aspects, and that humidity control could prevent surface drying.

Key words : infrared, air blast, thawing, physical, pork

Introduction

Freezing has been identified as the most effective tool for preservation. However, freezing can destroy some destruction of food structure due to ice crystal formation. Therefore, freezing of meat may lead to problems such as drip loss during thawing, oxidation of muscle pigment, and reduction in gel-forming ability of myofibrillar proteins (Sakata *et al.*, 1995). Because drip loss of meat during thawing contributes to decreased quality parameters including sensory properties, functionality, and weight, studies have sought to reduce the influence of freezing on drip loss upon thawing (Ngapo *et al.*, 1999). The amount of drip generated during thawing is directly related to the freezing rate, which, in turn, is related to the size and distribution of ice crystals in frozen meat (Hong *et al.*, 2005b). Until now, rapid freezing has been generally recommended to minimize the drip loss. In contrast to the extensive amount of literature concerning the effects of freezing rate on meat quality, few reports concerning the relationship of thawing rates with meat characteristics are available. Ambrosiadis *et al.* (1994) and Deatherage and Hamm (1960) noted that a faster thawing rate resulted in a product with significantly less drip. Gonzalez-Sanguinetti *et al.* (1985) reported that thawing drip increased with increased thawing time up to about 60 min over a temperature range from -5°C to -1°C, while at a thawing time greater than 60 min thawing drip was independent of the time. These results indicate that rapid thawing produces less drip loss.

A variety of thaw technologies exist, including high pressure (Hong *et al.*, 2007a; Ko *et al.*, 2006), microwave (Virtanen *et al.*, 1997), ohmic heating (Hong *et al.*, 2007b), and ultrasound (Miles *et al.*, 1999), and some have been successfully applied in the meat industry. These techniques are all based on heat generation during processing. Infrared (IR) wavelengths, which lie between the visible spectrum and the microwave region, have also been used in cooking food. The thermal radiation that is germane to food preparation extends in the electromagnetic spectrum from wavelengths of 0.1-1000 μm (IR

---

*Corresponding author : Sang-Gi Min, Department of Food Science and Biotechnology of Animal Resources, Konkuk University, Seoul 143-701, Korea. Tel: 82-2-450-3680, Fax: 82-2-455-1044. E-mail: foodeng301@paran.com radiation being 0.78-1000 μm, with wavelengths <5.6 μm being used practically). These wavelengths are emitted, transferred, and absorbed by the food, generating heat. Near-IR radiation with a wavelength around 1 μm is the most important in food applications (Lewicki, 2004).

As a cooking method, IR radiation has several advantages that include high heat fluxes directed at the sample surface and uniform heating over a broad surface area. Despite the high thawing rate of heat-based thawing techniques, radiation-based techniques including IR produce some product deterioration due to overheating, oxidation, surface drying, and impingement damage (Hong *et al.*, 2007b; Sheridan and Shilton, 1999).

To minimize these negative aspects, a combination of thawing technologies such as air blast, humidity, and temperature control are typically required. Currently, sufficient information regarding the combinational use of IR radiation is not available. This study evaluated the effect of the combination of IR irradiation with air blast thawing under controlled temperature environment on the physical properties of pork.

Materials and Methods

Materials and Sample Preparation

Pork *m. longissimus dorsi* was randomly obtained at 24 h post-mortem from three carcasses. The meat was trimmed of all visible fat and connective tissue, and cut into a cylindrical form (8 cm in diameter and 3 cm thick) from the centre of the muscle parallel to their fibre direction. Two k-type thermocouples were inserted into the geological centre and top surface of each sample, and the temperature during freezing and thawing was monitored using a model MV104 mobile recorder (Yokogawa Electric, Tokyo, Japan). All samples were frozen at -135°C in a model CLN-2300CW deep freezer (Nihon Freezer, Tokyo, Japan) until the temperature of the sample centre reached -30°C. The sample was stored at -30°C in a model NF-400SF deep freezer (Nihon Freezer) overnight prior to use.

Thawing Procedure

Thawing was conducted using a thawing apparatus shown in Fig. 1. A sample holder was placed on a drip holder at a height of 10 cm. A model R125IRR IR lamp (Royal Philips Electronics, Amsterdam, The Netherlands) was hung at the top of thawing chamber 17 cm from the sample top surface. A model NMB-MAT fan (Minebea-Matsushita Motor Manufacturing, Tokyo, Japan) was positioned at the front of the sample holder for air convection. The omni-directional inner wall of the thawing chamber was coated using aluminium foil to maximize IR efficiency. No IR radiation treatment (0 Watts; W) was conducted at ambient temperature, while the chamber was put into an -18°C freezer for IR treatments. The IR dose intensity was controlled using 100, 130, 160, 190, and 220 V at a frequency of 60 Hz using a Slidacs HCS-2SD05 voltage controller (Hanchang, Busan, Korea). Calculated wattages of the IR ramp were 47, 80, 121, 171, and 229 W. To determine the air velocity, the voltage for the work-

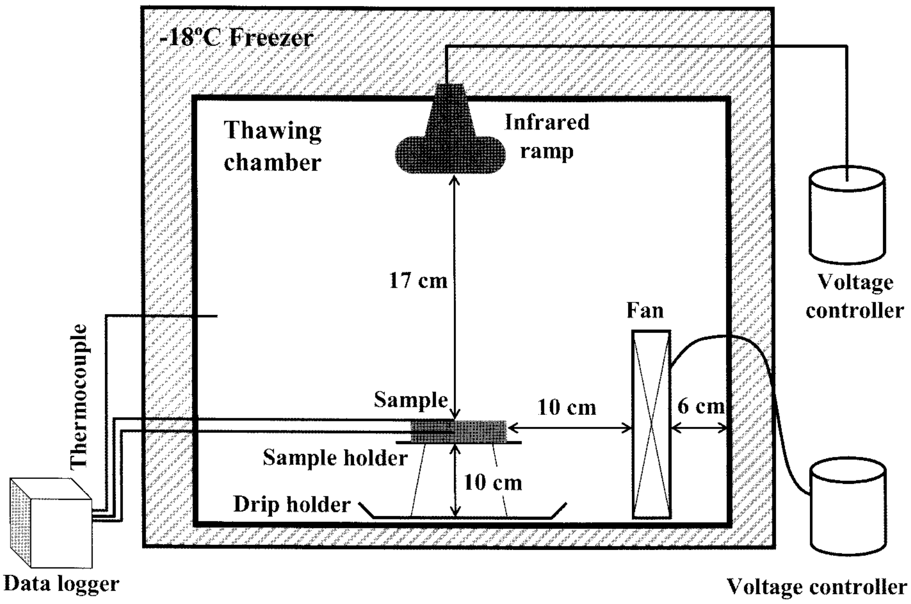

Fig. 1. Schematic diagram of infrared radiation treatment combined with an air blast thawing apparatus.

ing fan was changed from 140 to 220 V, and air velocity at each voltage was measured (Fig. 2). The adopted air velocities were 0, 3, and 6 m/s at controlled respective voltages of 0, 183, and 198 V at 60 Hz. Temperatures of the inner space of the chamber, and the top surface and centre of the sample during thawing were monitored using a model MV104 mobile recorder (Yokogawa Electric). To avoid sample overheating due to IR, the sample top surface temperature was maintained at 10°C-30°C by an on-off lamp (Fig. 3). Thawing was complete when the sample's centre temperature reached at 1°C.

Thawing Rate

The thawing rate of pork was calculated for half sample thickness as the time required to traverse the zone of maximum ice crystal formation (from -5°C–0°C):

$$\text{Thawing rate (cm/h)} = \frac{1}{2}\frac{D}{t_{0^\circ C}-t_{-5^\circ C}}$$

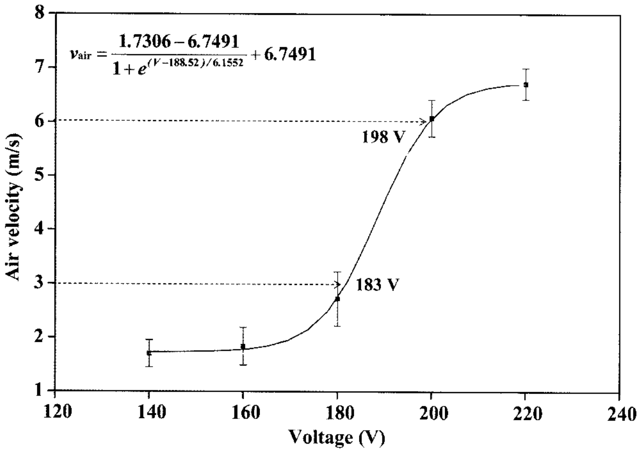

Fig. 2. Changes in air velocity as a function of voltage levels.

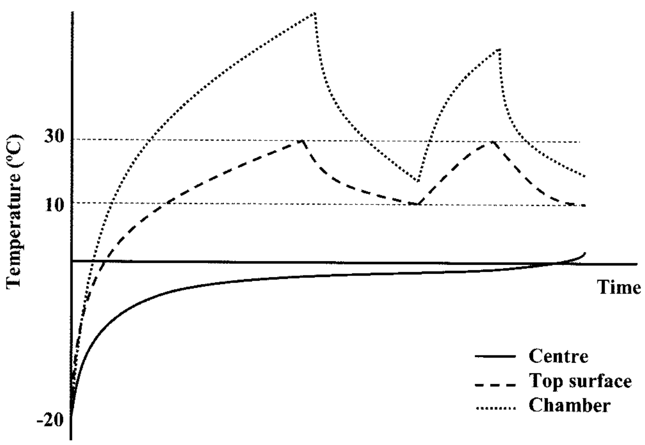

Fig. 3. Schematic time-temperature profiles of centre, top surface, and inner chamber during treatment with infrared radiation combined with air blast thawing.

where D and t are the mean sample thickness and time, respectively.

Drip Loss

Each sample was weighed before packaging (m_1) and reweighed after thawing (m_2). Thawing loss was determined from the difference in weights between the two measurements (m_1 - m_2) and expressed as a percentage of the initial weight (m_1). Cooking loss was determined by assessing the exudation values after thermal treatment. Three pork samples from each treatment were weighed before and after cooking at 75°C for 30 min. The cooking loss was expressed as a percentage of the initial weight.

Water Holding Capacity (WHC)

WHC was determined by the method of Hong *et al.* (2005a). Approximately 1 g of meat (m_1) was weighed and placed into a centrifuge tube along with gauze as an absorbent. The samples were centrifuged for 10 min at 3,000 rpm using a RC-3 automatic refrigerated centrifuge (Sorvall, Asheville, NC, USA) maintained at 4°C. After centrifuging, the meat was removed from the tube and the weight of the centrifuge tubes before (m_2) and after (m_3) drying was measured. WHC was expressed as a percentage of moisture remaining in the meat according to the following equation:

$$WHC(\%) = \left(1-\frac{m_2-m_3}{m_1}\right)\times 100$$

Shear Force

After measurement of the cooking loss, strips 10 mm in diameter and 35 mm in length were cut parallel to the longitudinal orientation of the muscle fibres. Each strip was sheared using a model DPS-20 digital gauge (IMADA, Northbrook, IL, USA). The head speed was 60 mm/min and an average was calculated. Analysis was determined from the means of 24 replicates.

Colour

Colour measurements were taken with a CR-10 colour reader (Konica Minolta Sensing, Tokyo, Japan) calibrated with a white standard plate (L* = +97.83, a* = -0.43, b* = +1.98, as indicators of lightness, redness, and yellowness, respectively). Commission Internationale de l'Eclairage (CIE) L*, a*, and b*-values were determined. Six measurements were taken from each sample surface.

Statistical Analysis

Completely randomized design was adopted in design-ing the experiment. Six IR powers (0, 47, 80, 121, 171, and 229 W) x three air velocities (0, 3, and 6 m/s) were analyzed by one way ANOVA using SAS software Ver. 9.1 (SAS Institute, Cary, NC, USA) and differences among the means were compared using Duncan's Multiple Range test at a 0.05 level of significance. The relationship between independent variables and corresponding responses were analysed by Pearson's correlation coefficients.

Results and Discussion

Thawing Profile

In natural convection treatment (0 W and 0 m/s), the thawing time (the time to traverse from -5°C-0°C) was approximately 150 min, compared to 46 and 35 min at 3 and 6 m/s of forced air convection (air blast), respectively. Thawing time also decreased with increasing IR dose intensity, and was reduced by about 50% when air blast was combined with IR. The calculated thawing rate at various IR intensities and air blast velocities are given in Fig. 4. Regardless of air velocity, increasing IR intensity produced an exponential increase in the thawing rate of pork. However, combination of air blast with IR further increased the speed of thawing. As expected, the thawing rate was dependant on the air flow velocity, consistent with an increased heat transfer coefficient (Hong *et al.*, 2005b). Contrary to the latter study, however, it was observed that increasing air velocity did not produce a linear increase in the thawing rate. This may have been due to temperature control during thawing. The pulsed IR power during thawing was not consistent in all treatments; some of samples were thawed with two cycles while others involved three cycles. IR also had an effect both on the incremental increase in chamber temperature and on heat transmittance through the sample. IR was both a heat source and also penetrates into the meat by virtue of its relatively long wavelength. Thus, IR radiation represents an efficient heating system (Sheridan and Shilton, 1999). According to our preliminary study (data not shown), IR radiation can increase the chamber temperature up to 120°C even at 50 W of power, necessitating temperature control in the present study to avoid surface overheating of the sample. Although the actual wavelength emitted from the IR lamp could not be measured in the current study, the wavelength from commercial IR lamps tends to be in the near-IR range (0.75-1.4 ìm). Since water has a high emissivity, foods containing water have a significant ability to absorb IR energy according to Kirchhoff's law; water absorbs IR energy maximally at a wavelength of 1.4 μm (Lewicki, 2004). Ice has a higher emissivity than water (Fellows, 1988), making IR applicable for the rapid thawing of meat. When combined with air blast, thawing of pork was enhanced.

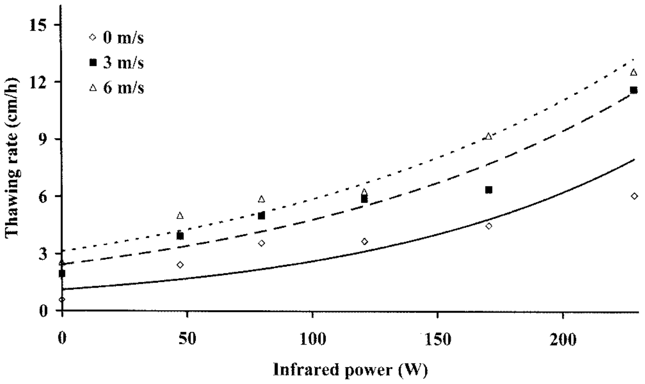

Fig. 4. Change in thawing rate of pork under various air velocities as a function of infrared power levels. Solid, dashed, and dotted lines represent regression line at 0 m/s ($R^2 = 0.74$), 3 m/s ($R^2 = 0.91$), and 6 m/s ($R^2 = 0.94$) of air velocity, respectively.

Thawing Loss

Fig. 5 depict the thawing loss of pork at each air velocity as a function of IR power level. Regardless of air velocity, IR treatments produced significantly lower thawing loss than 0 W treatment ($p<0.05$). For natural convection (0 m/s), increasing IR power tended to decrease the thawing loss of pork; however, no significant differences among IR treatments were evident ($p>0.05$). Significantly low thawing loss was found at IR and air velocity conditions of 229 W and 3 m/s, and 171 W and 6 m/s. Meanwhile, increasing air velocity under constant IR power level tended to increase the thawing loss of pork. In general, the content of thawing drip is related to

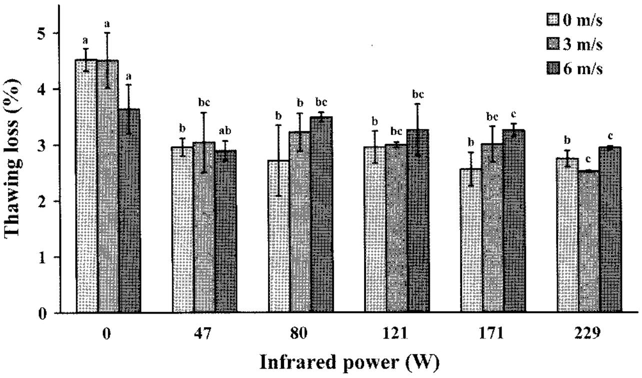

Fig. 5. Change in thawing loss of pork under various air velocities as a function of infrared power levels.

the rate of freezing, which, in turn, is related to the size and location of ice crystals in the frozen meat (Ngapo *et al.*, 1999). Drip loss at a high freezing rate is decreased by an increasing thawing rate, in contrast with low freezing rate, emphasizing the importance of the thaw rate as well as the freezing rate (Hamm *et al.*, 1982). In the current study, rapid freezing was conducted using a -135°C deep freezer to reduce thawing drip. Both IR power and air velocity increased the thawing rate of pork, with thawing loss decreasing as the IR power increased. However, air velocity positively correlated with thawing loss ($p<0.01$). This was mainly attributed to sample surface drying. IR radiation is a kind of surface process, which is effective to a depth of approximately 1 μm (Lewicki, 2004). Increasing IR dose intensity increases surface temperature, and, hence, surface evaporation. This surface acts as a boundary between the heat source and the portion of the sample below the impermeable surface, and facilitates convective transport of energy and water vapour. Liquid water transported to the surface from the interior is evaporated and then convected away (Datta and Ni, 2002). Thus, IR dose is the major influence on surface drying. However, when the power is off at a relatively low temperature (30°C) discontinuation of IR energy can cause a rapid temperature depression in the thawing chamber, which may presently have contributed in a minor way to moisture loss. On the other hand, continuous air convection with a simultaneous temperature fluctuation during the thawing can manifest as a significant surface drying.

Table 1. Changes in water binding properties of pork under various air velocities as a function of infrared (IR) power levels

IR power (W)	Air velocity (m/s)		
	0	3	6
Cooking loss (%)			
C[1]	27.5±1.41$^{\text{BCx}}$[2]	28.6±0.17$^{\text{Ax}}$	28.1±0.26$^{\text{Ax}}$
0	28.8±0.31$^{\text{Ax}}$	28.2±0.59$^{\text{Ax}}$	27.9±0.50$^{\text{Ax}}$
47	28.1±0.30$^{\text{ABy}}$	28.0±1.36$^{\text{Ay}}$	26.2±0.35$^{\text{Bx}}$
80	27.8±0.15$^{\text{ABy}}$	28.9±0.42$^{\text{Ax}}$	26.5±0.60$^{\text{Bz}}$
121	26.6±0.17$^{\text{Cy}}$	28.0±0.13$^{\text{Ax}}$	26.3±0.51$^{\text{By}}$
171	27.4±0.23$^{\text{BCx}}$	26.2±0.12$^{\text{By}}$	25.9±0.24$^{\text{By}}$
229	25.3±0.49$^{\text{Dx}}$	25.5±0.67$^{\text{Bx}}$	24.8±0.25$^{\text{Cx}}$
Water holding capacity (%)			
C	86.2±1.05$^{\text{Ax}}$	87.1±0.74$^{\text{Ax}}$	86.4±1.16$^{\text{Ax}}$
0	84.5±0.39$^{\text{ABy}}$	84.7±0.89$^{\text{By}}$	86.5±0.43$^{\text{Ax}}$
47	82.2±1.02$^{\text{BCy}}$	83.0±1.24$^{\text{BCy}}$	86.7±2.26$^{\text{Ax}}$
80	83.8±1.39$^{\text{ABCx}}$	83.8±0.57$^{\text{Bx}}$	83.0±4.74$^{\text{ABx}}$
121	83.1±1.51$^{\text{BCx}}$	83.0±0.50$^{\text{BCx}}$	82.4±2.52$^{\text{ABx}}$
171	82.2±2.25$^{\text{BCx}}$	82.2±2.25$^{\text{BCx}}$	82.3±2.58$^{\text{ABx}}$
229	81.4±0.84$^{\text{Cx}}$	81.0±1.94$^{\text{Cx}}$	80.9±1.18$^{\text{Bx}}$

[1] C, Control.

[2] Means±SD from three replicate determinations.

$^{\text{A-C}}$Means with different superscript within same column are significantly different ($p<0.05$).

$^{\text{x-z}}$Means with different superscript within same row are significantly different ($p<0.05$).

Water Binding Properties

Table 1 summarizes the water binding properties of pork at each air velocity as a function of IR power. The unfrozen control showed 28.3% of mean cooking loss. Increasing both IR power and air velocity tended to decrease the cooking loss of pork. Significantly lower cooking loss of pork than control was shown at 171, 80, and 47 W of IR radiation, which corresponded to 0, 3, and 6 m/s of air velocity, respectively ($p<0.05$). Regarding air velocity, the 6 m/s condition produced the lowest cooking loss ($p<0.05$), while the differences between the 0 m/s and 3 m/s treatments were not significant ($p>0.05$). Cooking loss had a significant negative correlation with both air velocity ($p<0.01$) and IR power ($p<0.001$) (Table 4). This result could be explained by rapid thawing. In the current study, the decision to cool to 4°C before subsequently freezing to -30°C was based on previous observations that cooling a material very slowly to the point where crystal formation is initiated, followed by rapid freezing, can produce a frozen material with smaller ice crystals than if the material is rapidly cooled throughout the whole process (Reid, 1999; Farouk *et al.*, 2003). The precooling temperature of 4°C and subsequent rapid thawing rate are considered to give a stable yield during the thawing process, resulting in an improved cooking yield at higher IR power and air velocity (Hong *et al.*, 2005b).

Increasing IR power level tended to decrease the WHC of pork. Significant decreases in WHC were apparent at 47 W of IR power for 0 m/s and 3 m/s, and 229 W for 6 m/s of air velocity ($p<0.05$), compared to control. As a consequence of the irregular temperature fluctuation during thawing, WHC did not presently show any ordered tendency, with a high standard deviation being evident. In general, WHC of frozen meat is related to the state of myofibrillar protein (Hong *et al.*, 2005b). Petroviæ *et al.* (1993) noted that slowly frozen beef has lower protein solubility than quickly frozen beef. Wagner and Añón (1985) reported greater protein denaturation in slowly frozen myofibrillar protein, and attributed the difference to the partial unfolding of the protein molecules with exposure of their constituent hydrophobic groups. However, the thawing process probably does greater damage to meat than freezing, because thawing occurs more slowly than freezing (Forrest *et al.*, 1975). Protein denaturation during thawing results from recrystallization (Hong *et al.*, 2005b). However, WHC of frozen meat may be influenced by the fat content due to the ratio of moisture to protein (Dawood, 1995). Hong *et al.* (2005b) also reported no significant difference in WHC between fresh and thawed pork loin. Therefore, significantly low WHC presently found can be mainly attributed to the IR dosage as revealed by the correlation coefficient ($p<0.001$).

Shear Force

Table 2 presents the effects of IR power levels and air velocities on shear force of pork. Non-irradiated pork displayed a significantly higher shear force than that of fresh control ($p<0.05$), ranging from 10.5-11.2 N. However, increasing IR power tended to decrease the shear force of pork, although the differences were not significant ($p>0.05$). In addition, shear force increased with increasing air velocity. As shown by correlation coefficient determinations, both IR power ($p<0.01$) and air velocity ($p<0.001$) had a significant effect on shear value. High shear values of frozen meat are mainly due to the generation of thawing drip, as well as protein aggregation from cold denaturation (Hong *et al.*, 2007a; Smeller, 2002). In the current study, increasing IR power accelerated thawing velocity, resulting in low thawing loss. This phenomenon effectively retards toughness in the meat product (Hong *et al.*, 2007b). Moreover, temperature control might positive affect shear force. In reality, continuous IR radiation may not be suitable for thawing, given our present observations that IR irradiated meat had a surface that was overcooked and dried (Fig. 6). However, avoiding a severe temperature rise from a subzero temperature could prevent excessive thawing loss originating from surface drying. Accordingly, IR radiation combined with air blast thawing has a potential advantage in maintaining meat quality after thawing, and control of temperature can extend the applicability of IR radiation from cooking to thawing.

Table 2. Changes in shear force of pork under various air velocities as a function of infrared (IR) power levels

IR power (W)	Air velocity (m/s)		
	0	3	6
Shear force (N)			
C$^{1)}$	$9.1\pm0.57^{Cy,2)}$	10.0 ± 1.62^{CDx}	9.5 ± 1.20^{Bxy}
0	10.6 ± 0.92^{Ax}	11.2 ± 1.27^{Ax}	11.2 ± 0.97^{Ax}
47	9.9 ± 0.97^{Bx}	10.4 ± 0.82^{BCx}	10.1 ± 1.25^{Bx}
80	9.7 ± 0.71^{By}	11.2 ± 1.15^{Ax}	9.9 ± 0.87^{By}
121	9.7 ± 0.71^{By}	10.9 ± 1.29^{ABx}	10.0 ± 1.21^{By}
171	9.2 ± 0.54^{Cy}	10.3 ± 0.87^{BCx}	9.9 ± 1.18^{Bx}
229	9.5 ± 0.33^{BCx}	9.5 ± 0.77^{Dx}	9.7 ± 0.91^{Bx}

$^{1)}$ C, Control.

$^{2)}$ Means±SD from three replicate determinations.

$^{A\text{-}C}$ Means with different superscript within same column are significantly different ($p<0.05$).

$^{x\text{-}z}$ Means with different superscript within same row are significantly different ($p<0.05$).

Colour

Table 3 summarizes the effects of various air velocities and IR powers on CIE colour of pork. All thawing treatments produced a significantly lower L*-value than that of control ($p<0.05$). For thawing treatments, no effect of IR power on L*-value was generally found, although some significant differences were evident ($p<0.05$). Air velocity also had no effect on L*-value of pork ($p>0.05$), with the exception of the 0 W treatment ($p<0.05$). Significantly lower a*-value of pork was found at air velocities up to 3 m/s ($p<0.05$) compared to control. However, no

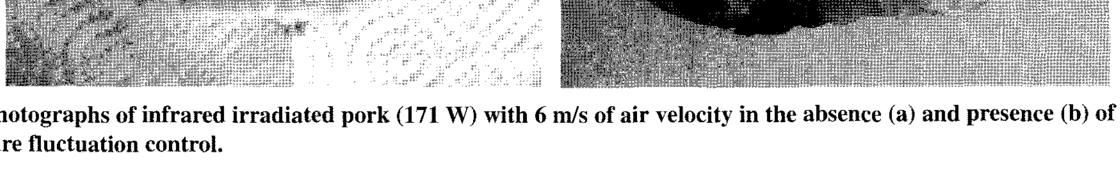

Fig. 6. Photographs of infrared irradiated pork (171 W) with 6 m/s of air velocity in the absence (a) and presence (b) of temperature fluctuation control.

Table 3. Change in CIE colour of pork under various air velocities as a function of infrared (IR) power levels

IR power (W)	Air velocity (m/s)		
	0	3	6
L* value			
C$^{1)}$	48.6±1.74$^{Aa,2)}$	50.0±1.12^{Aa}	49.8±0.74^{Aa}
0	46.1±2.01^{Bab}	43.3±2.59^{Cb}	48.8±2.32^{ABa}
47	45.4±1.96^{Ba}	47.6±3.31^{ABa}	44.4±2.20^{Ca}
80	45.6±1.79^{Ba}	49.4±2.56^{ABa}	45.2±1.65^{Ca}
121	45.3±1.78^{Ba}	46.0±2.82^{BCa}	46.3±3.17^{BCa}
171	45.3±2.20^{Ba}	46.8±2.81^{ABa}	46.0±1.73^{Ca}
229	45.1±1.00^{Ba}	46.8±2.38^{ABa}	46.3±1.92^{BCa}
a* value			
C	10.4±0.80^{Aa}	10.1±0.74^{Aa}	7.9±1.03^{Ab}
0	6.7±0.46^{Bb}	8.3±1.16^{Ba}	6.1±0.36^{Cb}
47	6.7±0.59^{Ba}	6.9±1.19^{Ca}	7.0±0.72^{Ba}
80	6.1±0.59^{Bb}	7.3±0.73^{BCa}	7.3±0.43^{ABa}
121	6.2±0.34^{Bc}	8.0±0.30^{BCa}	7.5±0.44^{ABb}
171	6.2±1.26^{Ba}	7.2±0.67^{Ca}	6.7±0.55^{BCa}
229	6.5±0.91^{Ba}	7.0±1.32^{Ca}	7.3±0.69^{ABa}
b* value			
C	12.5±0.86^{Aab}	12.8±1.03^{Aa}	11.3±1.15^{Ab}
0	10.7±0.50^{Ba}	10.6±1.20^{Ba}	8.9±0.25^{Db}
47	10.5±0.46^{Ba}	11.0±1.10^{Ba}	10.4±0.60^{ABCa}
80	10.2±0.58^{Bab}	10.9±0.56^{Ba}	9.9±0.83^{BCb}
121	9.8±0.50^{Bb}	11.2±0.62^{Ba}	10.9±0.78^{ABa}
171	10.5±1.01^{Bab}	10.8±0.67^{Ba}	9.6±0.33^{CDb}
229	10.0±1.16^{Ba}	10.7±0.99^{Ba}	10.3±1.01^{BCa}

$^{1)}$ C, Control.

$^{2)}$ Means±SD from three replicate determinations.

$^{A-C}$ Means with different superscript within same column are significantly different ($p<0.05$).

$^{x-z}$ Means with different superscript within same row are significantly different ($p<0.05$).

Table 4. Correlation coefficients between independent variables and dependent responses

	Air velocity	Infrared power
Thawing rate	0.46*	0.83***
Thawing loss	0.37**	-0.67***
Cooking loss	-0.43**	-0.77***
Water holding capacity	0.14	-0.58**
Shear force	0.29***	-0.30**
L* value	0.11	0.01
a* value	0.03	-0.34**
b* value	-0.15*	-0.25**

* Significant at 0.05 levels.

** Significant at 0.01 levels.

*** Significant at 0.001 levels.

significant differences in a*-value were evident above 80 W of IR power with 6 m/s of air velocity ($p>0.05$). No air velocity treatment was significantly different ($p>0.05$), however, an air velocity of 6 m/s best maintained the redness of pork samples, when compared to the a*-value of control. The b*-value results were similar to the a*-value results. In general, the absence of any trends in CIE colour could be due to temperature fluctuation during thawing. However, it is conceivable that temperature control prevented discolouration from overheating of the sample surface. As shown in Fig. 6, in the absence of temperature control, severe overheating at the surface was apparent, while no overheated region was apparent when the temperature was controlled.

In agreement, a study by Hong *et al.*, (2007b) also showed that IR radiation combined with air blast confers a potential advantage in rapid thawing of pork, and that the excessive overheating found in thermal processing can be effectively avoided by simultaneously applied temperature control.

Acknowledgemants

This study was partially supported by a grant of LG Electronics Inc. and by the Brain Korea 21 Project from Ministry of Education and Human Resources Development, Republic of Korea.

References

1. Ambrosiadis, I., Theodorakakos, N., Georgakis, S., and Lekas, S. (1994) Influence of thawing methods on the quality of frozen meat and the drip loss. *Fleischwirtschaft.* **74**, 284-287.
2. Datta, A. K. and Ni, H. (2002) Infrared and hot-air-assisted microwave heating of foods for control of surface moisture. *J. Food Eng.* **51**, 355-364.
3. Dawood, A. A. (1995) Physical and sensory characteristics of Najdi-camel meat. *Meat Sci.* **39**, 59-69.
4. Deatherage, F. E. and Hamm, R. (1960) Influence of freezing and thawing on hydration and changes of the muscle proteins. *Food Res.* **25**, 623-629.
5. Farouk, M. M., Wieliczko, K. J., and Merts, I. (2003) Ultra-fast freezing and low storage temperature are not necessary to maintain the functional properties of manufacturing beef. *Meat Sci.* **66**, 171-179.
6. Fellows, P. (1988) Food processing technology. Chichester: Ellis Horwood.
7. Forrest, J. C., Aberle, E. D., Hedrick, H. B., Judge, M. D., and Merkel, R. A. (1975) Principles of meat science. San Francisco: W. H. Freeman and Company.
8. Gonzalez-Sanguinetti, S., Añon, M. C., and Calvelo, A. (1985) Effect of thawing rate on exudates production of frozen beef. *J. Food Sci.* **50**, 697-700.
9. Hamm, R, Gottesmann, P., and Kijowski, J. (1982) Einfrieren und Auftauen von Fleisch: Einfluesse auf Muskel-

gewebe und Tausaftbildung. *Fleischwirtschaft.* **62**, 6-11.

10. Hong, G. P., Ko, S. H., Choi, M. J., and Min, S. G. (2007a) Effects of pressure assisted freezing on physicochemical properties of pork. *Korean J. Food Sci. Ani. Resour.* **27**, 190-196.
11. Hong, G. P., Min, S. G., Ko, S. H., Shim, K. B., Seo, E. J., and Choi, M. J. (2007b) Effects of brine immersion and electrode contact type low voltage ohmic thawing on the physicochemical properties of pork meat. *Korean J. Food Sci. Ani. Resour.* **27**, 416-423.
12. Hong, G. P., Park, S. H., Kim, J. Y., Lee, S. K., and Min, S. G. (2005a) Effects of time-dependent high pressure treatment on physico-chemical properties of pork. *Food Sci. Biotechnol.* **14**, 808-812.
13. Hong, G. P., Park, S. H., Kim, J. Y., Lee, C. H., Lee, S., and Min, S. G. (2005b) The effect of thawing rate on the physicochemical properties of frozen ostrich meat. *Food Sci. Biotechnol.* **14**, 676-680.
14. Ko, S. H., Hong, G. P., Park, S. H., Choi, M. J., and Min, S. G. (2006) Studies on physical properties of pork frozen by various high pressure freezing process. *Korean J. Food Sci. Ani. Resour.* **26**, 464-470.
15. Lewicki, P. P. (2004) Water as the determinant of food engineering properties. A review. *J. Food Eng.* **61**, 483-495.
16. Miles, C. A., Morley, M. J., and Rendell, M. (1999) High power ultrasonic thawing of frozen foods. *J. Food Eng.* **39**, 151-159.
17. Ngapo, T. M., Babare, I. H., Reynolds, J., and Mawson, R. F. (1999) Freezing rate and frozen storage effects on the ultrastructure of samples of pork. *Meat Sci.* **53**, 159-168.
18. Petroviæ, L., Grujiæ, R., and Petroviæ, M. (1993) Definition of the optimum freezing rate. 2. Investigation of the physicochemical properties of beef *M. longissimus dorsi* frozen at different freezing rates. *Meat Sci.* **33**, 319-331.
19. Reid, D. S. (1999) Factors which influence the freezing process on examination of new insights. Paper presented at the 20th International Congress of Refrigeration. IIR/IIF, Sydney.
20. Sakata, R., Oshida, T., Morita, H., and Nagata, Y. (1995) Physico-chemical and processing quality of porcine *M. longissimus dorsi* frozen at different temperature. *Meat Sci.* **39**, 277-284.
21. Sheridan, P. and Shilton, N. (1999) Application of infra-red radiation to cooking of meat products. *J. Food Eng.* **41**, 203-208.
22. Smeller, L. (2002) Pressure-temperature phase diagrams of biomolecules. *Biochim. Biophys. Acta.* **1595**, 11-29.
23. Virtanen, A. J., Goedeken, D. L., and Tong, C. H. (1997) Microwave assisted thawing of model frozen foods using feed-back temperature control and surface cooling. *J. Food Sci.* **62**, 150-154.
24. Wagner, J. R. and Añón, M. C. (1985) Effect of freezing rate on the denaturation of myofibrillar protein. *J. Food Technol.* **21**, 9-18.

(Received 2009.3.24/Revised 2009.6.5/Accepted 2009.6.9)