KOREAN J. FOOD SCI. TECHNOL.
Vol. 18, *No.* 5 (1986)

Effects of Temperature and Composition on the Thermal Conductivity and Thermal Diffusivity of Some Food Components

Yong Hee Choi

Department of Food Science and Technology, Kyung Pook National University, Taegu

Abstract

The thermal conductivity and thermal diffusivity of food are heavily dependent on temperature and composition. The thermal properties of pure component solids were determined by the proposed model at a temperature range of -40°C to 150°C from the experimental values of 10%, 30% and 60% solid content suspensions. The major components of food products were proteins (albumin, casein, whey protein, meat protein and gluten), lipids (milk fat, vegetable oil, lard and corn oil), carbohydrates (dextrose, lactose, sugar and starch), fibers (cellulose and pectin), and milk salts. A modified probe method was used to measure these properties of pure component suspensions of each major component of food products. General mathematical models which were developed by an optimization technique can be applied to predict the properties of food products.

Introduction

Knowledge of thermal conductivity and thermal diffusivity of food substances is essential to researchers and designers for predicting the drying rate or temperature distribution within foods of various compositions when subjected to different drying, heating and cooling conditions. This information is also necessary for the optimization design of heat transfer equipment, dehydrating and sterilizing apparatus. Therefore, there is a great need for these property values of foods for good processing and preservation.

The direct dependence of the properties of frozen foods on the state of water in the product has been demonstrated by Heldman (1982) and this dependence must be acknowledged in any analysis of these property data for frozen foods.

Several researchers have developed mathematical models, which can be used to predict the properties of food products. However, they are for specific foods and do not apply to all the physical situations. When these properties are needed for various process conditions the most efficient and practical way to obtain them is by models based on the process conditions. In general, composition and temperature are the main factors or process conditions affecting these properties. Therefore, the overall objective of this study is to develop general models to predict the thermal conductivity and thermal diffusivity of food products.

Materials and Methods

Sample Preparation

The major components of milk protein are casein and whey protein. The casein is present in the form of micells made up of the various components of casein bonded together as calcium caseinate and complexed further with calcium, phosphate, magenesium and citrate ions. Therefore, salt-casein serum was made by dialyzing skim milk with a salt solution using a 50,000 molecular weight cut-off membrane. It was dialyzed for 48 hours with the salt solution being changed every 6 hours. Then, by placing it in a freeze dryer for 48 hours, salts-casein powder was obtained. Proteins remaining after the casein has been removed from skim milk are known as whey protein or milk serum proteins. Therefore, for whey protein powder, after precipitating skim milk by 0.5 N HCl at pH = 4.6, through the centrifuge at 2400 rpm for 15 min., the casein was removed. Then, it was dialyzed with a 3,500 molecular weight cut-off membrane for 48 hours with distilled water being changed every 6 hours. Finally it was placed in a freeze dryer for 48 hours, and whey protein powder was obtained. The schematic preparation process of casein-salts powder and whey protein powder is shown in Fig. 1. Meat protein was prepared by the similar method from groundbeef. Egg albumin powder for egg white protein and gluten powder for plant protein were purchased from Fisher Scientific Company and Sigma Chemical Company, respectively.

For a milk fat, butter oil was used for the measurement in this study. Butter oil is a refined product made by separating the milk fat from high fat cream. The product contains only small amounts of moisture and protein. The composition is 99.5% milk fat, 0.2% moisture and 0.3% protein. Commercial oil products, such as corn oil for grain foods, vegetable oil for vegetable foods and lard for meat foods, were used for the measurement of the properties of the fat component of food products.

Dextrose powder was punchased from Fisher Scientific Company. Lactose powder for milk carbohydrates was also purchased from Pfanstichl Laboratories, Inc.. Pectin powders from by Sigma Chemical Company and microcrystalline cellulose powder from by FMC Corporation were used for the property measurements of fiber materials Commercial pure cane sugar and corn starch powder was also used.

The salt components for all the food products are comprised of some of the chlorides, phosphates, citrates and sulfates along with such elements as sodium, potassium, calcium, magnesium and so on. The amounts of each salt component are very slightly different in different kinds of food products. Also, the percentage of salt components among food products is very small compared to the other major components of food products. Therefore, the milk salts, which have all the above salt components and can be easily prepared, were assumed as a basic salt for all kinds of food products. Jenness (1962) reported on the preparation of a salt solution, which simulates milk salt solution, by using a dry blended mixture, as shown in Table 1.

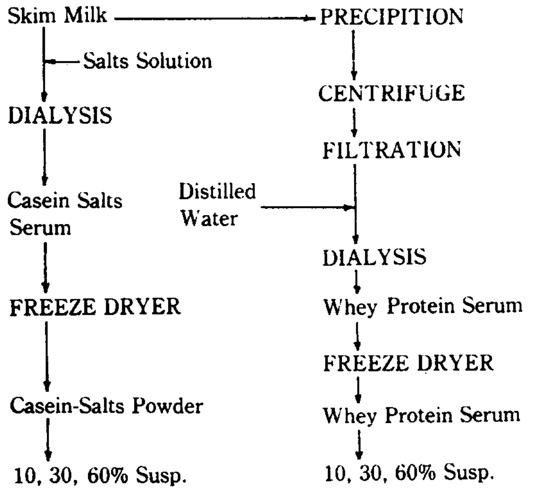

Fig. 1. Schematic Process for Casein-Salts Powder and Whey Protein Powder

Measurement procedure

The line heat source probe was employed for the simultaneous determination of thermal conductivity and thermal diffusivity for pure component suspensions at different concentrations such as 10%, 30%, 60% at the temperature range of -40°C to 150°C. This method is based on the fact that the temperature rise at a point close to a line heat source, in a semi-infinite solid subjected to a step change in temperature, is a function of time, the thermal properties of solid, and the source strength. The equation from which the thermal conductivity may be obtained is expressed in the following expression.

$$K=\frac{Q}{4\pi(T_2-T_1)}\ \ln\frac{t_2-t_0}{t_1-t_0}$$

The time-temperature data at given some power were measured through computer system. Using the slope of the linear portion from a plot of temperature versus the logarithm of time, the following equation was used to calculate the thermal conductivity of the sample.

$$\frac{\Delta T}{\Delta \ln t}=\text{Slope}=\frac{Q}{4\pi k}$$

The statistical coefficient R^2 was used to check the linearity of log time-temperature data. Any set of read-

Table 1. Quantities of chemicals for making milk salt solution

Chemicals	Quantity (g)
KH_2PO_4	1.580
K_3 citrate-H_2O	0.508
Na_3 citrate-$5H_2O$	2.120
K_2SO_4	0.180
$CaCl_2$-$2H_2O$	1.320
Mg_3 citrate-H_2O	0.502
K_3CO_3	0.300
KCl	1.078

ings giving a correlation coefficient less than 0.98 was discarded.

Thermal diffusivity of samples was determined by iterative solution of the following equation after measuring the thermal conductivity.

$$T=\frac{Q}{2\pi k}\left(-\frac{Ce}{2}-\ln\beta+\frac{\beta^2}{2\cdot 1!}-\frac{\beta^4}{4\cdot 2!}+\cdots\cdots\right)$$

For each trial, on assumed thermal diffusivity, α, at a given particular time, t (approximately 10 sec), and a given thermocouple distance, r, yield a value of β which together with known heat source strength, Q, and measured thermal conductivity, K, can be solved for temperature. The calculated temperature is then compared with the measured temperature. A new value of thermal diffusivity is generated based on the disagreement between these temperatures, and this process is continued using a Linear Search Method (Interval Helving) to adjust a thermal diffusivity value until the temperatures agree (difference is less than 0.0001 deg.). The details for the construction of a probe and measurement apparatus and procedure are in the paper of Choi, et al., (1983).

Prediction of the unfrozen water fractions

Staph and Woolrich (1951) proposed that a gradual depression of the freezing point in the unfrozen product fraction occurs throughout the freezing process. Based on the chemical potential of pure solute and pure liquid, the equation for freezing point depression can be derived:

$$\frac{\lambda}{R}\left(\frac{1}{T_0}-\frac{1}{T}\right)=\ln X_A$$

Therefore, the unfrozen water fraction of a food system can be predicted at a given temperature below the initial freezing point.

Results and Discussion

Thermal properties

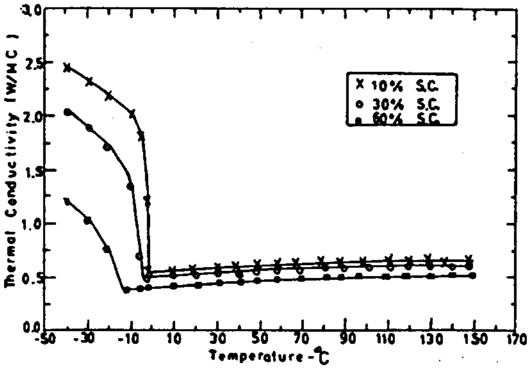

Fig. 2. Thermal conductivity of dextrose suspensions

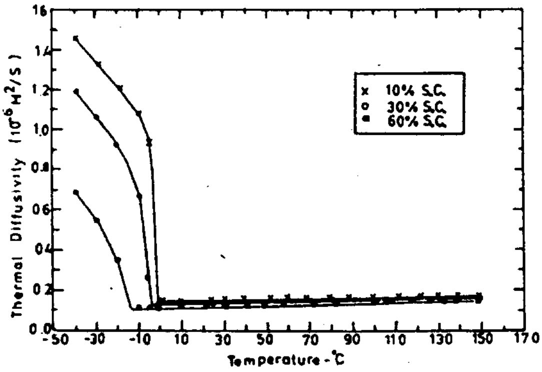

Fig. 3. Thermal diffusivity of dextrose suspensions

Thermal conductivities and thermal diffusivites for pure component suspensions were measured at different concentrations such as 10%, 30%, 60% at the temperature range of -40°C to 150°C. For dextrose, one of the samples, the experimental data are shown in Fig. 2 and Fig. 3. Thermal conductivity and thermal diffusivity of sample suspensions at the temperature below initial freezing point were much higher than that at the temperature above initial freezing point. Fats are relatively poor conducts of heat. Thermal conductivity of milkfat in liquid state at the melting point of 34°C was 6.1% lower than that in solid state. For thermal diffusivity, liquid milkfat had a 5.1% lower thermal diffusivity than solid milkfat at the melting point. Thermal conductivity and thermal diffusivity of whey protein, milkfat, lactose, starch and milk salts were measured in the test run of heating, cooling, reheating and recooling. The cycling results on milkfat, lactose and milk salts suspensions show that the heating and cooling do not have a significant effect on the thermal conductivity and thermal diffusivity of samples. For whey protein suspension, thermal conductivity and thermal diffusivity have a 4.9%-11.7% lower value in the recycling process below 70°C, because of thermal denaturation. Thermal denaturation of protein, which usually occurs at 60°C-70°C, is a radical change in the protein structure. This change has a decreasing effect on the thermal properties. In the case of polysaccharides, starch is gelatinized at the temperature between 62°C and 70°C. When starch is gelatinized, the crystalline region is disrupted and will gradually disappear. With this reason, thermal conductivity and thermal diffusivity of corn starch suspension were 3.6%-10.8% lower in the recycling process below 60°C.

Modeling

Based on the theoretical view of the rate of heat transfer to the material, the structural arrangement of the constituents should be considered in the model to predict the properties. The model proposed for parallel structural arrangement of two component system:

$$K=Ks\,Xs^{v}+K_f\,X_f^{v} \quad \cdots\cdots\cdots\cdots \quad (M1)$$

for perpendicular structural arrangement:

$$K=\left[\frac{Xs^{v}}{Ks}+\frac{X_f^{v}}{K_f}\right]^{-1} \quad \cdots\cdots\cdots\cdots \quad (M2)$$

for fluid continuous system of material:

$$K=K_f\left[\left(1-2Xs^{v}\frac{1-\frac{Ks}{K_f}}{2+\frac{Ks}{K_f}}\right)\Big/\left(1+Xs^{v}\frac{1-\frac{Ks}{K_f}}{2+\frac{Ks}{K_f}}\right)\right] \quad \cdots\cdots\cdots\cdots \quad (M3)$$

for a solid continuous system of material:

$$K=Ks\left[3\frac{K_f}{Ks}+2Xs^{v}\left(1-\frac{K_f}{Ks}\right)\right]\Big/\left[3-Xs^{v}\left(1-\frac{K_f}{Ks}\right)\right] \quad \cdots\cdots\cdots\cdots \quad (M4)$$

and for a random mixture of the two phases:

$$K=\frac{1}{4}\{(3Xs^{v}-1)Ks+(3X_f^{v}-1)K_f+[([3Xs^{v}-1]Ks+[3X_f^{v}-1]K_f)^{2}+8Ks\,K_f]^{1/2}\} \quad \cdots\cdots\cdots\cdots \quad (M5)$$

Another type of models based on a packed bed system of material have been proposed by Yagi and Kunii (1957), Kunii and Smith (1960), Okazaki, et al., (1977) and Chen and Heldman (1972). Generally speaking, these models are complicated. A number of experiments and calculations are reguired to obtain the necessary input data. They are less applicable for practical applications, but may provide insights to basic researchers.

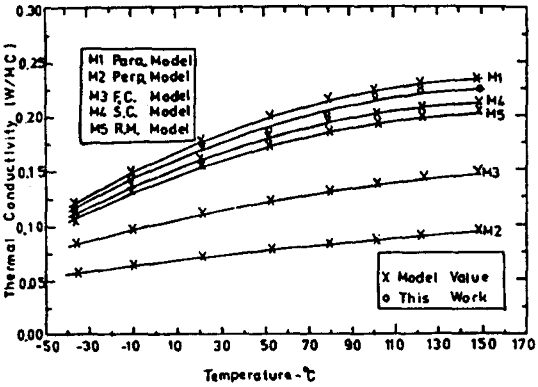

Fig. 4. Thermal conductivity of dextrose powder

The experimental thermal conductivity values of dextrose powder were comparde with the five proposed model values at the temperature range of -40°C to 150°C, as shown in Fig. 4. It was found that the parallel model has a less error of 4.7% than the other models. The statistical comparison of the expreimental thermal conductivity values of prepared powder samples to the five proposed model values are listed in Table 2. Based on these results and simplicity in models, the parallel model was proposed in this study for the prediction of properties of foods.

Table 2. Comparison of thermal conductivities of powder samples to the proposed models

Powder Samples	Model No.	Standard error	Standard % error (%)
Dextrose	M1	.0087	4.70
	M2	.1113	59.91
	M3	.0674	36.30
	M4	.0112	6.04
	M5	.0191	10.30
Whey Protein	M1	.0093	6.21
	M2	.0908	60.70
	M3	.0574	38.33
	M4	.0105	7.25
	M5	.0213	14.26

The thermal conductivity of a sample solid at a given temperature was determined by the following equation, because a suspension was composed of a pure component and water.

$$Ks = \frac{K - KwXw^{v}}{Xs^{v}}$$

Since the calculated thermal conductivities and thermal diffusivities of pure component solids from three different solid content suspensions showed that they were not dependent linearly on temperature, a quadratic model was proposed for both thermal conductivity and thermal diffusivity of pure solids. Based on the theoretical view of the rate of heat transfer to the parallel structured arrangement of the constituents, it was found that the values of thermal properties of a material were expressed as the sum of the each property value proportional to the fraction of each component. The thermal conductivity and thermal diffusivity of dextrose solids were plotted in Fig. 5. and Fig. 6.

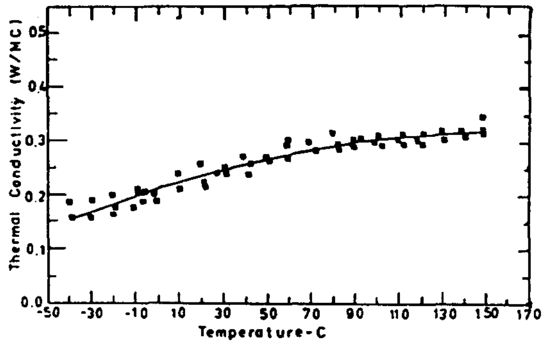

Fig. 5. Thermal conductivity of dextrose solids

The coefficients in the proposed thermal conductivity and thermal diffusivity models of each pure component solid at the temperature range of -40°C to 150°C were determined by the Optimization Computer Subroutine from the calculated these property-temperature data. Quadratic models for the properties of liquid water and ice were developed, as shown in Table 3, and the obtained thermal conductivity and thermal diffusivity models of pure components of foods are listed in Table 4 and Table 5, respectively.

Table 3. Property models of water and ice

	Property Models	Standard Error	Standard % Error (%)
Water	$K = 5.7109 \times 10^{-1} + 1.7625 \times 10^{-3}T - 6.7036 \times 10^{-6}T^2$	.0028	.45
	$\alpha = 1.3168 \times 10^{-1} + 6.2477 \times 10^{-4}T - 2.4022 \times 10^{-6}T^2$	$.0022 \times 10^{-6}$	1.44
Ice	$K = 2.2196 - 6.2489 \times 10^{-3}T + 1.0154 \times 10^{-4}T^2$	.0078	.79
	$\alpha = 1.1756 - 6.0833 \times 10^{-3}T + 9.5037 \times 10^{-5}T2$	$.0044 \times 10^{-6}$	.33

Table 4. Thermal conductivity models of pure components of foods

Pure Components	Thermal conductivity models (W/M °C)	Standard error	Standard % error (%)
Albumin	$K = 1.8068 \times 10^{-1} + 1.1462 \times 10^{-3}T - 2.6888 \times 10^{-6}T^2$	.0086	3.84
Casein	$K = 1.7138 \times 10^{-1} + 1.1234 \times 10^{-3}T - 2.4592 \times 10^{-6}T^2$	.0066	2.98
Whey Protein	$K = 1.8627 \times 10^{-1} + 1.2444 \times 10^{-3}T - 2.9499 \times 10^{-6}T^2$	.0060	2.57
Meat Protein	$K = 1.6266 \times 10^{-1} + 1.1726 \times 10^{-3}T - 2.3735 \times 10^{-6}T^2$	.0129	5.49
Gluten	$K = 1.8671 \times 10^{-1} + 1.3229 \times 10^{-3}T - 3.4197 \times 10^{-6}T^2$	.0108	4.58
Milkfat	$K = 1.7809 \times 10^{-1} - 2.4381 \times 10^{-4}T - 5.5169 \times 10^{-7}T^2$	.0020	1.23
Vegetable Oil	$K = 1.8224 \times 10^{-1} - 2.1949 \times 10^{-4}T - 7.3411 \times 10^{-7}T^2$	.0041	2.39
Lard	$K = 1.8220 \times 10^{-1} - 2.0565 \times 10^{-4}T - 7.3267 \times 10^{-7}T^2$	.0020	1.18
Corn Oil	$K = 1.8109 \times 10^{-1} - 2.0145 \times 10^{-4}T - 7.8395 \times 10^{-7}T^2$	.0035	2.15
Dextrose	$K = 2.1277 \times 10^{-1} + 1.2946 \times 10^{-3}T - 3.9135 \times 10^{-6}T^2$	.0133	5.19
Lactose	$K = 1.9898 \times 10^{-1} + 1.4760 \times 10^{-3}T - 4.5666 \times 10^{-6}T^2$	.0079	3.16
Sugar	$K = 2.0456 \times 10^{-1} + 1.3774 \times 10^{-3}T - 4.2079 \times 10^{-6}T^2$	.0066	2.62
Starch	$K = 1.9001 \times 10^{-1} + 1.3698 \times 10^{-3}T - 4.4318 \times 10^{-6}T^2$	.0125	5.33
Cellulose	$K = 1.7944 \times 10^{-1} + 1.2169 \times 10^{-3}T - 3.2086 \times 10^{-6}T^2$	.0110	4.92
Pectin	$K = 1.8644 \times 10^{-1} + 1.2914 \times 10^{-3}T - 3.1286 \times 10^{-6}T^2$	.0112	4.78
Milk Salt	$K = 3.2962 \times 10^{-1} + 1.2914 \times 10^{-3}T - 2.9070 \times 10^{-6}T^2$	.0083	2.15

Table 5. Thermal diffusivity models of pure components of foods

Pure components	Thermal diffusivity models ($\times 10^{-6}$ M²/S)	Standard error ($\times 10^{-6}$)	Standard % error (%)
Albumin	$\alpha = 6.8609 \times 10^{-2} + 4.6513 \times 10^{-4}\,T - 1.3685 \times 10^{-6}\,T^2$	.0027	3.37
Casein	$\alpha = 6.7010 \times 10^{-2} + 4.8916 \times 10^{-4}\,T - 1.5164 \times 10^{-6}\,T^2$	.0033	3.95
Whey Protein	$\alpha = 7.1005 \times 10^{-2} + 4.4448 \times 10^{-4}\,T - 1.1217 \times 10^{-6}\,T^2$	.0018	2.03
Meat Protein	$\alpha = 6.4727 \times 10^{-2} + 4.7811 \times 10^{-4}\,T - 1.3773 \times 10^{-6}\,T^2$	.0032	3.91
Gluten	$\alpha = 7.2129 \times 10^{-2} + 4.9481 \times 10^{-4}\,T - 1.8567 \times 10^{-6}\,T^2$	.0036	4.15
Milkfat	$\alpha = 9.8514 \times 10^{-2} - 1.5590 \times 10^{-4}\,T - 1.5590 \times 10^{-7}\,T^2$	.0014	1.53
Vegetable Oil	$\alpha = 9.8888 \times 10^{-2} - 5.4195 \times 10^{-5}\,T - 6.6961 \times 10^{-7}\,T^2$	.0026	2.78
Lard	$\alpha = 9.9719 \times 10^{-2} - 6.5479 \times 10^{-5}\,T - 4.3242 \times 10^{-7}\,T^2$	.0024	2.53
Corn Oil	$\alpha = 9.4123 \times 10^{-2} - 1.5958 \times 10^{-5}\,T - 3.9922 \times 10^{-7}\,T^2$	.0042	4.94
Dextrose	$\alpha = 8.5340 \times 10^{-2} + 2.1663 \times 10^{-4}\,T - 2.1663 \times 10^{-6}\,T^2$	.0025	2.53
Lactose	$\alpha = 7.9723 \times 10^{-2} + 5.0988 \times 10^{-4}\,T - 2.1430 \times 10^{-6}\,T^2$	.0022	2.38
Sugar	$\alpha = 8.3948 \times 10^{-2} + 4.7982 \times 10^{-4}\,T - 1.7738 \times 10^{-6}\,T^2$	.0027	2.76
Starch	$\alpha = 7.2978 \times 10^{-2} + 4.8956 \times 10^{-4}\,T - 1.9715 \times 10^{-6}\,T^2$	.0031	3.44
Cellulose	$\alpha = 7.2421 \times 10^{-2} + 4.9180 \times 10^{-4}\,T - 1.9850 \times 10^{-6}\,T^2$	.0040	4.64
Pectin	$\alpha = 7.3389 \times 10^{-2} + 4.9195 \times 10^{-4}\,T - 1.9484 \times 10^{-6}\,T^2$	.0038	4.30
Milk Salt	$\alpha = 1.2461 \times 10^{-2} + 3.7321 \times 10^{-4}\,T - 1.2244 \times 10^{-6}\,T^2$	.0022	1.61

Comparison Between the Proposed Model and Literature Values

Using all the developed property models with known fraction of each major component, the thermal conductivity and thermal diffusivity values were calculate and compared to the literature values of liquid foods. As shown in Table 6, the property values by the proposed models of major components were predicted within average 3.8% error to the literature values.

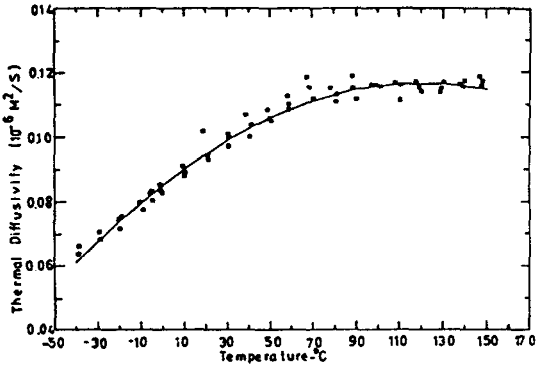

Fig. 6. Thermal diffusivity of dextrose solids

Table 6. Comparison between the proposed model and literature values

Property	No. of data	Standard error	Standard % error (%)
K	300	.0172	2.91 (.31-5.86)
α	115	$.0053 \times 10^{-6}$	3.81 (.85-6.94)

Nomenclature

K	:	Thermal Condutivity (W/M°C)
M	:	Molecular Weight
m	:	Mass Fraction
R	:	Gas Constant
T	:	Temperature (°C)
To	:	Freezing Point of Pure Liquid
X	:	Weight Fraction of Composition
Xv	:	Volume Fraction of Composition
α	:	Thermal Diffusivity (M²/S)
λ	:	Molal Latent Heat of Fusion
Ce	:	Euler's Constant

Subscripts

f	:	Fluid
s	:	Solid
w	:	Water

Dimensionless parameter

ß : $r/2\,(\alpha t)^{.5}$

Acknowledgement

Author is grateful to Dr. Martin R. Okos for his inspiring guidance and valuable comments.

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(Received July 31, 1986)

온도와 조성이 식품성분의 열전도도와 열확산도에 미치는 영향

최 용 희

경북대학교 식품가공학과

식품의 주요 구성 성분의 현탁액에 대한 열전도도와 열확산도를 −40°C −150°C의 온도 범위와 10%−60%의 농도 범위에서 측정하였다. 세 종류의 서로 다른 농도에서 측정된 실험값으로부터 가정된 모델에 의해 순수 성분의 열전도도와 열확산도를 각각의 온도에서 구한 다음 컴퓨터 프로그램을 이용하여 모델의 상수들을 구하였다. 본 연구에서 발전시킨 모델을 사용하여 얻은 식품의 열전도도와 열확산도 수치를 기발표된 모든 액체식품의 데이타와 비교해 본 결과 3.8%의 오차가 있었다. 식품의 주요 구성 성분의 함량과 온도가 주어지면 본 연구에서 발전시킨 모델을 이용하여 열전도도와 열확산도 수치를 위의 오차 한계에서 구할 수 있다.