A THESIS FOR THE DEGREE OF MASTER OF SCIENCE

Effects of temperature fluctuation on moisture loss of fresh foods in household refrigerator

가정용 냉장고의 온도 제어 변동폭이 신선 식품의 수분 손실에 미치는 영향

February, 2018

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석사학위논문

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지도교수 최영진

이 논문을 석사학위 논문으로 제출함

2018년 2월

서울대학교 대학원 농생명공학부

이 은 지

이은지의 석사학위 논문을 인준함

2018년 2월

위 원 장 장판식 (인)

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ABSTRACT

Household refrigerator which is commonly used, operates the temperature rise and drop of ±2.0℃ distribution inside the fridge. It is well known that food can be deteriorated by a high storage temperature, but temperature fluctuation in fridge also can cause severe quality loss in foods. In this study, the effects of temperature fluctuation on storage quality of fresh foods including eye of round (meat), mackerel (fish), spinach and pak-choi (leafy vegetables) in refrigerator was investigated. According to the samples, mean temperatures were set to -2.5℃ or 0.5℃ (code L) and -1.0℃ or 2.5℃ (code H) and temperature fluctuations were designated in ±0.5℃, ±1.0℃, ±2.0℃ (code 0.5, 1.0, 2.0). Changes of storage quality were identified by measuring protein decay, lipid rancidity and moisture loss of food during the storage period. As a result, there was no significant difference in the degree of protein decay, fat rancidity of eye of round and mackerel between temperature fluctuations condition during storage. However, eye of round was frozen only at L2.0 condition during the storage and mackerels were frozen from the day of 3, 6 and 8 at L2.0, L1.0 and L0.5, respectively. Also, both weight loss of spinach and pak-choi were accelerated as the temperature fluctuation increased. In addition, model food, daikon, was introduced to investigate freezing and evaporation phenomena of stored food according to the temperature fluctuation condition. Freezing phenomenon as larger temperature fluctuation had relevance to that more chance to pass through the freezing point. Thus, ice nucleus could be formed and once nucleation occurred, freezing accelerated. Also, each temperature condition was expressed in terms of periodic sine function with constant amplitude and phase in order to interpretation of evaporation, and the amount of evaporation was calculated according to the temperature fluctuation through cumulative time data. As a results, the larger the temperature fluctuation was, the greater the driving force as partial pressure difference, more heat escaped from the food.

In this study, it was verified that relatively constant temperatures had advantages in maintaining moisture on foods. It is expected that this research will be used as a basis for the effects of temperature fluctuation control on fresh food in the domestic refrigerator and it could be used as a valuable reference for refrigerator technology research.

Keywords: household refrigerator, cold storage, temperature fluctuation, eye of round, mackerel, spinach, pak-choi, daikon.

Student number: 2016-21739

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Ⅰ. INTRODUCTION

Economic development and improved standards of living lead to rise of peoples' preference for natural and non-processed foods and also increase the consumption of fresh vegetables and fruits (Lee et al., 2009). These fresh foods can easily be damaged by physical or chemical factors such as external invasion of microorganisms, endogenous enzymes, water activity, pH, oxygen, light and temperature after harvest. Those factors affect the quality of foods, leading the loss of the available portions during storage. To prevent these influences and increase the availability with extended shelf life, food industry applies many technologies like product packaging, sterilization, refrigeration and freezing.

Especially, refrigeration or cold storage is one of the most classical and commonly used methods for food preservation. This is suitable for storage of fresh foods in relatively short periods, and it is an easily available way to use by household refrigerator.

However, many domestic refrigerators operate a fluctuating range of ±2.0℃ based on the mean setting temperature and some cases exhibit temperature fluctuations as much as ±5.0℃. This fluctuating temperature occurs because of the periodic refrigeration systems like vapor-compression and the need for automatic defrost in the device. Vapor-compression system in the refrigerator cycle is turned on and off at high and low set points (Evans, 2008; Giel, 1998). In this way, the temperature is shown as a continuous fluctuating flow with a cyclical pattern. As a results, a net migration of moisture was generated due to this temperature fluctuation from the interior towards the surface of the foodstuff or to the packaging (Yue et al., 2013). Also, it caused physiochemical changes which alter the quality of foods and shorten their shelf life (Singh & Wang, 1977).

Recently, a linear compressor has developed and applied in the household refrigeration instead of conventional rotary compressor. This can minimize energy loss in refrigeration and maintain constant temperature distribution in the fridge cell (Lee et al., 2000). However, there is no research on how the quality of food is affected when temperature fluctuation is reduced by the linear compressor. Furthermore, many studies on the storability of food depending on temperature have been carried out but there are few case in which actual temperature fluctuation are considered. Also, there are many researches about temperature fluctuation during freezing storage of food products (Gormley et al., 2002; Phimolsiripol et al., 2011; Reid & Perez-Albela Saettone, 2006), but the refrigeration circumstances are very different to those of the freezing about thermal properties of materials, air condition and situation.

In this study, the temperature fluctuation condition was set up to ±0.5℃, ±1.0℃ and ±2.0℃. And then, storage experiment was conducted to examine the effects of temperature fluctuation in representative food groups, such as eye of round (beef, meat), mackerel (fish), spinach and pak-choi (leaf vegetable). Those representative food groups selections were considered by Domestic commonly consumed foods (KCDC, 2014) and Food volume (LG electronics, 2015) which is a value expressed as a percentage of the amount present in the practical household refrigerator. For the results interpretation, further experiment about moisture evaporation and freezing was carried out using a daikon as a model food which is homogenous, isotropic material.

Ⅱ. MATERIALS AND METHODS

2.1. Sample preparation

All samples were obtained from a local market and had been kept in cool until arrival. For the minimization of sample variations, one chunk of meat covered each set of experiments. Also, harvest date and inventory history of leaf vegetables was traced before the experiments.

Eye of round (*Bos Taurus*) was cut regularly about 150g and half of one mackerel fillet (*Scomber scombrus*) was used as sample. Spinach (*Spinacia oleracea*) and pak-choi (*Brassica rapa subsp. Chinensis*) were removed soil and sampled about 7.5 g, 33 g, respectively. To reduce effects of surroundings, all sampling was conducted in 1 hour after foodstuffs arrived in laboratory. Only product without injury was selected and all of them were packed in a Tupperware or polypropylene container (Packsis MA-1, 255 x 490 x 370 mm). Experiments were carried out in a refrigerator with appropriate temperature and location of each sample was randomly changed once a day to minimize the location effect.

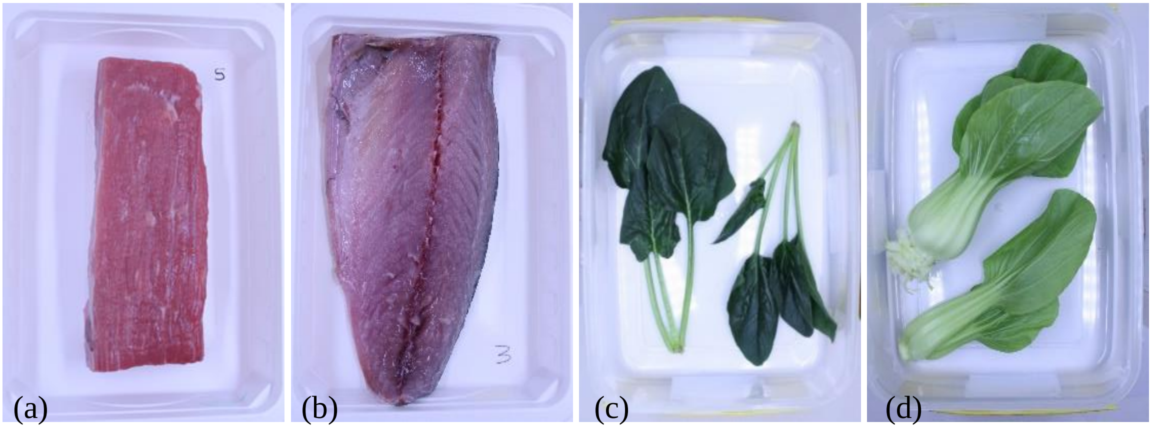


Figure 1. Sample appearance in (a) eye of round, (b) mackerel, (c) spinach and (d) pak-choi.

2.2. Temperature setting on refrigerator

LG Electronics supplied refrigerators (F877SS32, LG, Seoul, Korea) that were programmed to adjust the mean temperature and temperature fluctuation. The temperature and temperature fluctuation inside the refrigerator were recorded using a data logger (MX100-E1F, Yokogawa, Tokyo, Japan) by connecting a copper cable thermocouple. Fluctuation condition range was ±0.5℃, ±1.0℃ and ± 2.0℃, respectively. Setting temperatures were monitored to confirm the setting values properly maintained for each food group by data logger software (MX100 Standard 3.3.1.1). The room temperature where the refrigerator was placed maintained at 18℃ to reduce the influence of an external temperature. Only the middle shelf was used for minimization of the temperature variations regarding the location of refrigerating chamber.

Storage conditions for each food was shown in Table 1. For the sake of convenient presentation, code L signified mean temperature -2.5℃ or 0.5℃ and code H signified mean temperature -1.0℃ or 2.5℃. Also temperature fluctuation ±0.5℃, ±1.0℃ and ±2.0℃ simply expressed in 0.5, 1.0 and 2.0.

Table 1. Setting temperature conditions of each sample for storage

Sample	Mean temperature (℃)		Temperature fluctuation (℃)	Code
Eye of round (meat)	high	-1.0	±0.5	E-H0.5
			±1.0	E-H1.0
			±2.0	E-H2.0
	low	-2.5	±0.5	E-L0.5
			±1.0	E-L1.0
			±2.0	E-L2.0
Mackerel (fish)	high	-1.0	±0.5	M-H0.5
			±1.0	M-H1.0
			±2.0	M-H2.0
	low	-2.5	±0.5	M-L0.5
			±1.0	M-L1.0
			±2.0	M-L2.0
Spinach* (leaf vegetable)	high	2.5	±0.5	S-H0.5
			±1.0	S-H1.0
			±2.0	S-H2.0
	low	0.5	±0.5	S-L0.5
			±1.0	S-L1.0
			±2.0	S-L2.0
Pak-choi* (leaf vegetable)	high	2.5	±0.5	P-H0.5
			±1.0	P-H1.0
			±2.0	P-H2.0
	low	0.5	±0.5	P-L0.5
			±1.0	P-L1.0
			±2.0	P-L2.0
Daikon**	high	2.5	±0.5	D-H0.5
			±1.0	D-H1.0
			±2.0	D-H2.0
	low	-2.5	±0.5	D-L0.5
			±1.0	D-L1.0
			±2.0	D-L2.0

* In the case of leaf vegetable, the storage quality much affected by relative humidity during storage. Therefore, the condition of humidity in the container was controlled by sealed or punched packages, and the quality change due to the humidity was further analyzed. High humidity condition (95 ~ 97%, ●) were used in fully enclosed vessels and low humidity condition (90 ~ 95%, ○) were adjusted by drilling holes in the container.

** Sealed and unsealed container condition represent mark ● and ○, respectively.

2.3. Storage quality

2.3.1. Volatile basic nitrogen

Volatile basic nitrogen (VBN) was determined by the Conway micro-diffusion technique with slight modification (Tomohisa, 1975). Sample (10 g) was mixed with 90 ml of distilled water using a blender, 1 min. The homogenate was filtered through a filter paper (Whatman No.1, England). Glycerin was plastered on to the cover and the contact surface of a Conway tool. One milliliter of the filtrate was put into the outer space of the Conway unit and 1 ml of 0.01 N H_3BO_3 and 50 μL of Conway reagent (0.066% methyl red: 0.033% bromocresol green, 1:1) were added to the inner space. The Conway tool was sealed immediately after adding 1 ml of 50% potassium carbonate to the outer space. The sealed Conway was shaken slowly and incubated at 37°C for 120 min. After then, 0.02 N H_2SO_4 was added to the inner space for a titration until the color change. The VBN content was calculated by the following equation [1] (Miwa & Iida, 1973):

$$\text{VBN mg \%} \left(\frac{\text{mg}}{\text{100g sample}}\right) = \frac{(a-b)\times f\times 28.014}{S} \times 100 \qquad [1]$$

2.3.2. Thio-barbituric acid reactive substances

Malondialdehyde (MDA) is a decomposition product of peroxidized poly-unsaturated fatty acids and it forms a 1:2 adduct with the 2-thiobarbituric acid. This compound can be measured by fluorometry or spectrophotometry.

2-thiobarbituric acid-reactive substances (TBARS) were determined using the muscle extraction procedure (Lemon, 1975) in which ethylenediaminetetraacetic acid (EDTA) was added to the extraction solution to lessen development of TBARS during the analytical procedure. Around 25 g of tissue was blended with 100 mL of the distilled water (w/w=1:4). Then, the homogenate mixed with TCA extraction solution (w/w=1:2) which was composed of 7.5% trichloroacetic acid and 0.1% EDTA. Reaction this solution during 15 min and filtered through the filter paper. Five milliliters of 0.02 M 2-thiobarbituric solution reacted with 5 mL filtrate in 95℃ water bath during 30 min and cool down at 4℃. The reaction mixture was chilled, and the absorbance was measured at 532 nm using a UV-Visible spectrophotometer (UV-1700, Shimadzu, Japan). For quantification, standard solutions of MDA in 7.5% TCA were prepared from 1,1,3,3-Tetraethoxypropane (TEP) and calibration curves were prepared at a concentration ranging from 0.6 to 10 μM (r^2 = 0.999). The TBARS data are expressed as mg of MDA per kg sample.

2.3.3. Weight loss

To confirm the drip or evaporation, weight loss was measured during storage. Samples were withdrawn from each controlled temperature chamber and removed the package. The foodstuff was weighed with ±0.01 g precision in the scales (AX423, Ohaus, New Jersey, USA). This whole process took less than 3 min, but if the sample was frozen, thawing it out during 2 hours before weighting the sample. The weight loss was determined according to equation [2]:

$$\text{Weight loss} = \frac{weight_{\,before\ storage} - weight_{\,after\ storage}}{weight_{\,before\ storage}} \times 100 \qquad [2]$$

2.3.4. Appearance

Changes in appearance were photographed (Cannon EOS 450D, Cannon, Tokyo, Japan). To keep the brightness of the image constantly, the aperture value, shutter speed and ISO were fixed to F 8.0, Av 1/100s and ISO 800, respectively.

2.4. Daikon as numerical model

All daikon samples was prepared by cutting 7.5 x 7.5 x 1.5 cm^3 constantly and appearance was shown Figure 2. Experiments were conducted in sealed and unsealed conditions and surface temperature of daikon was also measured using a data logger by connecting a copper cable thermocouple. Thermal properties of daikon were referred from several papers and calculated in the formula (Table 2).

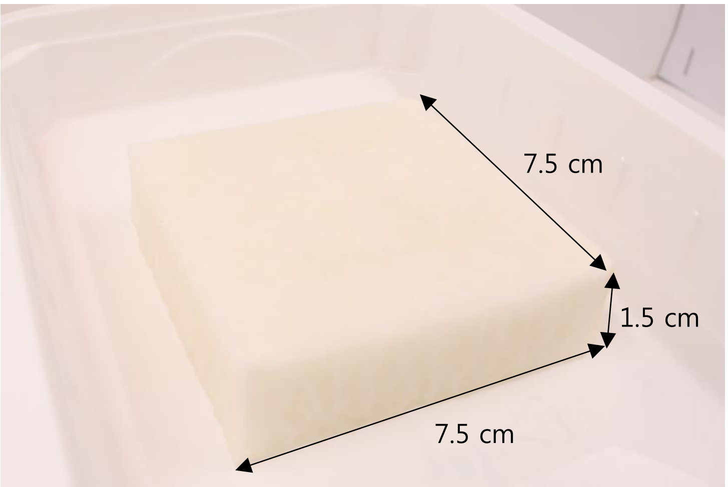


Figure 2. Appearance of daikon as a model food.

Table 2. Thermal properties of daikon used in numerical model

Sample	Property		Reference
Daikon	Moisture content	95.6%	
	Density, ρ	0.96 kg/m^3	
	Specific heat above freezing, c_p	4.08 kJ/kg·K	(Cantwell, 2008)
	Thermal conductivity, k_q	0.49 W/m·K	(Krokida et al., 2001)
	Skin mass transfer coefficient, h_m	0.42 kg/m^2·h·kPa	(Chau, 1987)

2.5. Statistical analysis

All experiments were conducted in triplicate and the data were analyzed using IBM SPSS 22 (SPSS Inc., Chicago, IL, USA). Duncan's multiple comparison test was used for investigating in order to determine significant difference ($p < 0.05$) of the results.

Ⅲ. RESULTS AND DISCUSSION

3.1. Temperature profiles

Inner temperature of the refrigerator was shown as Figure 3. Mean temperature was set differently according to the samples and conditions, but the temperature fluctuation was identically regulated as shown. Assumed that the temperature distribution is a constant periodic function, the cycle of 0.5 condition was about 0.35 hours. 1.0 condition and 2.0 condition was about 0.7, 1.1 hours, respectively.

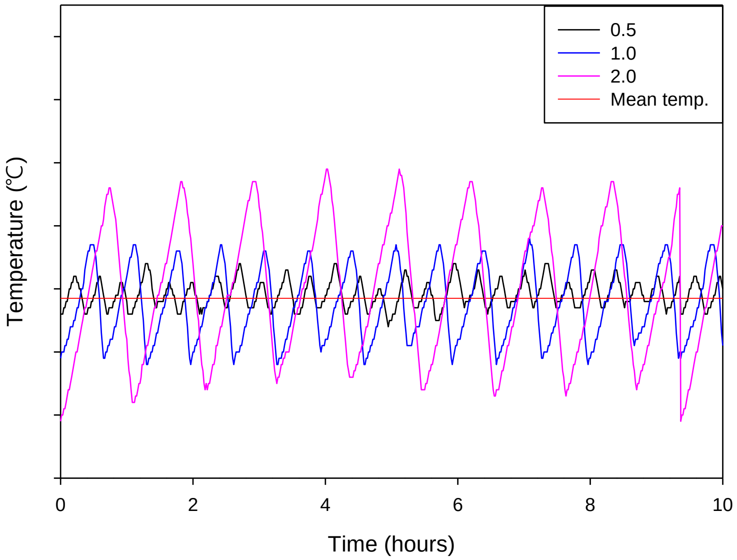


Figure 3. Temperature profiles in the refrigerator chamber during storage.

3.2. Quality changes during storage at various temperature conditions

3.2.1. Eye of round

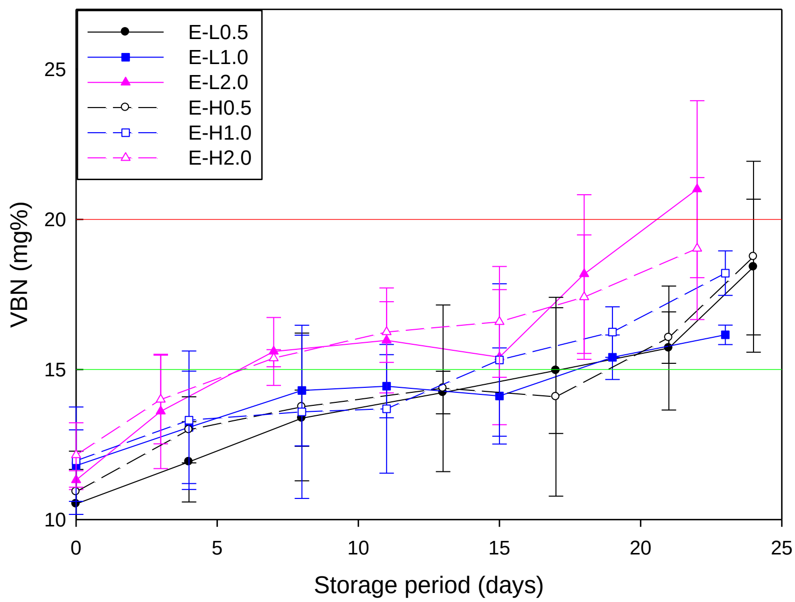
The influence of temperature and temperature fluctuation on VBN, TBARS and weight loss of eye of round was presented in figure 4. All eye of round samples tended to gradually increase VBN value during storage but interaction in temperature fluctuation was no significant difference. VBN is the result of the degradation of proteins in samples by microorganism so it can be a freshness index of foods. Many research reported that off-flavor in the meat begins to generate from more than VBN 15 mg% (Jang et al., 2014; Park et al., 1988). According to the KFSC (Korean Food Standards Codex), the standards and specifications of raw or packaged meat are defined as below VBN 20 mg%. Based on this, the criteria of off-flavor perception and spoilage were set as 15 mg% and 20 mg%, respectively, which was shown in Figure 4a.

The amount of TBARS was increased with time at all conditions (Figure 4b) and TBARS value was proportional to mean temperature. After more than three weeks of storage, L groups were more higher TBARS than H, but interaction in temperature fluctuation was no statistically significant ($p<0.05$). TBARS value which is an extent of lipid oxidation, also indicates the freshness of food quality. It was suggested that about 0.5 mg MDA/kg meat TBARS values corresponds to the detection limit for rancid off-flovors in pork (Lanari et al., 1995).

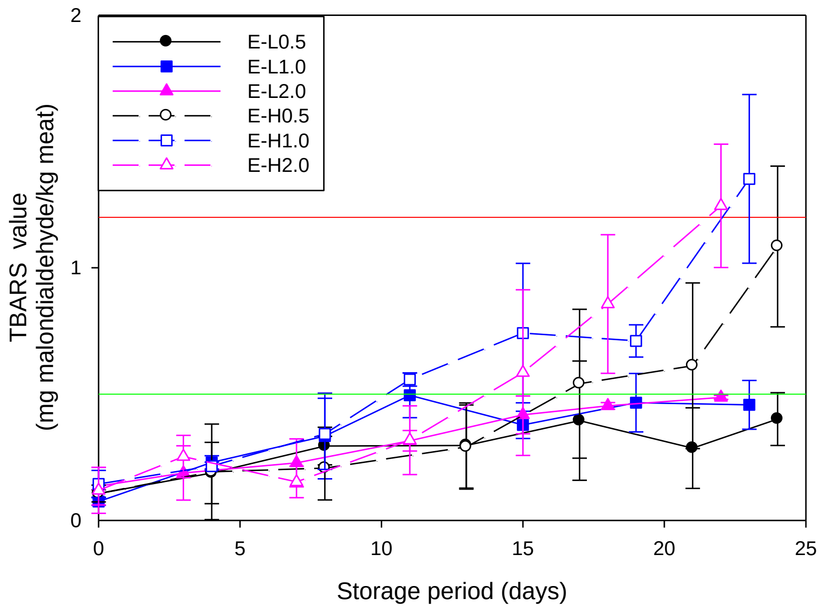
L2.0 was shown large weight loss about 4.6% because some samples frozed during storage (Figure 4c). However, others were within 2% weight loss and the drip rarely occurred. Weight loss on meat usually come from drip loss, which the loss in weight of food products owing to extruding and dripping away of tissue juices. This drip is caused by a change in microsturtures of the muscle from sarcomeres to contract and it is also known to occur as the internal moisture moves outside as the internal space of the muscle becomes narrow (Correa et al., 2007).

For the storage period, unfrozen state was maintained at L0.5 and L1.0 conditions, but frozen sample was discoverd at L2.0 since 7 days of storage (Table 3).

(a)


E-L0.5
E-L1.0
E-L2.0
E-H0.5
E-H1.0
E-H2.0
VBN (mg%)
10
15
20
25
0
5
10
15
20
25
Storage period (days)

(b)


E-L0.5
E-L1.0
E-L2.0
E-H0.5
E-H1.0
E-H2.0
TBARS value
(mg malondialdehyde/kg meat)
0
1
2
0
5
10
15
20
25
Storage period (days)

(c)

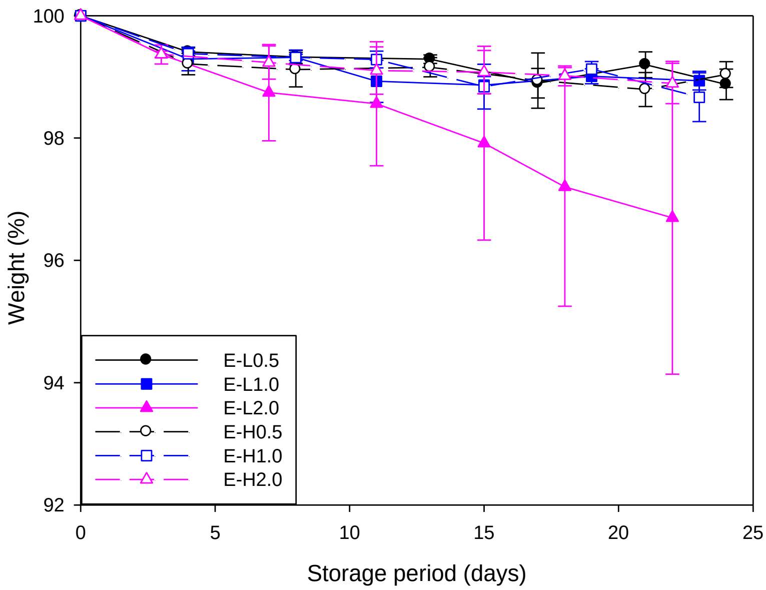


Figure 4. Changes in (a) VBN (mg%), (b) TBARS (MDA mg/kg sample) and (c) weight loss (%) of eye of round with different temperature conditions during storage. Error bars indicate standard deviations.

Table 3. First point (day) of the frozen eye of round

Code	**E-L0.5**	**E-L1.0**	**E-L2.0**
Day	ND[1)]	ND	7

1) The frozen samples were non-detected during storage.

3.2.2. Mackerel

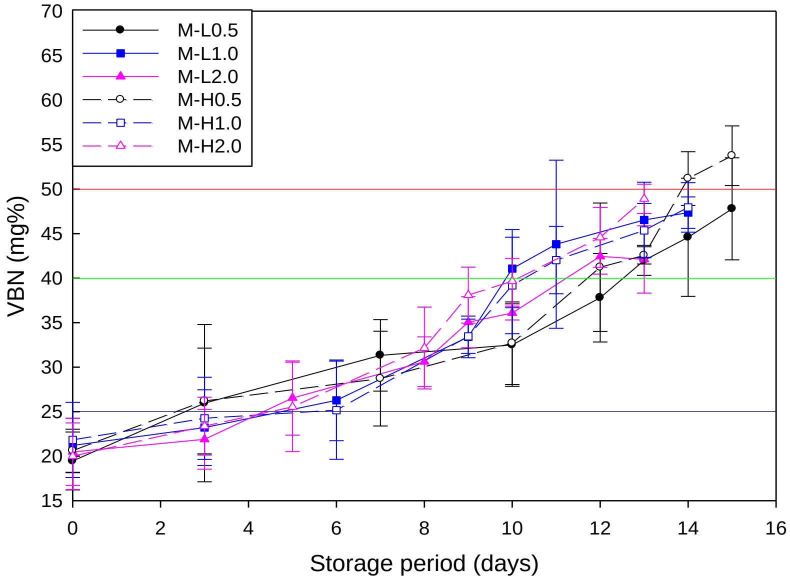
VBN, TBARS and weight loss of mackerel during storage was presented in Figure 5. All samples shown a tendency to increase the VBN value during storage but interaction in temperature fluctuation was no significant difference ($p<0.05$). Unlike meats, freshness of fishes can generally judge to be 5 ~ 10 mg% on fresh fish, 15 ~ 25 mg% on regular, 30 ~ 40 mg% under decaying period and above 50 mg% on rotten state (Chae & Kim, 1998). Based on this, the criteria of the fresh state, the off-flavor perception and the spoilages was set as 25 mg%, 40 mg% and 50 mg%, respectively, which was represented in the Figure 5a.

TBARS value was also no significant differnce between various temperature fluctuation conditions ($p<0.05$). However, TBARS value at 14 day in L2.0 shown 4.315 mg MDA/kg sample which is lower value than L1.0 and L0.5. Furthermore, the overall increment of TBARS value was greater than that of eye of round. This is because mackerels was containing more unsaturated fatty acid than eye of round.

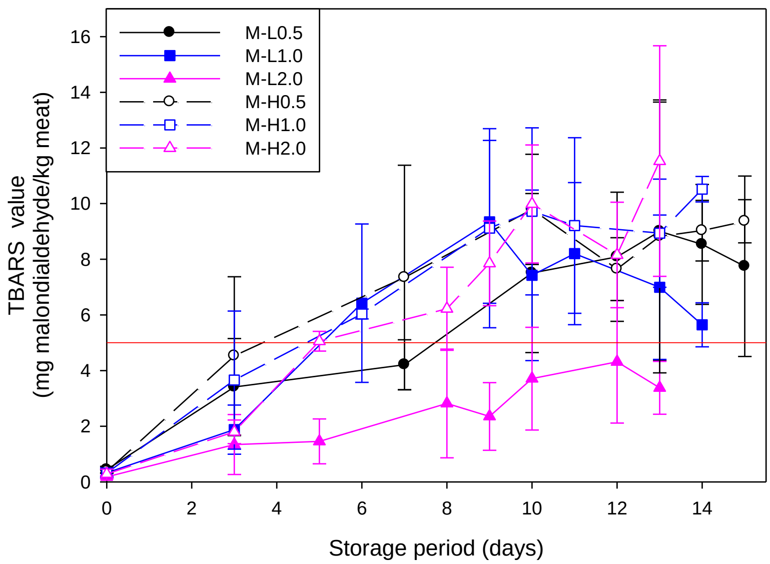
Weight loss of mackerel during storage was presented in Figure 5c. At the lower mean temperature condition, weight loss steeply generated becasue of sample freezing. L2.0 condition was shown 7.78% loss during total storage period.

For the storage period, first day point that found the frozen state was shown in Table 4. In L2.0, the sample was more faster frozen than L1.0 and L0.5 condition. The mackerel freezed at 3 day in larger fluctuation condition and frozen samples were discovered at 6, 8 day in the L1.0 and L0.5,

(a)


M-L0.5
M-L1.0
M-L2.0
M-H0.5
M-H1.0
M-H2.0
VBN (mg%)
70
65
60
55
50
45
40
35
30
25
20
15
0
2
4
6
8
10
12
14
16
Storage period (days)

(b)


M-L0.5
M-L1.0
M-L2.0
M-H0.5
M-H1.0
M-H2.0
TBARS value
(mg malondialdehyde/kg meat)
16
14
12
10
8
6
4
2
0
0
2
4
6
8
10
12
14
Storage period (days)

(c)

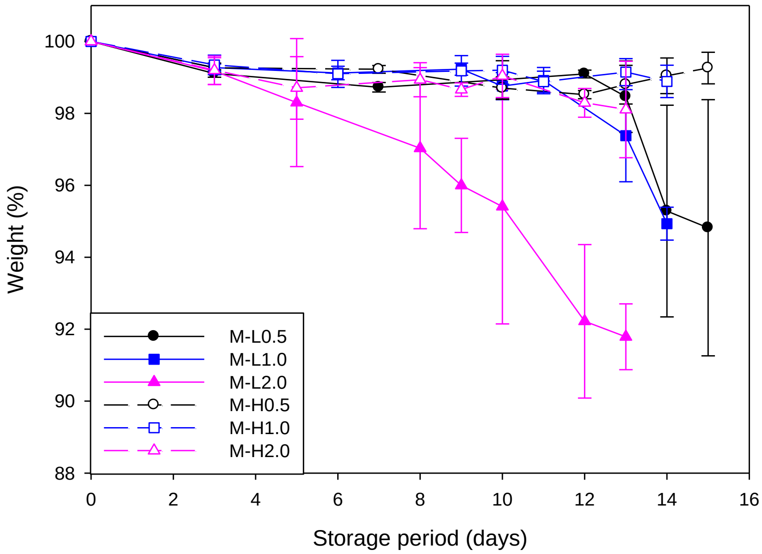


Figure 5. Changes in (a) VBN (mg%), (b) TBARS (MDA mg/kg sample) and (c) weight loss (%) of mackerel with different temperature conditions during storage. Error bars indicate standard deviations.

Table 4. First point (day) of the frozen mackerel

Code	**M-L0.5**	**M-L1.0**	**M-L2.0**
Day[1)]	8^{a}	6^{ab}	3^{b}

1) Different letters from a to b in the each row are significantly different (p<0.05).

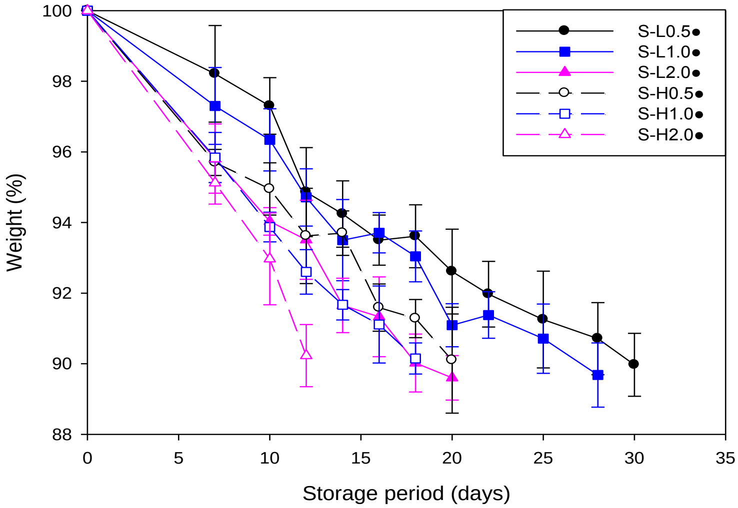
3.2.3. Spinach

Weight loss of spinach was represented in Figure 6. The weight loss was generally occurred more rapidly in the high temperature H group at sealed container (Figure 6a). Especially, freshness change of spinach began to be detected when weight loss reaches at 6% and quality was completely deteriorated and inedible state at 10% of weight loss. At the sealed container condition, it could be seen freshness change was detected at 10 days in L2.0, at 13 days in L1.0 and at 15 days in L0.5. Whole deterioration was about 18 days, 27 days and 30 days, respectively. The similar tendency was observed at the higher mean temperature H group. In the H2.0, freshness change was identified at 9 days. On the other hand, H1.0 and H0.5 condition was confrimed at 10, 12 days of storage. Complete deterioration at high mean temperature was 12, 18 and 20 days, respectively. Weight loss decreased faster as the temperature fluctuation increases in both L and H groups. Hence, temperature fluctuations affected to quality losses of spinach.

In the case of punched condition, weight loss of spinach was shown in Figure 6b. At low mean temperature with unsealed condition, it could be seen freshness change was detected at 4 days in all fluctuation conditions and deteriorated state was observed about 7 days. At H group, weight loss reached

6% at 3 days and completely deterioration was discovered at 5 days during storage. There was no significant difference between fluctuation during storage both of L, H groups in punched ($p<0.05$). It was different results from sealed container conditions and this is because very thin section and stoma structure on the surface of spinach was sensitively affected in open system like unsealed conditions in the refrigerator. Air circulation was continuously performed between the inside of the refrigerator having a low relative humidity (55%) and the punched container, thereby forming a condition in which the rate of water evaporation on the spinach surface was maximized. As a result, the effects of temperature fluctuation on the water evaporation of spinach could not be seen clearly because it is affected by open system.

(a)



(b)

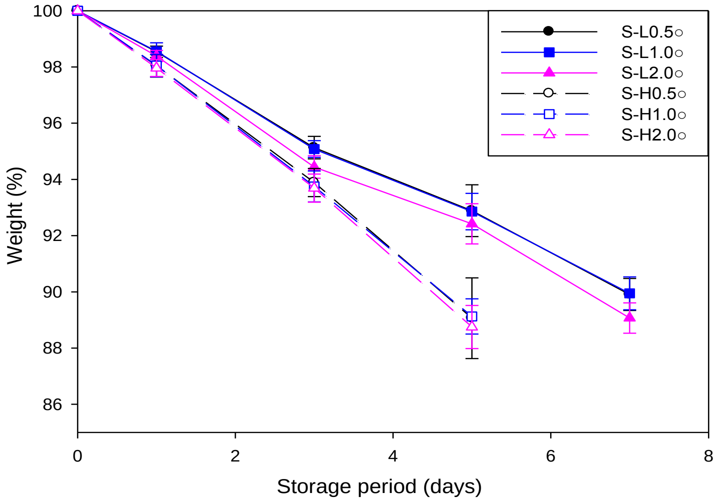


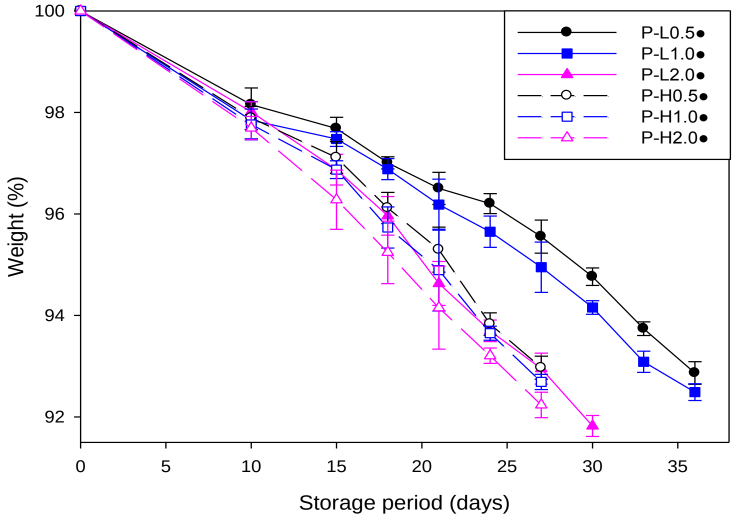
Figure 6. Changes in weight loss (%) of spinach on (a) sealed and (b) punched container with different temperature conditions during storage.

3.2.4. Pak-choi

Weight loss of pak-choi was presented in Figure 7. Likewise, weight loss was occurred more rapidly in the high temperature group at sealed condition (Figure 7a). Freshness change of pak-choi particularly began to be detected when weight loss reaches at 5% and quality was completely deteriorated and inedible state at 7% weight loss. At the sealed container, it could be seen freshness change was detected at 20 days in L2.0, at 27 days in L1.0 and at 29 days in L0.5. Whole deterioration was about 27 days, 34 days and 36 days, respectively. The similar tendency was observed at H condition. In the large fluctuation condition, H2.0, freshness change was identified at 19 days. On the other hand, H1.0 and H0.5 condition was confrimed at 21, 22 days of storage. Complete deterioration at H group was 26, 26 and 27 days at various temperature fluctuation, respectively. Weight loss decreased faster as the temperature fluctuation increases in both mean temperature. Hence, temperature fluctuations affected to the quality losses of pak-choi.

In the case of punched condition, weight loss was represented in Figure 7b. At low mean temperature with unsealed condition, it could be seen freshness change was detected at 6 days in all fluctuation conditions. Totally deteriorated state was observed about 8 days at fluctuation L2.0, L1.0 and about 7 days at L0.5. In H storage condition, weight loss reached 5% at 4 days and completely deterioration was discovered at 6 days during storage. Unlike the case of spinach in punched condition, there was significant difference between some fluctuation conditions during storage both of mean temperature groups ($p<0.05$). This is because pak-choi having a relatively thick cross section than spinach was less influenced in open condition. However, pak-choi that is leafy vegetable, was still affected air circulation easily and storage date reduced up to about one-fourth in punched condition.

(a)



(b)

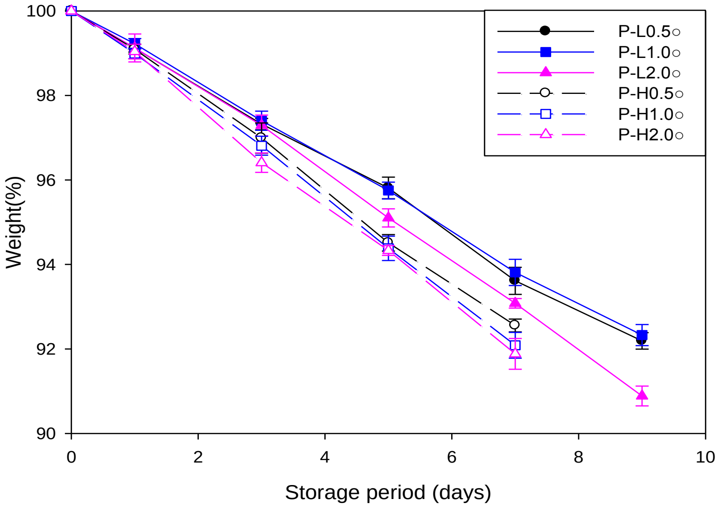


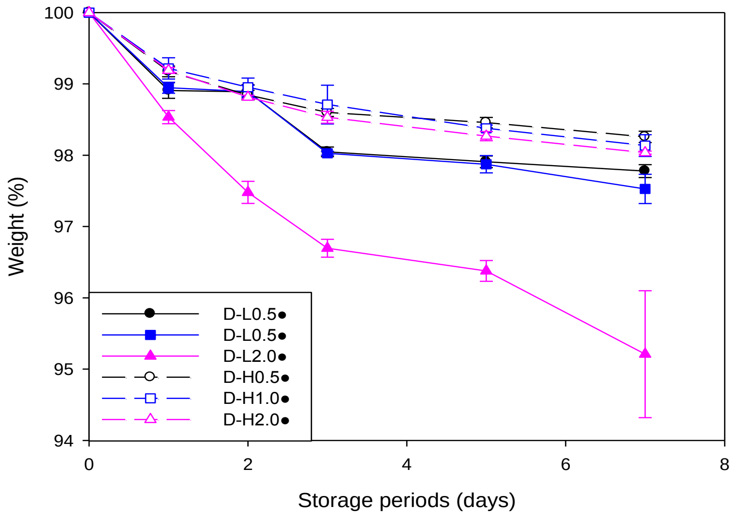
Figure 7. Changes in weight loss (%) of pak-choi on (a) sealed container and (b) punched container with different temperature conditions during storage.

3.3. Weight loss of daikon as a modeling

Daikon as a model food was introduced to re-examine the freezing and the evaporation phenomenon of food according to temperature fluctuation. Changes of weight loss in sealed condition during storage were shown in Figure 8a, Table 5. Weight loss was occurred more rapidly in the low temperature group because of sample freezing. Low mean temperature condition was deliberately set up at -2.5℃ to searching the freezing aspect depending on temperature fluctuation, as was sufficient condition to freeze. As a results, some samples in L2.0 and L1.0 condition were frozen during storage, which occured at 3 days and 5 days, respectively. However, there was no frozen sample at L0.5. Also, L2.0 condition was frozen within a day, and consequently samples in L2.0 were frozen hard over time. Weight loss was noticeable appeared with the passage of time. This phenomenan was agreed with tendency of eye of round and mackerel storage in low mean temperature. On the other hand, H group was no significant difference between temperature fluctuation during storage ($p<0.05$) and weight loss did not exceed 2% during storage.

Changes of weight loss in unsealed during storage were presented in Figure 8b, Table 6. Weight loss was also occurred more rapidly in the low temperature group because of sample freezing. Unlike the results of sealed packaging, unsealed samples under all fluctuation conditions were frozen in a day. This could be seen as a result of heat transfer from foods more quickly by the outside air in a fridge. Moreover, the larger temperature fluctuation was, the more the sample froze hard, causing more moisture loss during thawing ($p<0.05$). In the case of H group, weight loss was conspicuously affected with temperature fluctuation. Weight loss was larger in 41.47% at H2.0 while 7 days storage and H1.0, H0.5 conditions were 36.7% and 33.94%, respectively.

(a)



(b)

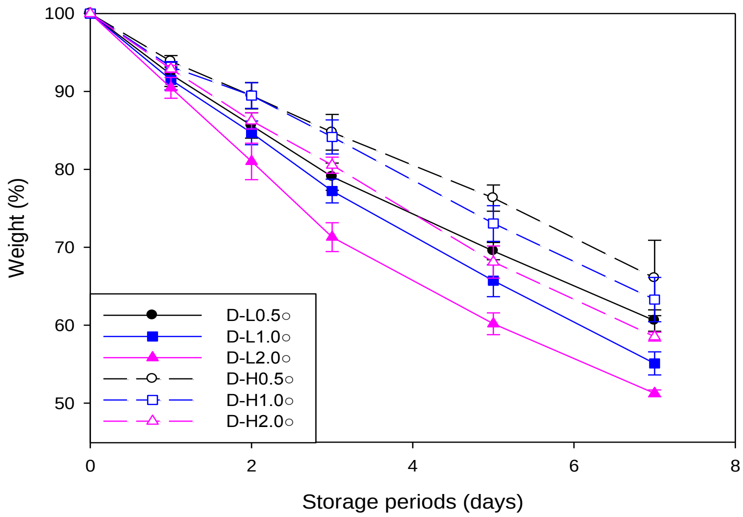


Figure 8. Changes in weight loss (%) of daikon on (a) sealed and (b) unsealed container with different temperature conditions during storage.

Table 5. Changes in weight loss (%) of daikon on sealed container with different temperature conditions during storage

Storage period (days)	Weight loss (%)[1)]					
	L0.5●	L1.0●	L2.0●	H0.5●	H1.0●	H2.0●
1	1.09^{Ab}	1.05^{Ab}	1.47^{Ac}	0.83^{Aa}	0.78^{Aa}	0.81^{Aa}
2	1.11^{Aa}	1.11^{Aa}	2.52^{Bb}	1.16^{Ba}	1.05^{ABa}	1.19^{Ba}
3	1.95^{Bb}	1.97^{Bb}	3.30^{BCc}	1.40^{Ca}	1.29^{BCa}	1.47^{Ca}
5	2.09^{Bb}	2.13^{Bb}	3.62^{Cc}	1.54^{Ca}	1.62^{CDa}	1.73^{Da}
7	2.22^{BCa}	2.47^{Ca}	4.79^{Db}	1.74^{Da}	1.87^{Da}	1.96^{Ea}

1) Different letters from A to E in the each column and from a to c in the each row are significantly different (p<0.05).

Table 6. Changes in weight loss (%) of daikon on unsealed container with different temperature conditions during storage

Storage period (days)	Weight loss (%)[1)]					
	L0.5○	**L1.0○**	**L2.0○**	**H0.5○**	**H1.0○**	**H2.0○**
1	7.8^{Aab}	8.5^{Aab}	9.5^{Ab}	6.1^{Aa}	6.8^{Aa}	7.1^{Aab}
2	14.4^{Bab}	15.3 ^{Bb}	19.0^{Bc}	10.6^{ABa}	10.5^{Aa}	13.8^{Bab}
3	21.0^{Cc}	22.8^{Cc}	28.7^{Cd}	15.3^{Ba}	15.8^{Bab}	19.5^{Cbc}
5	30.5^{Dbc}	34.3^{Dc}	39.8^{Dd}	23.7^{Da}	27.0^{Cab}	31.9^{Dc}
7	39.4^{Eabc}	44.9^{Bcd}	48.7^{Ed}	33.9^{Ea}	36.7^{Dab}	41.5^{Ebc}

1) Different letters from A to E in the each column and from a to d in the each row are significantly different (p<0.05).

3.4. Relationship between heat & mass transfer and temperature fluctuation during cold storage

3.4.1. Freezing at large temperature fluctuation

Freezing phenomenon due to temperature fluctuation on foods can be explained as follows. Food usually begins to freeze from its surface by the cold outside air, across which heat transfer occurs by conduction. As the ice layer formed from the outer surface increases gradually, the heat of foods is taken by the outside air and freezing is accelerated. This ice layer formed on the surface serves to help heat transfer more quickly because of thermal conductivity difference between water (0.58 W/m·K) and ice (2.20 W/m·K). However, in the case of thawing, it is not merely the reverse of freezing, and it can take far longer time that that required by freezing. Frozen foods begin to defrost and melt on the surface ice of foods and water layer is formed on it. This water layer slows the heat transfer due to thermal conductivity difference and takes more time to absorb the heat needed to thawing. As a results, thawing rate of foods is more smaller than its freezing and this difference in the rate of heat transfer that causes the time required to thawing a food to be longer than that required to freeze it (Figure 9).

In this context, the freezing phenomenon with temeprature fluctuation can be explained as follows. Storage conditions of frozen samples were higher than its freezing point. When the temperature fluctuation was large, the inner air temperature on refrigerator was periodically reached more lower temperature below he freezing point. Although the temperature was rose again by the same amplitude, this did not instantly affected the thawing because of difference of thermal condcutivity as stated above. As a results, accumulated temperature falling provided heat transfer with phase change and made the sample frozen hard during storage. By contrast, ±0.5℃ temperature fluctuation condition did not reach freezing point and there was no or less frozen samples. Figure 10 represented the surface temperature profile of daikon from the onset storage and it confimed that L2.0 has passed through the zone of maximum ice crystal formation quickly after phase transition.

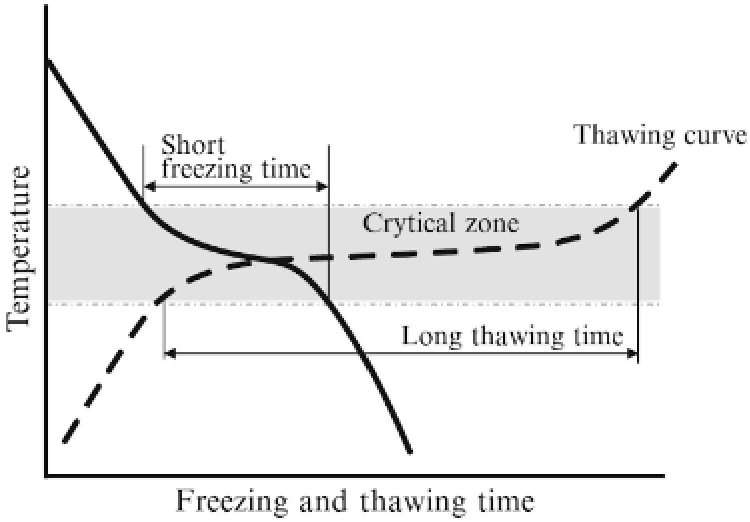


Figure 9. Comparison between freezing and thawing time (Neoh et al., 2016).

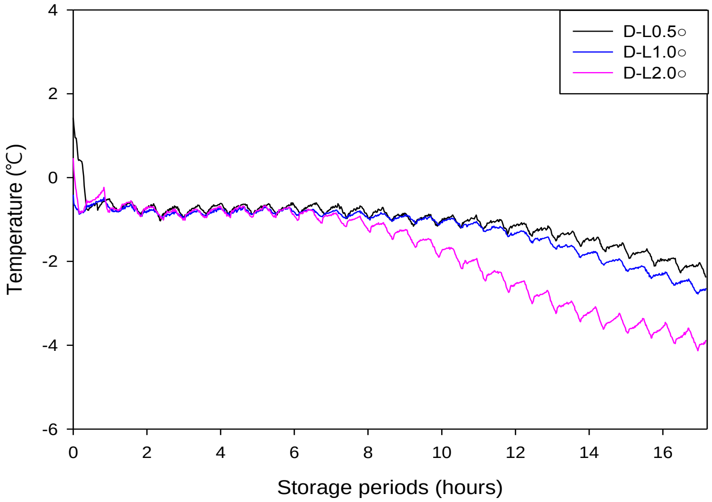


Figure 10. Surface temperature profiles of daikon from the onset storage.

3.4.2. Evaporation at large temperature fluctuation

Daikon as Numerical model was introduced to analysis the evaporation phenomenon caused by temperature fluctuation and its size was regulated in 7.5 x 7.5 x 1.5 cm^3. Since the shortest thickness 1.5 cm is more four times smaller than the others, only one direction of heat transfer was considered (Kuitche et al., 1996). Therefore, it could assume that daikon sample is an infinite slab and heat transfer situation in the surface of daikon expressed as follows equation [3], [4] and [5] (Hayakawa, 1978):

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x} + Q_V(T) \qquad t > 0 \ \ and \ \ 0 < x < l \qquad [3]$$

$$\frac{\partial T}{\partial t} = 0 \qquad at \quad x = 0, t > 0 \qquad [4]$$

$$k_q \frac{\partial T}{\partial x} = h(T_a - T_s) - L\, h_m(P_s - P) \qquad at \quad |x| = l, \ \ t > 0 \qquad [5]$$

Also, vegetables commonly generate respiration heat during storage so generation term $Q_V(T)$ should be considered in the governing equation. However, calculated the total respiratory heat by equation [6] (Hardenburg et al., 1986), it was found to be very small compared to the heat required for water evaporated during storage (Figure 11).

$$Q_V(T) = 7.4 \text{ x } 10^{-3}\ e^{0.096\,T} \qquad [6]$$

Therefore, internal generation term in the respiratory heat could be ignored. In additions, there is no difference between the surface temperature and center temperature of daikon during storage (Figure 12). It meant that conduction term is negligible because heat transfer inside is hardly occurred. Ambient temperature T_a and surface temperature T_s of daikon was expressed in terms of periodic sine function with constant amplitude and phase (Table 7). In general, food stuff’s temperature does not change instantaneously to the temperature change of the outside, but there was no lag time between air temperature and material temperature in this experiment. Consequentially, it was concluded that convection heat transfer was used as all evaporative latent heat and equation [5] was simplified as follow equation [7]:

$$h(T_a - T_s) = L\, h_m(P_s - P) \quad at \quad x = l, \; t > 0 \qquad [7]$$

Product surface partial water vapor P_s is not easily estimated due to changes in water activity and heterogeneous composition in surface during cooling process. Therefore, it assumed that moisture loss in experiment was maximum value and P_s was equal to the saturating water vapor pressure at the formerly calculated surface temperature (Kuitche et al., 1996). In this study, the Arden Buck equation [8] was used for calculating P_s and this equation is an empirical correlation that relates the saturation vapor pressure to temperature for humid air. Also, partial pressure P was also obtained by using an ideal gas law and Arden Buck formula (equation [9]).

$$P_s(T) = 0.61121 \exp\left(\left(18.678 - \frac{T_s}{234.5}\right)\left(\frac{T_s}{257.14 + T_s}\right)\right) \qquad [8]$$

$$P(T) = \frac{rh}{100} \cdot \left\{\frac{(T_a + 237.6)}{(T_s + 237.6)}\right\} \cdot 0.61121 \exp\left(\left(18.678 - \frac{T_a}{234.5}\right)\left(\frac{T_a}{257.14 + T_a}\right)\right) \qquad [9]$$

Total evaporated moisture in each temperature condition H2.0, H1.0 and H0.5 was 38.4 g, 34.1 g and 31.5 g during 7 days of storage. Latent heat was calculated in 2496 kJ/kg at mean temperature 2.5℃ referred saturated steam table (Geankoplis, 2013). Figure 11 was represented total heat loss amount during 7 days of storage from each temperature condition. As a result, heat input and output at the surface during storage period, the convective heat transfer coefficient, *h*, was found to vary for each temperature condition and value was 1.362, 1.034 and 0.886 $J/cm^2h℃$ the order of increasing temperature fluctuation. Since the temperature difference on the left side of Eq. [7] is linear, no significant difference was observed during storage period. However, in the case of the right side, the partial pressures difference was large by exponential term. Consequently, the larger the partial pressure difference was caused, convective heat transfer coefficient was affected.

To determine whether convective heat transfer coefficient is a suitable range value, dimensionless numbers were calculated. Also, thermal properties of humid air at 2.5℃ with 55% relative humidity was obtained and shown in Table 8. The Grashof number, *Gr*, is a measure of the relative magnitudes of the buoyancy force and the opposing viscous force acting on a fluid and the Prandtl number, *Pr*, is also a dimensionless number, defined as a measure of relative thickness of the velocity and thermal boundary layer where fluid properties are. The Rayleigh number, *Ra*, is associated with buoyancy-driven flow, also known as free convection or natural convection. The Nusselt number *Nu* is the ratio between total heat transfer in a convection dominated system and the estimated conductive heat transfer. Equation [10], [11], [12], [13] and [14] for obtaining the dimensionless numbers was expressed as follows. The value under 2.5℃ and 55% relative humidity condition was calculated and convection heat transfer coefficient was calculated to be 1.018 J/cm^2h℃ at this point. This value was similar to the experimental value in this study.

$$Gr = \frac{buoyancy\,forces}{viscous\,forces} = \frac{L^3 {\rho_a}^2 g \beta \Delta T}{\mu^2} \quad [10]$$

$$Pr = \frac{momentum\,diffusivity}{thermal\,diffusivity} = \frac{c_{pa}\mu}{k_a} \quad [11]$$

$$Ra = Gr \times Pr \quad [12]$$

$$Nu = \left\{0.6 + \frac{0.387\,Ra^{1/6}}{\left[1+(\frac{0.4559}{Pr})^{9/16}\right]^{8/27}}\right\}^2 \quad for\,Ra < 10^{12} \quad [13]$$

$$h = \frac{k}{D} Nu \quad [14]$$

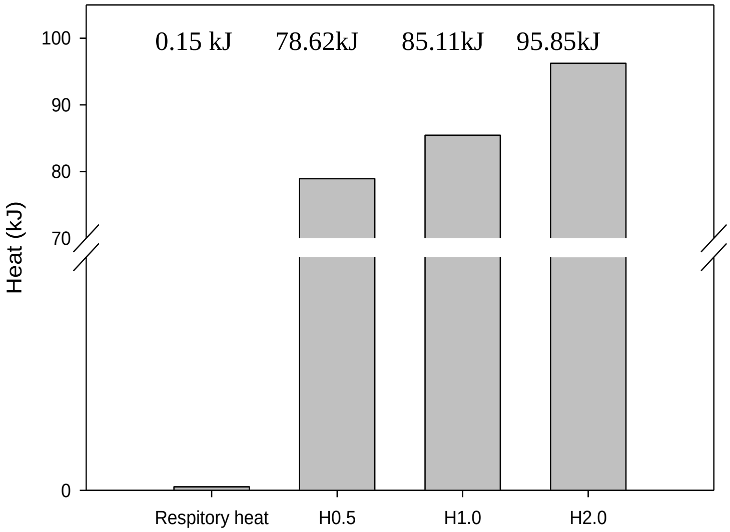


Figure 11. Total generated respiratory heat and actual total heat loss at various temperature fluctuation condition from daikon sample during storage.

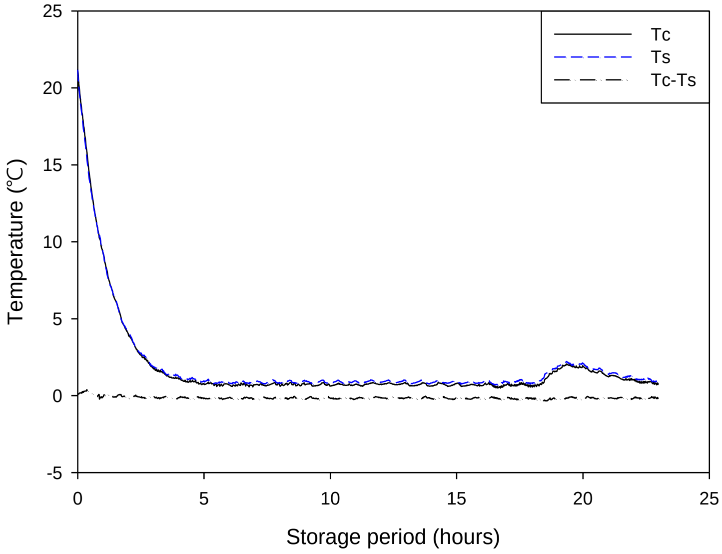


Figure 12. Difference between surface and center temperature of daikon.

Table 7. Amplitude and periodic representation in ambient temperature condition and results of surface temperature as measurement

$T = c + d\sin(\frac{2\pi}{\omega}t)$	Temperature (℃)	c	d	ω
	2.5±0.5		0.5	
T_a	2.5±1.0	2.5	1.0	0.70
	2.5±2.0		2.0	
	1.2±0.3		0.3	
T_s	1.2±0.8	1.2	0.8	0.70
	1.2±1.0		1.0	

Table 8. Thermo-physical and transport properties of humid air at 2.5℃ and 55% relative humidity (Tsilingiris, 2008)

Properties	Symbol	value	Unit
Characteristic length	D	0.075	m
Density	ρ_a	1.273	kg/m^3
Thermal expansion coefficient	β	3.640×10^{-3}	K^{-1}
Gravitational acceleration	g	9.8	m/s^2
Kinematic viscosity	μ	1.3639×10^{-5}	$N\cdot s/m^2$
Thermal conductivity	k_a	2.415×10^{-2}	W/m·K
Specific heat capacity	c_{pa}	1.010	kJ/kg·K

Ⅳ. CONCLUSION

In this study, effects of temperature fluctuation on storage quality of fresh food in household refrigerator was examined. No significant difference in the chemical reaction like VBN and TBARS was observed between the various temperature fluctuations, but effects related to the moisture could be confirmed. When stored at slightly above freezing point of food, the larger the temperature fluctuation was, the faster food was frozen. It can be seen that freezing accelerated by the difference in thermal conductivity once ice nuclei are formed in foods. Also, moisture evaporation accelerated at refrigeration temperature. Temperature fluctuation was induced partial pressure difference between the air and the surface of food in the fridge cell and this led to change of convective heat transfer coefficient. This convective heat transfer coefficient is similar to the results obtained by using the numerical solution in dimensionless value of fluid mechanics. As a result, the larger the temperature fluctuation was, the more active the water evaporation generated. In conclusion, it was confirmed that keeping the refrigerator temperature condition relatively constant is more advantageous for food storage. This study can be used as a basis for the effects of temperature fluctuation control on fresh food in in the household refrigerator.

V. NOMENCLATURE

a	Volume of added H_2SO_4 in the sample (mL)
b	Volume of added H_2SO_4 in blank (mL)
c	Mean temperature for sinusoidal changes in ambient temperature (℃)
c_p	Specific heat above freezing of daikon (kJ/kg·K)
c_{pa}	Specific heat of humid air (kJ/kg·K)
D	Characteristic length (m)
d	Amplitude for sinusoidal changes in ambient temperature (℃)
f	Standard factor of H_2SO_4
g	Gravitational acceleration (m/s^2)
h	Surface convective heat transfer coefficient (J/m2·h·K)
h_m	Skin mass transfer coefficient of daikon (kg/m2·h·kPa)
k_a	Thermal conductivity of humid air (W/m·K)
k_q	Thermal conductivity of daikon (W/m·K)
L	Latent heat for vaporization of moisture (kJ/kg)
P	Partial pressure (kPa)
P_s	Product surface partial water vapor (kPa)
Q_v	Rate of respiration heat generation

rh	Relative humidity (%)
S	Sample weight (g)
T	Temperature (℃)
t	Time (h)
x	Location variable (m)
α	Thermal diffusivity of daikon (m^2/s)
β	Thermal expansion coefficient (1/K)
μ	Kinematic viscosity ($N \cdot s/m^2$)
ρ	Density of daikon (kg/m^3)
ρ_a	Density of humid air (kg/m^3)
ω	Cycle for sinusoidal changes in ambient temperature (h)

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Ⅶ. 국문초록

일반 가정에서 많이 쓰이는 냉장고는 설정 온도를 기준으로 내부의 온도 분포가 크게는 ±2.0℃까지 온도의 상승, 강하가 나타난다. 높은 저장 온도뿐만 아니라 이러한 큰 폭의 온도 변동폭은 식품의 품질 열화를 야기시킬 수 있다. 본 연구에서는 홍두깨살(육류), 고등어(어류), 시금치와 청경채(엽채류)를 식품군으로 선정하여 냉장고 내 중심 온도를 L 조건(-2.5℃ 또는 0.5℃), H 조건(-1.0℃ 또는 2.5℃)과 제어변동폭 ±0.5℃, ±1.0℃, ±2.0℃으로 설정한 뒤, 각 온도 조건에 따른 식품의 단백질 부패, 지방 산패, 수분 감소의 저장 품질 변화 양상을 확인하였다. 그 결과, 저장 기간 중 온도 제어변동폭에 따른 홍두깨살, 고등어의 단백질 부패와 지방 산패 정도의 차이는 나타나지 않았다. 그러나 저장기간 중 L2.0에서만 홍두깨살은 저장 7일경 동결되었고, 고등어는 L2.0에서 평균 3일, L1.0에서 평균 6일, L0.5에서 평균 8일경에 시료가 동결되었다. 엽채류인 시금치와 청경채의 경우, 저장 기간 동안 제어변동폭이 클수록 식품의 무게 감소율이 더 크게 나타났다. 온도 제어변동폭에 따른 식품의 동결 및 증발 현상을 살펴보고자, 모델 식품으로써 형

태를 규격화한 무를 이용하였다. 식품의 동결은 저장 기간 동안 제어변동폭이 가장 큰 L2.0 조건이 L1.0, L0.5보다 식품의 어는점 이하를 더 많이 통과해 더 빠르게 얼음 핵이 형성되고, 결과적으로 누적되는 동결량으로 인해 식품의 동결이 더 빠르게 나타난 것으로 해석할 수 있다. 또한, 각 온도 제어변동폭 조건을 일정한 진폭과 위상의 주기 함수로 단순화시킨 뒤, 열전달 및 물질전달 계산식을 통해 제어변동폭에 따른 열 출입 양상을 확인하였다. 그 결과, 제어변동폭이 클수록 더 많은 누적 에너지가 식품으로부터 빠져나갔고, 이때의 열 에너지가 모두 증발 잠열로 쓰였다는 가정을 통해 손실된 수분량을 확인할 수 있었다.

결과적으로 더 작은 제어 변동폭이 식품 내 수분을 유지하는데 이점이 있는 것을 확인하였다. 본 연구 결과는 가정용 냉장고의 온도 제어변동폭이 식품의 저장 품질에 영향을 주는 근거 자료로 활용될 것으로 기대되며 냉장고 기술 연구에 도움이 될 것이다.

주요어: 가정용 냉장고, 냉장, 온도 제어변동폭, 홍두깨살, 고등어, 시금치, 청경채, 무.

학 번: 2016-21739