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Diffusion of Sodium Chloride in Chinese Cabbage during Salting

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Abstract

The diffusivity of sodium chloride in Chinese cabbage was evaluated from its absorption data obtained by immersing the cabbage stalk in a salt solution. By using least squares method, the absorption and desorption diffusivity of NaCl in the cabbage stalk have been estimated to be 1.7×10^{-11} and $11.6\times10^{-11}m^2/s$, respectively. The apparent diffusivity was not strongly dependent on the concentration of brine and the variety of Chinese cabbage. The influence of temperature on the apparent diffusivity could be expressed as the Arrhenius type equation, in which the activation energy was estimated to be 66 KJ/mol.

Key words: salting, salt diffusivity, Chinese cabbage

Introduction

Salt level is one of the most important parameters in the preparation of Kimchi. The quality of Kimchi is greatly influenced on the rheological and microbial changes that take place during the salting of Chinese cabbage(1,2).

For salting, trimmed Chinese cabbages are cut lengthwise into 2 to 4 pieces, and dry salt is directly sprayed over the cabbage surface in amount of 5-7% cabbage. The salted cabbage is tightly packed in a vat and then kept at room temperature for 12 hours. Sometimes, for uniform salting, the cabbage is dipped into 15-20% brine solution for 3 to 5 hours. Diffusion of salt plays an important role in the processing, preservation and quality of Kimchi. Recently, the rate of salt penetration into Chineses cabbage was investigated by Kim, *et al.*(3,4)

However, no quantitative data on the diffusivity of salt in Chinese cabbage are available in the literature. Diffusion phenomena are extremely complex, due to the wide diversity of chemical composition and physical structure of food materials, so reliable data are scarce(5). More accurate data on food properties are needed for effective quality control and design in the future.

The purposes of the present study are to determine the salt diffusivity in Chinese cabbage from the absorption and desorption data of salt, and to evaluate the effect of salt concentration and temperature on the salt diffusion.

Materials and Methods

Materials

Chinese cabbage was purchased from a local market in Seoul, Korea. The cabbage stalk was cut into 4×7cm size. The cut faces were sealed with paraffin to avoid salt diffusion simultaneously from several directions.

Methods

Diffusion of sodium chloride in Chinese cabbage was studied by submerging the side sealed cabbage stalks in brines of 5 different salt concentrations. The brine was continuously circulated by a pump for all tests. A ratio of 50:1(salt solution : cabbage) was chosen in order to maintain the concentration of salt solution constant.

For each experiment a known number of cabbage stalks was suspended over a brine bath, and two samples were taken from the brine bath at fixed intervals. The salted samples were homogenized for 3 minutes and then filtered with Whatman filter paper No. 1. The amount of sodium chloride

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absorbed by the cabbage was calculated from the calibration curve by measuring the conductivity of the filtrate with conductivity meter. At the same time, the weight change in the cabbage stalk was obtained by weighing individual stalk. Just before weighing, the cabbage stalks were wiped with tissue paper in order to remove the excess salt solution adhering to the surface.

The maximum amount of salt absorbed was estimated from the amount of salt absorbed after 24 hours brining, since after that time no further change in the salt content of the cabbage could be detected.

Calculation of the diffusion coefficient

The diffusivity of sodium chloride in solids can be estimated from sorption data by the appropriate solutions of the second Fick equation(6,7).

Solid foodstuffs are mostly heterogeneous as cellular structure and exact analytical solutions can not be always found due to the wide variation of the diffusivity of the diffusing substance in the various parts of multilayer celluar systems(8,9) That is the reason why a multidimensional diffusion is normally approximated by a one dimensional solution using an apparent diffusivity, Da, which can be determined experimentally.

The diffusion model of sodium chloride in Chinese cabbage stalk can be simulated with the following assumptions:

1. The Chinese cabbage stalk is an infinite slab with thickness L.
2. The flesh of the Chinese cabbage stalk is homogeneous and isotropic.
3. There is no surface resistance.

Under these conditions the unsteady state diffusion equation

$$\frac{\partial C}{\partial t} = D_a \frac{\partial^2 C}{\partial X^2} \quad \cdots\cdots (1)$$

can be applied with the following initial and boundary conditions:

$$C=0 \text{ at } t=0 \text{ and } -L/2 \leq X \leq L/2 \quad \cdots\cdots (2)$$

$$C=Ce \text{ at } t>0 \text{ and } x=-L/2,\ L/2 \quad \cdots\cdots (3)$$

where C = average salt concentration in the cabbage moisture (kg NaCl/100kg H_2O)

Ce = equilibrium salt concentration in the cabbage moisture (kg NaCl/100kg H_2O)

Da = apparent salt diffusivity(m^2/h)

L = thickness of the cabbage stalk(m)

t = time(s)

The salt concentration in the cabbage is expressed as kg salt per 100kg water contained in Chinese cabbage. The initial and boundary conditions are valid if the initial concentration Co is equal to zero through all the cabbage flesh except for x = -L/2 and L/2 where it is constant and equal to Ce. It is assumed that Ce is in equilibrium with a given surrounding of constant composition, Cs. In a well agitated system the external resistance to mass transfer may be very low. In this case the mass transfer process is controlled by the internal diffusion and the boundary condition(3) becomes valid.

The equation(1) can be solved in terms of an infinite series with the conditions(2) and (3).

$$\frac{M(t)}{M(\infty)} = 1 - \sum_{n=0}^{\infty} \frac{8}{(2n+1)^2 \pi^2} \exp[-Da(2n+1)^2 \pi^2 t/4L^2] \quad \cdots\cdots (4)$$

where

M(t) = total uptake of salt at time t(kg)

M(∞) = total uptake of salt after infinite time(kg)

The diffusivity in the diffusion equation(4) was estimated from absorption kinetic data by using non-linear least squares method(10), which minimized the sum of squares(5) of the deviation between the experimental values, Cexp and the predicted value, Ccal. The minimization value of criterion:

$$S = \sum_{i=1}^{n} (Cexp - Ccal)^2 \quad \cdots\cdots (5)$$

was obtained by the golden section method.

Results and Discussion

Salt Absorption by Chinese Cabbage

The experimental results for salt absorption in the cabbage stalk were plotted as a function of time and brine concentration. Under all salting conditions studied, there was a rapid salt gain for approximately 2 hr, after which the salt diffused more slowly into the cabbage stalks. Fig. 1 shows that greater salt absorption rates were obtained by increasing the brine concentrations.

The salt absorption results were plotted as fractional salt uptake(Mt/M_∞) to estimate the apparent salt diffusivity in the cabbage using the least squares method. The salt diffusivity in the cabbage was considered to be constant for the regression analysis. The apparent diffusivity of NaCl in the cabbage stalk has been found to be $1.7\times10^{-11}m^2/s$.

Statistical analysis showed that the brine concentration had no significant effect on the salt diffusivity as shown in Fig. 2, since all experimental values lie within 95% confidence limits.

From a practical point of view, knowledge of the diffusion coefficient permits calculation of the salt concentration at any time during salting. Fig. 3 shows that the correlation between the calculated and measured values of the concentration profiles is excellent. The experimental data reported by Kim[4] and Choi[13] were slightly deviated from the expected concentration because of the difference in the base for expressing salt concentration. Here, the salt concentration was expressed as salt amount in the cabbage moisture, whereas Kim's and Choi's were based on the wet weight of the cabbage. The close agreement between the experimental and predicted salt absorption values indicates that the one-dimensional solutions for salt absorption in Chinese cabbage stalk are reasonably accurate.

The diffusivity of NaCl in cabbage moisture was found to be about two orders of magnitude less

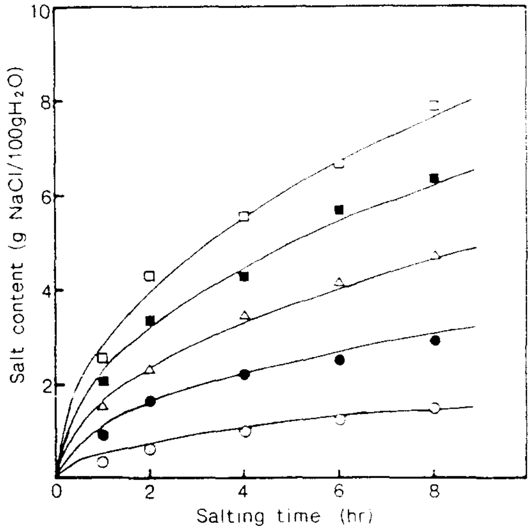

Fig. 1. Salt in moisture concentration in Chinese cabbage stalk during salting at 25°C.
Brine concentration:
○——○, 5%; ●——●, 10%; △——△, 15%;
■——■, 20%; □——□, 25%.

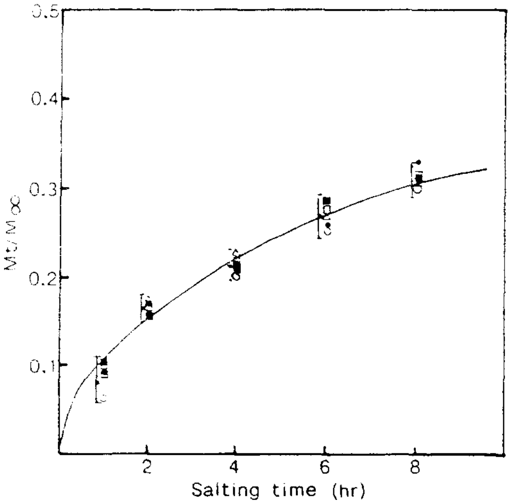

Fig. 2. Fractional salt uptake(Mt/M_∞) in Chinese cabbage stalk and confidence limits(95%) for experimental results.
Brine concentration: ○——○, 5%; ●——●, 10%; △——△, 15%; ■——■, 20%; □——□, 25%.
Calculated: — computer simulation with Eq.(4) and diffusivity ($1.7\times10^{-11}m^2/s$).

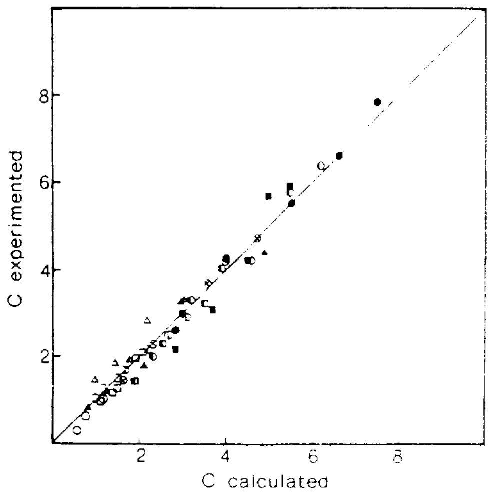

Fig. 3. Correlation between the calculated and the experimental values of salt concentration

Brine Conc.	Present data	Kim's data	Choi's data
5%	○	□	△
10%	◐	◧	◭
15%	⊗	■	▲
20%	◑		
25%	●		

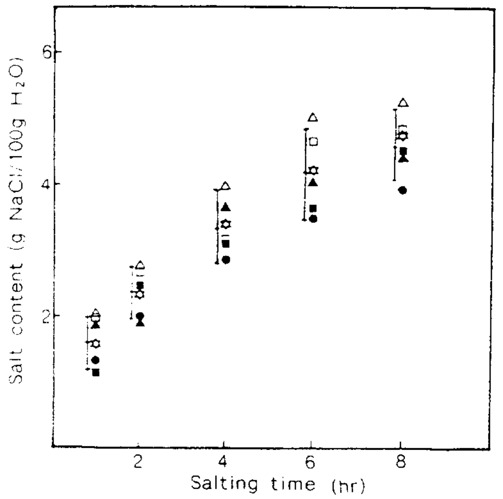

Fig. 4. Salt absorption rate of various variety of Chinese cabbage stalk during salting in 15% brine at 25°C and confidence limits (95%) for experimental results.

than that in pure water, which is 10m^2/s. The diffusion impedance of NaCl in Chinese cabbage moisture appears to be caused by the high resistance of the cabbage skin and cell wall. The skin of cabbage has a dense structure, which could be expected to retard the diffusion of sodium chloride.

Drusas and Saravacos[11,12] reported low salt diffusivity values, ranging from 3.2×10^{-11} to 4.3×10^{-11}m^2/s, due to the high resistence to mass transfer of the olive skin and fresh. Pretreatment of the olives in 1.8% caustic soda increased the salt diffusivity 5 fold, presumably by breaking down the olive skin and loosening olive fresh.

Fig. 4 shows that the results of salting experiments were conducted with 6 varieties of Chinese cabbage at constant temperature(25℃) and salt concentration(15%). It is considered that the apparent diffusivity of NaCl in the cabbage stalk is not strongly dependent on the variety.

Generally the Chinese cabbage is washed after salting to remove the excess salt. As would be expected, the desorption rate of NaCl was greater than the absorption rate as shown in Fig. 5. The desorption diffusivity of NaCl for the salted cabbage was 11.6×10^{-11}m^2/s, about 7 fold as much as for the absorption diffusivity. This is probably due to the loss of viability and irreversible changes in cell structure during salting.

Displacement of the Water

Transport of salt into the Chinese cabbage can be treated as an impeded mutual process involving salt diffusion into the cabbage accompained by an outward migration of water by osmotic pressure gradient. Generally far less salt is absorbed than moisture lost, resulting in a substantial loss of weight. Guert *et al.*[14,15] claimed that water molecules diffuse more quickly than Na^+ and Cl^-. The changes in moisture content of the cabbage stalk are shown in Fig. 6. Initial moisture content ranged from 98 to 96%, and it reduced to 88-95% after salting in the brine of various concentration for 8 hours.

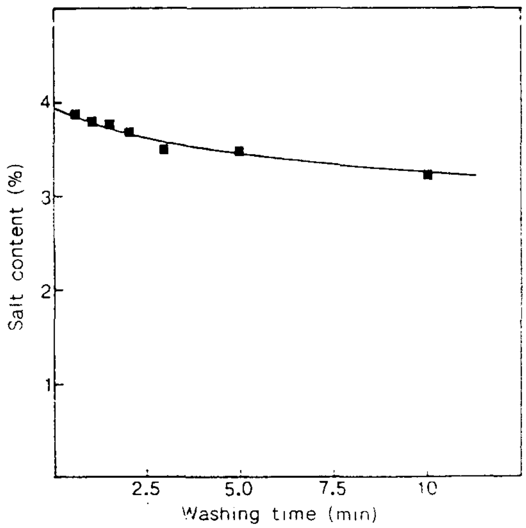

Fig. 5. Changes in salt content of salted Chinese cabbage stalk during washing.

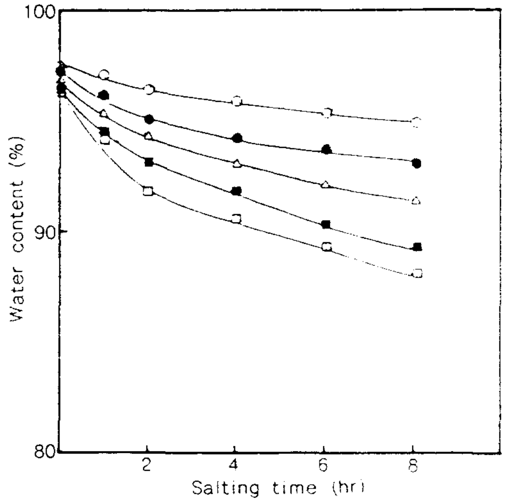

Fig. 6. Moisture changes in Chinese cabbage stalk during salting at 25°.
Brine concentration:
○——○, 5%; ●——●, 10%; △——△, 15%;
■——■, 20%; □——□, 25%.

Geurts *et al.* reported a simple relation between transports of salt and moisture during salting of cheese. We found also a linear relationship between salt and water transport in the cabbage stalk as shown in Fig. 7. The relation can be

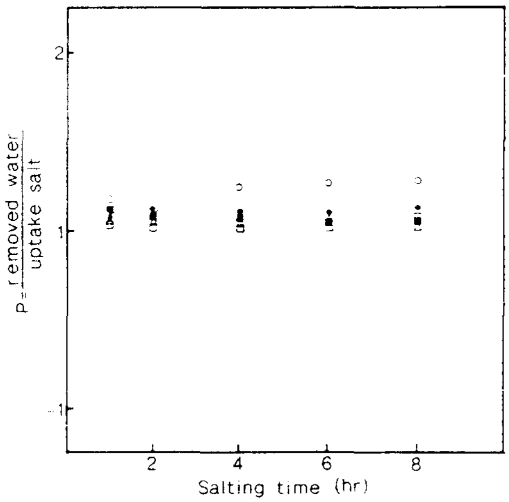

Fig. 7. Flux ratio or removed water to uptake salt during salting.
Brine concentration:
○——○, 5%; ●——●, 10%; △——△, 15%;
■——■, 20%; □——□, 25%.

expressed as the following simple equation.

$$W = P \triangle S \quad \cdots\cdots (5)$$

where

W = change in moisture content(%)

S = amount of salt absorbed(g NaCl/100g moisture in the cabbage)

P = proportionality factor or flux ratio

The value of P was nearly constant for each brine concentration, but it decreased from 1.3 for 5% brine to 1.02 for 25% brine. This implied that P would be independent of time, but salt uptake increased with salt concentration. Values of P as given in Fig. 7 can be used to predict approximately the water content and the weight loss of the cabbage during salting.

Effect of Temperature

In order to evaluate the influence of temperature on the salt diffusion in the cabbage stalk, salting experiments in 15% brine were carried out at various temperatures. Fig. 8 shows semi-logarithmic plot of Da versus 1/T. The activation energy for diffusion was calculated from the slope of the

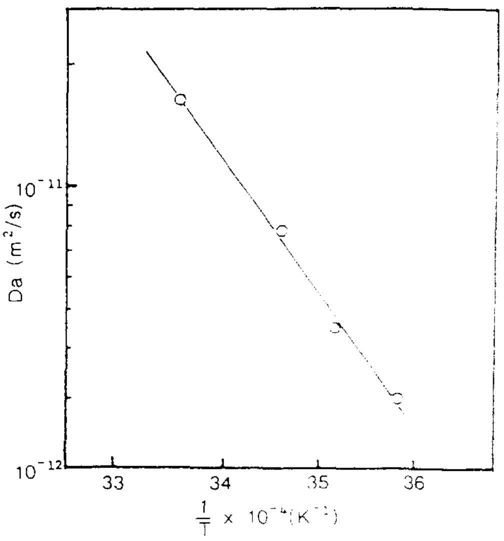

Fig. 8. Influence of temperature on apparent diffusion coefficient in Chinese cabbage stalk.

straight line by assuming the Arrhenius equation applied.

Da = Do exp(-Ea/RT)

where

Do = constant(m^2/s)

Ea = activation enery(J/mol)

R = gas constant(J/mol · K)

T = absolute temperature(K)

The activation energy for diffusion was calculated to be 66 KJ/mol. This value is reasonably close to the other published values for the diffusion of similar food materials.

감사의 글

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배추의 염절임중 소금의 확산에 관한 연구

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배추의 염절임중 배추 조직으로의 소금흡수 속도를 측정하고 확산에 관한 수학적인 모델과 computer simulation을 통해서 확산계수를 구하였다. 배추 줄기로의 소금의 침투 및 탈염 될 때의 확산계수는 각각 $1.7\times10^{-11}m^2/s$와 $11.6\times10^{-11}m^2/s$이었다. Apparent diffusivity 는 소금의 농도와 배추의 종류에 커다란 영향을 받지 않으며, 온도 의존성은 Arrhenius식으로 나타낼 수 있고 이때의 활성화 에너지는 66 KJ/mol 이었다.