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Characterization of Thermophysical Properties of Iranian Ultrafiltrated White Cheese: Measurement and Modeling

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ABSTRACT

Information on the thermophysical properties of the Iranian ultrafiltrated (UF) white cheese is very limited. In this research, those thermal properties determined experimentally were thermal conductivity, specific heat, density and water activity. The thermal conductivity and specific heat of Iranian ultrafiltrated white cheese (IUFWC) ranged from 0.447 to 0.480 W m^{-1} °C^{-1} and from 3.871 to 4.005 kJ kg^{-1} °C^{-1} for temperatures varying from 1°C to 23°C and from 1°C to 40°C, respectively. Both thermal conductivity and specific heat increased with moisture content and temperature. A three-step model predicting thermal conductivity as a function of cheese composition and temperature was developed based on the parallel and Maxwell models. The effective thermal conductivity predicted by the model developed was in good agreement with the experimental data. The modeling of density and water activity using non-linear regression concepts showed that density was highly affected by salt concentration and temperature; water activity was also strongly dependent on salt concentration and moisture content.

Keywords: Modeling, Salting, Thermophysical properties, UF cheese.

INTRODUCTION

The most important type of the cheese in Iran is the Iranian ultrafiltrated white cheese (IUFWC) that accounts for half of the cheese consumed in Iran. IUFWC is one type of Feta cheese that is categorized as a semi hard cheese. Salting cheese is an important process that improves the texture, flavor and color of cheese mainly due to modification of microbial activity (Fox, Guinee, Cogan and McSweeney, 2000). The salting process can be carried out following different procedures, one of which is dry salting; this method is used for salting IUFWC. NaCl and temperature profiles are some of the most important operating parameters governing the final organoleptic and textural properties of cheese because, associated with water activity and NaCl concentration, they govern microbial growth, pH and enzyme activity (Guinee and Fox, 1987). To predict the temperature and NaCl profiles for assessment of the product behavior under process conditions, simulation of heat and mass transfer (Fourier and diffusion equations) and determination of accurate values of thermophysical properties of cheese are necessary and inevitable. The primary thermal properties of food are density, specific heat, thermal conductivity and water activity (Singh, 1992).

The bulk density of a porous object can be defined as the mass of the object divided by the total volume of the solid, liquid and gas in the porous matrix. Volume can be measured by various displacement methods (Bakshi and Yoon, 1984; Hwang and

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Hayakawa, 1980) or calculated from sample dimensions if the object has a regular geometry (Christenson, Tung and Lund, 1989). General models are reported in the literature, which allow the apparent density of any food product to be calculated as a function of chemical composition, moisture, porosity and temperature (Miles, Van Beek and Veerkamp, 1983).

Specific heat is one of the main thermal properties used to solve the non-linear heat diffusion equation taking into account phase transition. It is the rate of enthalpy change with respect to temperature, *dH/dT*. Since latent heat removal occurs over the freezing temperature domain, it is usual to include the latent heat contribution to the specific heat, which is then called the apparent specific heat, Cp_{app} (Hamdami, Monteau and Le Bail, 2004).

Both experimental and mathematical modeling approaches have been used to determine the specific heat of foods (Rahman, 1995) and several methods are used to measure specific heat as a function of temperature. These methods are based on experimental results obtained from calorimetric measurements (Lind, 1991; Tocci, Flores and Mascheroni, 1997). Most studies conducted on specific heat show that specific heat is strongly dependent to moisture content and temperature. Thus, there are semi-empirical models that describe the variation in the specific heat of baked products with moisture, such as the model of Christenson *et al.* (1989) for bread, muffins and biscuits.

One of the most important thermal properties is thermal conductivity. Measurement methods for thermal conductivity can be divided into two categories: Steady-State Methods (SSM) and unsteady state or Transient Methods (TM) (Nesvadba, 1982). Most researchers recommend TM (Nesvadba, 1982). Among TM, the simplest and most widely used is the line heat source thermal conductivity probe method. The advantages of this method are (i) the short duration of the experiments (range 5-20 s) and (ii) a reduced temperature rise of the sample (a few °C) (Rahman, 1995). Thermal conductivity data have been presented and modeled as a function of moisture content and/or process temperature. A great variety of more or less complicated equations for calculating thermal conductivities exists in the literature (Urbicain and Lozano, 1997). The most well known physical models are parallel, perpendicular (series), dispersed phase and Krischer models (Miles *et al.,* 1983; Rahman, 1995).

Methods for measuring a_w have been reviewed by several authors (Rizvi, 1986). Most of the methods used to determine a_w are based on equilibrium conditions but dynamic methods are also available (Fennema, 1981). Saurel, Pajonk and Andrieu (2004) proposed different models for Emmental cheese water activity based on the brining and ripening processes.

An extensive literature search on the thermophysical properties of cheese revealed that there are different works available on the estimation of the thermal properties of dairy products (Pajonk, Saurel, Andrieu, Laurent and Blanc, 2003; Sweat and Parmelee, 1978; Tavman and Tavman, 1999). In contrast, no published information is available concerning the thermophysical properties of IUFWC and so thus this research was designed to fill this gap. It is part of a study on ripening modeling of IUFWC.

The aims of this work were to:

The selected properties considered in this paper are bulk density, apparent specific heat, effective thermal conductivity and water activity.

MATERIALS AND METHODS

Production and Chemical Analysis of Cheese Samples

UF cheeses were produced by Pegah Dairy Products Inc. (Pegah, Isfahan branch, Iran), as described below. Standardized skimmed milk was concentrated to a given concentration factor (38 percent of dry matter) using filters, then homogenization and pasteurization (at 78°C for 3 minutes) was carried out, and retentate was transferred to the starter tank to add 3% starter. Afterwards, retentate was transferred to the filling machine and mixtures such as antifoam, rennet enzyme and anti acetic were added. After coagulation inside the incubation tunnel (about 20 minutes), the samples were selected before and after dry salting and called salted and non-salted UF cheese samples. After sealing, the cheese samples were conducted to the incubator for 24 hours. Then, they were kept in cold storage at 5°C. The chemical analysis of cheese samples (ash, salt, moisture, fat and protein) was preformed two weeks after production. The fat content of the samples was determined by Gerber's method and their water content by the oven method (Fil/IDF, 1968). The macro-Kjeldahl method was used for protein determination (AOAC, 2000). For ash content, the sample was first dried in an oven at 105°C before being transferred to a muffle furnace at 550°C, until a white or light gray ash resulted and the NaCl content was then measured by the Volhard method (Fil/IDF, 1961). All chemical analyses were performed in triplicate. The result of the chemical analysis of the cheese samples is given in Table 1, as percentage by weight.

Bulk Density

Firstly, the non-salted cheese slices (L×W×H= 0.05×0.03×0.02 m) were put in 6 different brine solutions (2, 4, 8, 12, 16, 24 g L^{-1}) at different temperatures (5, 11, 15, 21.5°C) for 10 days to become equilibrated. The ratio of brine volume to the volume of cheese samples was 10:1. Then, to determine the density, the cheese samples were weighed and their apparent volume was measured using a liquid pycnometer (Miles *et al.,* 1983). Finally, the moisture and NaCl contents of the sample were determined. The measurements were carried out in triplicate.

Specific Heat

A differential scanning calorimeter (Mettler TA 4000, Greifensee, Switzerland) was used to evaluate the specific heat of the cheese samples at atmospheric pressure. Samples (5 mg) were hermetically closed in aluminum pans and they were frozen *in situ* in the calorimeter by liquid nitrogen. Experiments were conducted 5 times from –50°C up to 40°C at a heating rate of 2°C min^{-1} (Zhong, 2003). An empty pan was used as a reference. The base-line was obtained from a scan performed with two empty pans. The corresponding specific heat was evaluated with the software of the calorimetric apparatus (Hamdami, Monteau and Le Bail, 2004).

The specific heat of a cheese at temperatures above its initial freezing point can be obtained from the following equation:

$$Cp(T) = \sum Cp_i(T)x_i \quad (1$$

where the subscript i represents the major components (lipid, protein, carbohydrate, water and ash), x_i their mass fraction, Cp_i their intrinsic specific heat values, and correlations for the temperature dependencies may be found in Singh (1992).

Table 1. Chemical composition of the ultrafiltrated cheese samples used in experiments (% by weight).

Cheese	Water	Fat	Protein	Ash	Carbohydrate[a]	salt
Salted	63.41(0.31)[b]	17.07(0.10)	11.12 (0.049)	3.89 (0.11)	4.51	3.14(0.216)
Non-salted	67.11 (0.061)	17.125(0.176)	11.16 (0.049)	1.47 (0.11)	3.135	0.27 (0.11)

[a] Carbohydrate percentage was calculated as 100 – (moisture%+fat%+protein%+ash%).
[b] Given values in parentheses represent standard deviations.

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Thermal Conductivity

Thermal Conductivity Measurement

The thermal conductivity of cheese samples was measured by the transient method using a thermal conductivity probe as described by Sweat and Parmelee (1978). It essentially consisted of a thermocouple with a constantan heater wire running along its length, which is the heat source, and a thermocouple (type K) as the temperature recorder. The entire assembly was then enclosed in a 21 gage stainless steel tubing 4.6 cm long and 1 mm outer diameter. The heater and thermocouple wires were insulated from each other and from the hypodermic tubing. A version of the thermal conductivity measurement system developed by McGinnis (1987) was used to supply power, measure current and record temperatures and voltage (Figure 1). The probe was inserted longitudinally into the sample. In this experiment, the probe with the cheese sample was packed in a polyethylene bag and assumed to have negligible contact resistance. The sample was equilibrated to the desired temperature by a programmable incubator. The accuracy of the current measurement in the heater circuit was ±0.1 mA. The temperature-time and voltage-time data were continuously collected by a digital recorder (Delta-T Devices Ltd., Cambridge, England) which was bi-directionally interfaced with a PC so that measurement could be programmed on a computer. The record of voltage was used to find the initial time of the heating. The slope of the linear portion of the plot of the temperature *vs.* ln (time) is equal to $Q/(4\lambda\pi)$. Thus, the thermal conductivity of the sample was calculated by using the following equation:

$$\lambda = \frac{Q}{4\pi S} \quad (2)$$

where Q is calculated by:

$$Q = I^2 R \quad (3)$$

In the above equations S, I and R are the slope of the linear portion of the plot of the temperature *vs. ln(time),* electrical current through heater wire (A) and electrical resistance (Ω m^{-1}) respectively.

Calibration of the probe was realized by measuring the thermal conductivity of glycerin and of a gel of 0.5% agar and water at selected temperatures between 5°C and 25°C. This calibration permitted determining the heater wire resistance (R= 185.2 Ω m^{-1}) which is used in the heater power calculation (Hamdami, Monteau and Le Bail, 2003). Data for the thermal conductivity measurement of cheeses was collected at 1 second intervals for over 20 seconds, and to obtain satisfactory linearity of temperature *vs. ln(time)* plot, the procedure was standardized by (1) choosing a power level to increase the temperature up to 10°C (initial temperature basis), (2) using a duration of 10 seconds, and (3) accepting thermal conductivity values measured only when r> 0.98.

Seven measurements were made in each

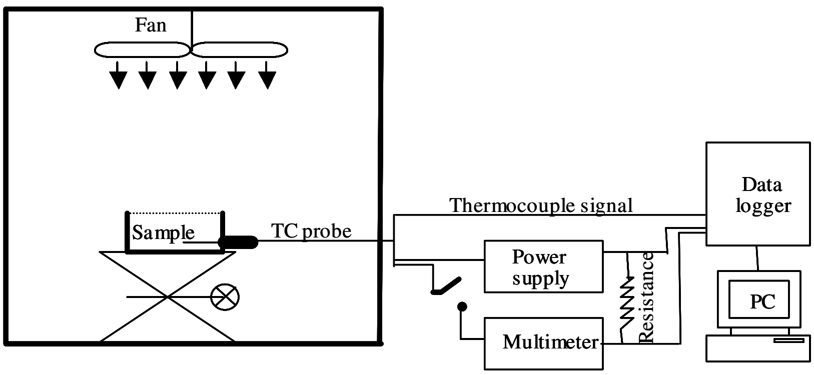


Figure 1. Set-up of the thermal conductivity measurement system.

sample at the selected sample temperature (1, 5, 10 and 23°C) which corresponds usually to the temperature range encountered during the industrial ripening process. The mean thermal conductivity and standard deviation were obtained from the seven experimental points. Reported thermal conductivity values are the mean thermal conductivity values.

Thermal Conductivity Model Development

IUFWC can be analyzed as a multicomponent system formed from a soluble solid substance (carbohydrates and ash), water, fat and protein. In this study, four physical models (parallel, series, Maxwell and developed models) were tested for thermal conductivity prediction of IUFWC.

Assuming that the food material is a four-phase system consisting of a soluble solid substance (ca), water (w), fat (f) and protein (p), the parallel (pa) and series (se) models are represented by the following equations, respectively (Miles *et al.,* 1983):

$$\lambda_{pa}(T) = \varepsilon_c(T)\lambda_c(T) + \varepsilon_a(T)\lambda_a(T) + \varepsilon_w(T)\lambda_w(T) + \varepsilon_f(T)\lambda_f(T) + \varepsilon_p(T)\lambda_p(T) \quad (4$$

$$\lambda_{se}(T) = \frac{1}{\frac{\varepsilon_c(T)}{\lambda_c(T)} + \frac{\varepsilon_a(T)}{\lambda_a(T)} + \frac{\varepsilon_w(T)}{\lambda_w(T)} + \frac{\varepsilon_f(T)}{\lambda_f(T)} + \frac{\varepsilon_p(T)}{\lambda_p(T)}} \quad (5$$

Where λ_c, λ_a, λ_f, λ_w and λ_p are, respectively, the thermal conductivities of carbohydrate, ash, fat, water and protein. The volume fraction of any component, ε_i, as a function of temperature is obtained from the following equation:

$$\varepsilon_i(T) = \frac{\rho_{app}(T)x_i}{\rho_i(T)} \quad (6$$

where x_i, ρ_i and ρ_{app} are respectively the mass fraction (kg kg^{-1} Product), density (kg m^{-3}) of the components and apparent density (kg m^{-3}) of the product. In all the calculations, the temperature dependencies of thermophysical properties were considered and correlations for temperature dependencies of major component of food may be found in Miles *et al.,* (1983) and Singh, (1992). The thermal conductivity of a food by the Maxwell equation is defined as (Miles et al., 1983):

$$\lambda_{Max}(T) = \lambda_c(T)\left(\frac{2\lambda_c(T) + \lambda_d(T) - 2\varepsilon_d(T)(\lambda_c(T) - \lambda_d(T))}{2\lambda_c(T) + \lambda_d(T) + \varepsilon_d(T)(\lambda_c(T) - \lambda_d(T))}\right) \quad (7$$

where *λc, λd and ε_d* are, respectively, the thermal conductivities of the continuous and discontinuous phases and the volume fraction of the discontinuous phase.

In addition to the two simple model series and parallel, we designed two complex models based on the components and structure of IUFWC. In one of them, we applied the Maxwell model to cheese in four steps and, at every step, we considered two distinct phases as a continuous and a dispersion phase. Table 2 presents a summary of the Maxwell modeling scheme. The main problem in analyzing and modeling of thermal conductivity of UF cheese is that this product is a heterogeneous and multiphase material so that we must consider the components of the cheese in the several steps. Natural cheese from renneting is essentially a calcium phosphateparacasein matrix. The integrity of the matrix is maintained by various interactions between paracaseins. Fat globules, moisture and dissolved substances, and enzymes (e.g. residual rennet and proteinases from starter and nonstarter microorganisms) exist in the pores of the matrix (Fox *et al.,* 2000). Based on the

Table 2. Descriptive scheme of the applied Maxwell model.

No	Continuous phase	Dispersion phase
Step 1	Water	Ash
Step 2	Water–ash	Carbohydrate
Step 3	Water–ash–Carbohydrate	Fat
Step 4	Protein	Water–ash–carbohydrate–fat

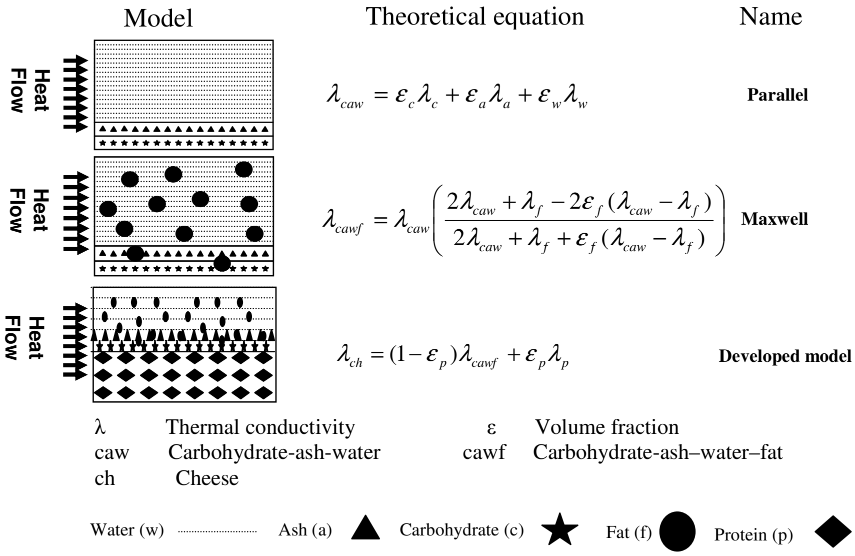


Figure 2. Developed thermal conductivity model.

cheese matrix, a three-step model was developed. In the first step of this model, three components (carbohydrate, ash and water) were considered as parallel structures. In the second step, two phases were considered: (1) a continuous phase (carbohydrate–ash–water) and (2) a discontinuous fat phase. Finally, in the third step, two phases were considered as parallel structures: (1) carbohydrate–ash–water–fat and (2) protein (Figure 2).

We used root mean square error (RMSE) in order to select the best model to represent the thermal conductivity evolution of Iranian ultrafiltrated white cheese as a function of temperature and chemical composition. This parameter can be calculated by:

$$RSME = \left[\frac{1}{N} \sum_{i=1}^{N} \left(\lambda_{\exp,i} - \lambda_{pre,i} \right)^2 \right]^{\frac{1}{2}} \qquad (8$$

where N, λ_{exp} and λ_{pre} are respectively the number of observation, thermal conductivity measured experimentally and thermal conductivity predicted by the model.

Water Activity

Firstly, the non-salted cheese sample slices were put in six different brine solutions (4, 8, 12, 16, 20, 24 g L^{-1}) at 25°C for 10 days before the experiments were equilibrated. Then, water activity of each cheese sample was determined at 25°C by using a water activity meter instrument (Novasina, Pfäffikon, Switzerland) based on the electrical conductivity measurement of immobilized salt solutions. The measurements were carried out in duplicate. Finally, the moisture and NaCl contents of the sample were evaluated.

Statistical Analysis

Statistical analysis was carried out using the Statistical Analysis System SAS software (SAS Institute Inc., 9.00, 2002) software package. Analysis of variance was performed by the ANOVA method and significant differences between means were obtained using Duncan's test at a 1% significant level. The least square method was used for multiple regression analysis.

RESULTS AND DISCUSSION

Density

Figure 3 shows the evolution of density as a function of the NaCl content in cheese samples at different temperatures. It can be

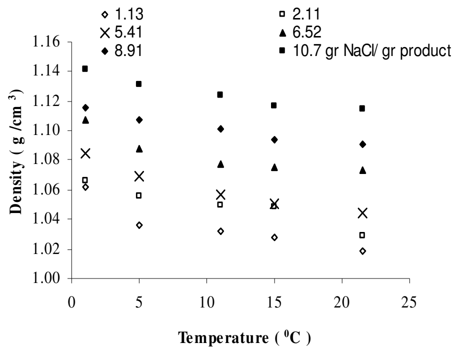


Figure 3. (a) Evolution of density as a function of temperature in UF cheese.

seen that the density of cheese decreases with increasing temperature and decreasing NaCl content. From these data, using linear multiple regression analysis, the following relationship was obtained (r^2= 0.97; Standard error = 0.0082):

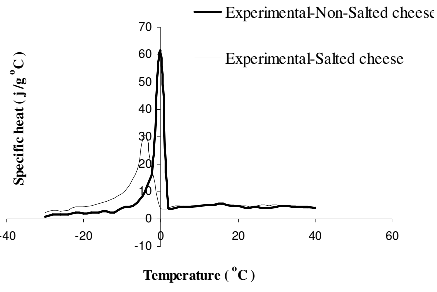
$$\rho = 1.042 - 0.002 \times T + 0.01 \times c_s \quad (9$$

This equation describes the density evolution of IUFWC as a function of two variables: the temperature, T (°C) and NaCl content, c_s (g NaCl 100 g^{-1} Product) of cheese.

This equation is valid for NaCl content values varying from 1.13 to 10.7 g NaCl 100 g^{-1} Product and for temperatures from 1 to 21°C. Densities of varieties cheese such as Cheddar, Hamburger, Fresh Cream, Mozzarella, Tulum, and Processed cheeses have been determined to be 1,102.0, 1,114.0, 1,014.1, 1,062.4, 1,110.0, and 1,107.0 kg m^{-3} at 30°C, respectively, by Tavman *et al.* (1999) and Zhong (2003) but the effect of temperature and NaCl content were not emphasized in their studies.

Specific Heat

Figure 4a shows the evolution of the experimental apparent specific heat values as a function of temperature for salted and non-salted Iranian ultrafiltrated white cheeses. As can be seen, because of an important NaCl mass fraction, salted cheese samples have a less intense phase change peak and a lower initial freezing point than that of non-salted cheese samples.



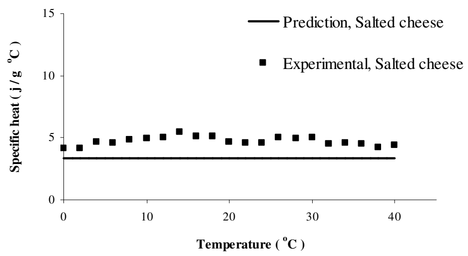


Figure 4. (a) Specific heat values obtained from the DSC compared with the model and (b) Comparison of the predicted and experimental values of specific heat.

From Equation (1), the specific heat was calculated as a function of temperature while knowing mass fraction of cheese components. Figure 4b shows the comparison of the predicted specific heat and experimental values as a function of temperature for a salted cheese respecting the given data in Table 1. As shown in Figure 4b, the experimental values have fluctuations above 0°C and are higher than the values estimated from the model. It can be related to the melting heat of the different fat components between 15 and 30°C. This phenomenon was not considered in the specific heat model. The same phenomenon has been observed by Pajonk *et al.* (2003) and Zhong (2003) during specific heat measurement of Emmental cheese from 0°C to 40°C.

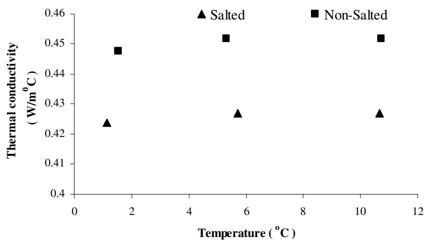
Effective Thermal Conductivity

Composition of white cheeses in Table 1 shows that their moisture contents are usually higher and the fat content is lower than those of cheese made by traditional techniques due to the high water holding capacity of whey proteins retained in UF cheeses (Abd El-Salam, Alichanidis and Zerfiridis, 1999; El Soda and Abd El-Salam, 2002). And since the thermal conductivity of water above the freezing point is higher than other food components (Urbicain *et al.,* 1997), the thrmal conductivity of UF cheese is greatly affected and, in comparison with other kinds of cheese with lower moisture content, the thermal conductivity of UF cheese is higher.

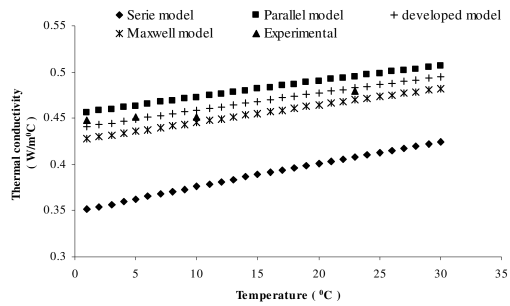
The values of thermal conductivity measured by the line source probe method for samples were reproducible and precise (2 % uncertainty "experimental standard deviation").

Figure 5a shows the effective thermal conductivity values measured for salted and non-salted Iranian ultrafiltrated white cheeses at different temperatures. This figure shows that the effective thermal conductivity is strongly dependent on both the physico-chemical properties and temperature. As can be observed, the effective thermal conductivity increases with increasing the temperature due to the increase of the thermal conductivity of the components. The thermal conductivity values of salted cheese, because of their lower moisture content, were slightly lower than those of the non-salted cheeses. A slight increase in thermal conductivity with temperature was also reported by Tavman *et al.* (1999) who reported a thermal conductivity of eleven types of cheese at 15 and 30°C, respectively.

Figure 5b presents the comparison between the experimental and predicted effective thermal conductivity values of IUFWC samples by the parallel, series, Maxwell and three step developed models as a function of temperature. As can be seen, two simple models (series and parallel) give the lower and the upper limits of the thermal conductivity (Urbicain *et al.,* 1997). The root mean square errors (RMSE) of experimental and predicted thermal conductivity values estimated by different models at different temperatures ranged from 0.0838 (for series model) to 0.0052 (for the developed model). The comparison between the experimental and predicted effective thermal conductivity values shows: (i) the series model always gives under-estimated thermal conductivity values, (ii) the parallel model gives over-estimated thermal conductivity values, and (iii) the predicted thermal conductivity values estimated by the proposed developed model are in good agreement with the experimental values (r^2> 0.99). It can be concluded that three step developed model is able to correlate the heat transfer in the cheese structure better than the other models.



(a)



(b)

Figure 5. (a) Thermal conductivity values measured for salted and non-salted UF cheese and (b) Comparison of the predicted and experimental values of thermal conductivity.

Table 3. Evolution of water activity of UF cheese samples as a function of NaCl and moisture contents at 25°C.

Moisture content ($g\ H_2O\ 100\ g^{-1}$ DM)	NaCl content (kg NaCl kg^{-1} Solution)	Water activity at 25°C
67.677	0.020	0.958
67.079	0.038	0.947
66.103	0.043	0.922
65.042	0.048	0.902
63.817	0.054	0.889
62.060	0.067	0.838

Water Activity

Table 3 and Figure 6 represent the evolution of water activity as a function of NaCl content in cheese samples at 25°C. As expected, the water activity of cheese samples decreased with a simultaneous decrease of the moisture content and increase of the NaCl content.

A multi variant regression was used to obtain the mathematical relationship between water activity of cheese samples and their moisture and NaCl contents at 20°C. The following equation gives the water activity of IUFWC as a function of NaCl content and moisture content (r^2= 0.99; Standard error= 0.007):

$$a_w = -0.356 + 0.02 \times m - 0.15 \times X_s \quad (10$$

where X_s and m represents NaCl content (kg NaCl kg^{-1} Solution) and moisture content ($g\ H_2O\ 100\ g^{-1}$ DM), respectively. This equation is valid for moisture contents between 62 to 67 (kg NaCl kg^{-1} Solution) and NaCl contents ranging from 0.02 to 0.07 (kg NaCl kg^{-1} Solution). Similar procedures were used by Saurel *et al.* (2004) for interpretation of the water activity for Emmental cheese as a function of the water, and NaCl concentrations during brining and ripening steps.

CONCLUSIONS

In this paper, some thermophysical properties, such as density, specific heat, effective thermal conductivity and water activity of the Iranian ultrafiltrated white cheese were estimated. The results showed that: (i) density of the Iranian ultrafiltrated white cheese samples varied between

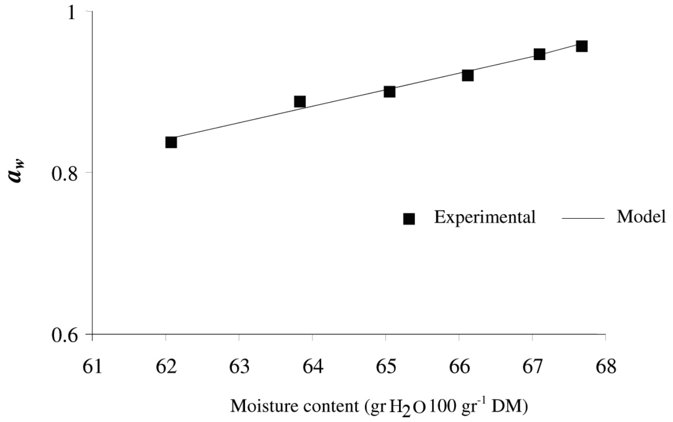


Figure 6. Comparison of the predicted and experimental values of water activity at 25°C.

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1.019±0.27 and 1.140±0.26, (ii) the specific heat values were in the range of 3.871±0.21 and 4.005±0.23 kJ kg^{-1} $^{o}C^{-1}$, (iii) thermal conductivity increases with temperature and water content, with values ranging from 0.4475 W m^{-1} $^{o}C^{-1}$ at 1^{o}C to 0.4801 W m^{-1} $^{o}C^{-1}$ at 23^{o}C, (iv) the three step developed model correlates thermal conductivity data in the IUFWC better than the other models (parallel, Maxwell and series models), and (v) water activity decreases with an increase in the NaCl content and decrease in the moisture content. Water activity values of IUFWC varied from 0.838 to 0.958.

These results could be used to model coupled heat and mass transfer during ripening of IUFWC.

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Nomenclature

a_w Water activity
c NaCl content, g NaCl 100 g^{-1} Product
Cp Specific (sensible) heat, kJ kg^{-1} °C^{-1}
DM Dry Matter
H Enthalpy, J kg^{-1}
I Current through heater wire, A
λ Thermal conductivity value
m Moisture content, g H_2O 100 g^{-1} DM
M Mass, kg
N Number of observation
Q Power generated by probe heater, W m^{-1}
R Correlation coefficient
r^2 Determination coefficient
R Electric resistance, Ω m^{-1}
RMSE Root mean square error
S Slope of the linear portion of the plot of the temperature *vs. ln(time)*
T Time, s
T Temperature, °C
X NaCl content, kg NaCl kg^{-1} Solution
X Mass fraction, kg kg^{-1} Product

Greek Letters

λ Thermal conductivity, W m^{-1} °C^{-1}
ν Kinematic viscosity, m^2 s^{-1}
ε Volume fraction, m^3 m^{-3} product
ρ Density, kg m^{-3}

Subscripts

a Ash
app Apparent
c Aarbohydrate or continuous phase
ca Carbohydrate–ash
caw Carbohydrate–ash–water
cawf Carbohydrate–ash–water-fat
ch Cheese
exp Experimental
d Dispersed phase
f Fat
i Initial or component *i*
re Reference
Max Maxwell
P Protein
Pa Parallel
pre Prediction
s Salt (NaCl)
sa Sample
se Series
w Water

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اندازه گیری و مدلسازی خصوصیات ترموفیزیکی پنیر سفید ایرانی تهیه شده با استفاده از اولترافیلتراسیون

م. دلوی و ن. همدمی

چکیده

اطلاعات موجود بر روی خصوصیات ترموفیزیکی پنیر سفید ایرانی تهیه شده با استفاده از اولترافیلتراسیون بسیار محدود می باشد. در این تحقیق، خصوصیات ترموفیزیکی مورد مطالعه عبارت بودند از هدایت حرارتی، گرمای ویژه، دانسیته و فعالیت آبی. هدایت حرارتی و گرمای ویژه اندازه گیری شده برای پنیر مذکور به ترتیب در محدوده ی ۰,۴۸۰ – ۰,۴۴۷ وات بر متر درجه سانتیگراد و ۴,۰۰۵ – ۳,۸۷۱ کیلو ژول بر کیلوگرم درجه سانتیگراد در دامنه ی دمایی ۲۳ – ۱ درجه سانتی گراد و دمایی ۴۰ – ۱ درجه سانتی گراد قرار گرفت. مقادیر هر دو ویژگی با افزایش دما و رطوبت نسبی افزایش یافت. برای پیش بینی هدایت حرارتی به صورت تابعی از دما و ترکیب شیمیایی پنیر، مدلی سه مرحله ای بر مبنای مدل های موازی و ماکسول توسعه یافت. مفادیر هدایت حرارتی پیش بینی شده با استفاده از مدل توسعه داده شده انطباق خیلی خوبی با داده های اندازه گیری شده نشان دادند مدل سازی دانسیته و فعالیت آبی با استفاده از رگرسیون غیر خطی نشان داد که دانسته تابعی از دما و میزان نمک، و فعالیت آبی تابعی از میزان آب و نمک پنیر می باشند.

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