Estimation model for electrical conductivity of red grape juice

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Abstract: The equations for predicting the electrical conductivities of red grape juice at different concentrations have been evaluated in this study.   Three samples of red grape juice having concentrations of 10.5, 12.5 and 14.5°Brix were ohmically heated by applying three different voltage gradients (10, 12 and 15 V/cm) in the temperature range of 25-80℃.   The mathematical models using multiple linear regression analysis indicated that electrical conductivity depended on temperature and concentration.   The predictions of electrical conductivities using the mathematical models was found to be highly accurate with R^2 value of 0.9975 when compared with the experimental data of red grape juice with concentration of 11.5°Brix.   The reducing chi-square (χ^2) and the root mean square error (*RMSE*) from the mathematical models were calculated and compared with the experimental data.   As the results, multiple linear regressions on the coefficients of the mathematical model of electrical conductivity prediction have given highest values of the R^2 and lowest χ^2 and *RMSE* so the established model was confirmed as highly accurate when estimating electrical conductivities of red grape juice.

Keywords: electrical conductivity, ohmic heating, estimation model, red grape juice

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1   Introduction

Ohmic heating, taken name from Ohm's law, is another option of fast heating technique for food products. The conversion of electrical energy into heat, resulting in internal energy generation is the basic principle of ohmic heating[1].   Ohmic heating has many advantages over conventional heating such as high heating rate, high energy conversion efficiency, uniform volumetric heating and wide usage for many applications of food processing which include thermal process, aseptic processing, thawing, blanching, pasteurization and sterilization[2,3]. Apart from water saving, ohmic thawing does not need water during the process, it provides many benefits such as no waste, shorter thawing time and easy process controlling[4].   The application of ohmic heating for pasteurization of liquid food has been studied in the past by various researchers.   It was first intended to be applied in liquid food processing and later in solid-liquid food mixtures[5-7].   The heat is internally generated within foods by the passage of alternating electric current. Ohmic heating works well because most food contain ionic species such as salts and acids, which act as electrolytes that allow electric current to pass through the food and generate heat inside it[8,9].   The efficiency of ohmic heating is dependent on conductive nature of the food to be processed[10], and hence a knowledge of the electrical conductivity of food as a whole and its components are essential in designing a successful thermal process[1].   In a conventional heating system, the thermal conductivity of a particle controls its heating rate whereas in an ohmic process, the electrical conductivity is the controlling factor[11].

The electrical conductivity is a function of food components and a complex function of temperature and other physical properties, which is directly reflected in the ohmic heating rate[3].   The salt components, acids,

and moisture are highly effective in increasing electrical conductivity, while fats, lipids, and alcohols decrease it[12]. The electrical conductivity (S/m) of food materials is the most important parameter in ohmic heating process and can be calculated from voltage and current data by using the following Equation (1)[12-14] :

$$\sigma = \frac{I}{V}\frac{L}{A} \qquad (1)$$

Where: σ is the specific electrical conductivity, S/m; I is alternating current through the sample, Amp; V is voltage, V; A is area of cross section of the sample, m^2; L is the gap between the electrodes, m.

Numerous researches have studied the electrical conductivity of fruit juice and purees during the ohmic heating process[15]. Lamsal[6] measured electrical conductivity and developed mathematical model in terms of total soluble solids and the temperature of three different fruit juice such as orange, pineapple and tomato. Assawarachan and Anchareekit[13] measured the electrical conductivity of orange juice, guava juice and mixed juice of orange and guava during ohmic heating at 30-80℃ for designed ohmically continuous pasteurization processes for fruit juice. Similarly Sarang et al.[8] determined electrical conductivities of six different fresh fruits (red apple, golden apple, peach, pear, pineapple and strawberry) and several different cuts of three types of meat at room temperature. Halden et al.[12] investigated changes in the electrical conductivity of food sample during ohmic heating.

Many reports have indicated that knowledge of electrical conductivity properties of fruit juice is required to design, optimize and control the ohmic heating process[3,5]. The design, optimization and controlled ohmic heating process are required for mathematical modeling of electrical conductivities, which further can be used for prediction. Marra et al.[11] developed a mathematical model of a solid food material undergoing heating in ohmic cell for simulated heat transfer phenomena. Therefore, it is important to study and determine prediction model of electrical conductivity of red grape juice during ohmic heating process. Hence the objectives of this experiment were to measure the electrical conductivity of red grape juice at different

concentrations and to develop the mathematical model for predicting electrical conductivity of red grape by using multiple linear regression analysis.
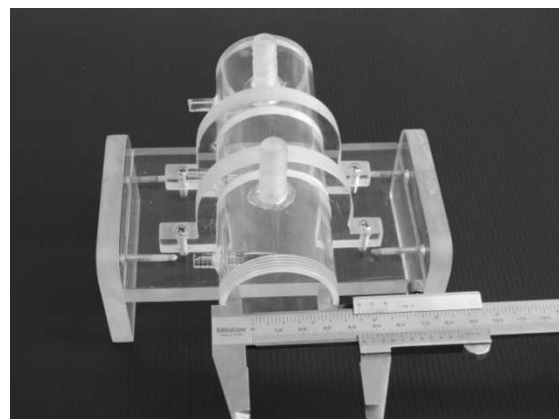
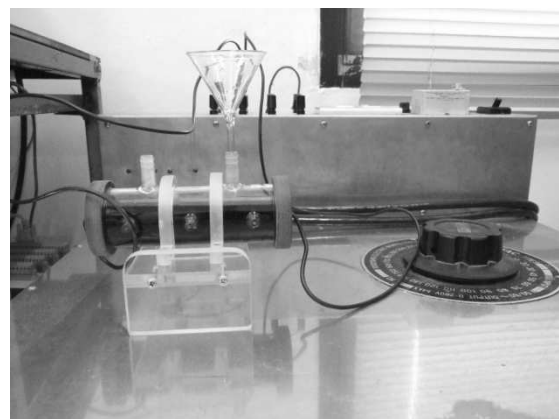## 2 Materials and methods

2.1 Sample preparation

The aqueous sodium chloride solution of 0.1 M concentration and five different concentrations of red grape juice (10.5, 11.5, 12.5, 13.5 and 14.5°Brix) were obtained from the local market, Thailand. The juice samples were packed in a plastic bag and kept at -20℃ for further experiment. The red grape juice samples were defrosted to 25℃ before the experiment.

2.2 Ohmic heating system

The experimental ohmic heating system consisted of three major parts: ohmic heating unit, controller system and data acquisition system. The ohmic heating unit consisted of an acrylic cylinder of 6 cm diameter and 4.8 cm length, and had stainless steel electrodes positioned at both ends of the cylinder (Figure 1).

a.Ohmic heating cell

b. Ohmic heating system

Figure 1   Experimental setup for electrical conductivity measurement

The electrodes were tightly held in position using rubber rings and acrylic cover plates with nuts and bolts. The controller system with circuit that consisted of PLC and many electronic devices was connected to the computer over a RS-232 interface. PLC contained solid state digital logic elements for controlling and logical decision. The calibration was done after the installation of I/O-AI4-A02 and I/O-AIC-8. The program of PLC control was written in Visilogic version 4.60 software using the I/O driver routine provided with I/O-AIC-8 module. The data acquisition system was used to measure the temperature distribution, voltage and electrical current signal output with respect to time by using a programmable logic controller. Three K-type thermocouple probes were inserted into 0.3 cm thin glass tubes filled with UH-102 Silicone heat-conductive material (Figure 2).
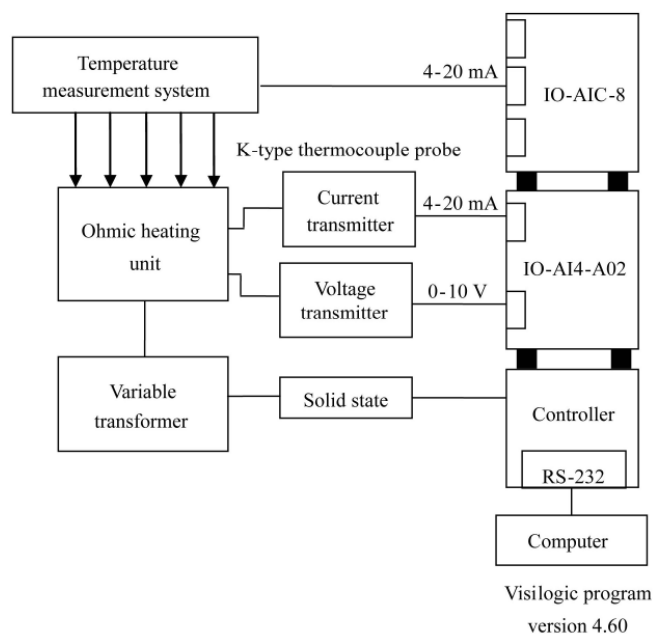

Figure 2   Schematic diagram of ohmic heating controlling system

2.3   Mathematical modeling of electrical conductivity

The mathematical model of electrical conductivity of red grape juice with three different concentration (10.5, 12.5 and 14.5°Brix) at temperature (25-80℃) during ohmic heating was calculated by using multiple linear regression analysis and Equation (2).

$$\sigma = A + B(T) + C(TSS) + D(T)(TSS) \qquad (2)$$

Where: A, B, C and D are regression constants; T is the temperature, ℃; TSS is the total soluble solids. All data were analyzed using the statistical package, SPSS (Version 11.5, SPSS Inc., US). The coefficients and regression statistics of the selected models were then determined using multiple regression analysis. The maximum fitness of electrical conductivity prediction was determined by the highest coefficient of determination (R^2) and three criteria, namely chi-square (χ^2) and root mean square error ($RMSE$) were adopted to evaluate the fitting probity of each model. These static parameters (χ^2 and $RMSE$) can be calculated by Equations (3) and (4) which are followed by many researchers[16,17]:

$$\chi^2 = \sum_{i=1}^{N} \frac{(\sigma_{experiment} - \sigma_{prediction})^2}{N - n_p} \qquad (3)$$

$$RMSE = \sqrt{\sum_{i=1}^{N} \frac{(\sigma_{experiment} - \sigma_{prediction})^2}{N}} \qquad (4)$$

Where: $\sigma_{experiment}$ is the experimentally observed electrical conductivity; $\sigma_{prediction}$ is the predicted electrical conductivity, N is the number of observations and n_p is the number of constants in the model.

3   Results and discussion

3.1   Calibration and accuracy of Ohmic heating setup

The ohmic heating set-up developed in this study was effectively used for determining the electrical conductivity of red grape juice based on their static heating. The accuracy of ohmic system was compared and calibrated with the standard conductivity. The calibration results for the accuracy of electrical conductivity of 0.1 M NaCl solution revealed that there was no significant difference between standard electrical conductivity of 0.1 M NaCl solution[14] and the experiment data.

The design of effective ohmic heating depends on electrical conductivity of food product[14]. Numerous researches indicated that increasing of the temperature and soluble solid increased electrical conductivity of fruit juice[6,13]. In all cases, the electrical conductivity of red grape juice increased with the increase in temperature because higher temperature accelerated the passage rate of alternating electric within the red grape juice sample[10,15]. Electrical conductivity increased with temperature for all products and conditions tested

following linear relations[2,8,12]. The relationships of temperature change with time of red grape juice at 14.5°Brix at 10, 12 and 15 V/cm are showed in Figure 3. The time required to heat red grape concentrate juice at 14.5°Brix from 25 to 80℃ were achieved in 6.93, 10.91 and 15.72 min and the ohmic heating rates were 0.1316, 0.0834 and 0.0573℃/s at three different voltage gradients (15, 12 and 10 V/cm), respectively. In addition, the time required to heat the red grape juice from 25 to 80℃ at 20 V/cm was 1.42 and 2.2 times less than those at 12.5 and 10.5°Brix, respectively. The changes in electrical conductivity curve of red grape juice with temperature at three different voltage gradients (10, 12 and 15 V/cm) and three different concentrations (10.5, 12.5 and 14.5°Brix) are showed in Table 1. The table revealed that electrical conductivity increased as concentration and temperature increased. The electrical conductivity at 15 V/cm was observed as slightly higher than those at 10 and 12 V/cm as shown in Figure 4. The result of this experiment shows no significant changes on electrical conductivity of red grape juice at all voltage gradients (10, 12 and 15 V/cm), indicating that the electrical conductivity is specific properties of red grape juice. However, the higher voltage gradients gave the higher heating rate. This illustrated a possible effect of voltage gradients on heating rate of red grape juice during ohmic heating. The higher voltage gradients accelerated electrical energy into red grape juice. The similar research results were found by Marra et al.[11], Halden et al.[12] and Filiz et al.[15].
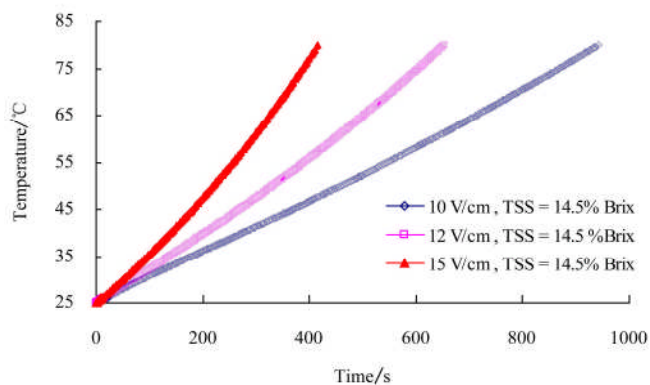
Table 1　Estimated electrical conductivity curve for three different concentratations and three different voltage gradients of red grape juice during ohmic heating

Soluble solid concentration	Electrical conductivity ($\sigma \times 10^{-2}$)/(S·m^{-1})		
	10 V/cm	12 V/cm	15 V/cm
10.5 °Brix	0.92 ± 0.008 [a]	0.91 ± 0.005 [a]	0.93 ± 0.014 [a]
12.5 °Brix	1.01 ± 0.005 [b]	1.01 ± 0.003 [b]	1.02 ± 0.008 [b]
14.5 °Brix	1.11 ± 0.007 [c]	1.09 ± 0.003 [c]	1.13 ± 0.002 [c]

Note: Mean ($n=3$) ± standard error of estimation, [a, b, c] Mean values followed by the different letters in the same column are significantly different ($P \leqslant 0.05$).
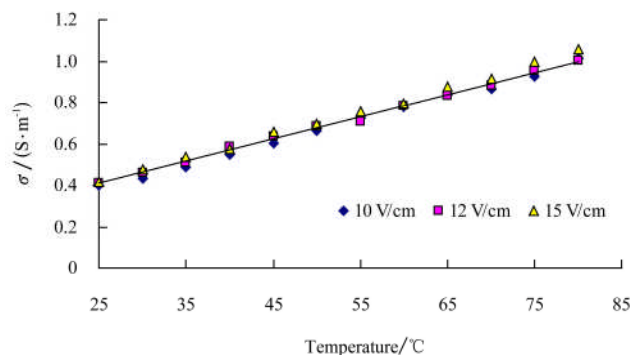

Figure 4　Changes in electrical conductivity (σ) of red grape juice with temperature during ohmic heating at three different voltage-gradients

Figure 5 shows the relationship between electrical conductivity changes during various temperature of pineapple concentration at 10.5, 12.5 and 14.5°Brix. The increase of concentration of red grape juice was highly significant on increasing the electrical conductivity. Because the concentration increased solid particle in red grape juice, and it accelerated more electric current passed through red grape juice than low concentrated juice. The concentration of soluble solid in red grape juice explained the change in electrical conductivity. Addition of external compounds, like sugar and citric acid, resulted in a decrease in the conductivity values, while evaporative concentration provided an increase in conductivity. It shows the similar results as Assawarachan and and Anchareekit[13] and Lamsal[6] who studied that the increasing temperature and concentration provide the increase in electrical conductivity of fruit juice product using ohmic heating methods.
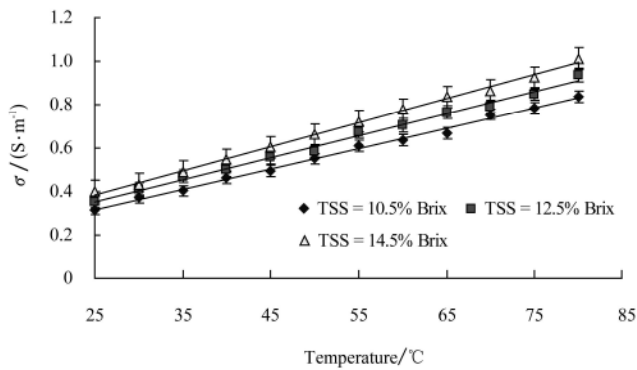

Figure 3　Heating rate of red grape juice during ohmic heating at three different voltage gradients

Figure 5   Changes in electrical conductivity (σ) of red grape juice with temperature during ohmic heating at three different concentrations

3.2   Modeling of electrical conductivity

The study found that the electrical conductivity of red grape juice was influenced by total soluble solids and temperature.   The various best fit equations obtained from multiple linear regression analysis are presented in Table 2.   It is obvious from the equations that the temperature of electrical conductivity at three different voltage gradients is lower than soluble solids coefficient, indicating the greater influence of total soluble solids (*TSS*) on the electrical conductivity values.   Variation in electrical conductivity of red grape juice could be expressed, with sufficient accuracy, through empirical relationships between temperature and TSS.   The errors in electrical conductivity prediction of the models depend on chi-square (χ^2) and root mean square error (*RMSE*) as the study of concentration changeable prediction of microwave vacuum evaporation for pineapple juice. The mathematical model from electrical conductivity prediction has given the highest values correlation coefficient (R^2) and lowest χ^2 and *RMSE* which proves high accuracy of the model[16,17].   For all experiments, the model values of R^2, χ^2 and *RMSE* ranged between 0.9961 to 0.9992, 0.0003 to 0.0051 and 0.0173 to 0.0538, respectively.

Table 2   Electrical conductivity prediction for mathematical model and statistical parameter during ohmic heating at 10, 12 and 15 V/cm

Voltage gradients	Mathematical modeling of electrical conductivity/S · cm^{-1}	*TSS*/°Brix	R^2	χ^2	*RMSE*
10 V/cm	$\sigma = 0.014 + 0.005T + 0.683TSS + 0.043(T)(TSS)$	11.5	0.9981	0.0029	0.0538
		13.5	0.9975	0.0016	0.0400
12 V/cm	$\sigma = 0.004 + 0.004T + 0.963TSS + 0.044(T)(TSS)$	11.5	0.9961	0.0051	0.0714
		13.5	0.9991	0.0003	0.0173
15 V/cm	$\sigma = 0.074 + 0.002T + 0.467TSS + 0.063(T)(TSS)$	11.5	0.9985	0.0010	0.0316
		13.5	0.9992	0.0004	0.0200

As the results, multiple linear regressions on the coefficients of the mathematical model of electrical conductivity prediction demonstrated in Table 2 have given the highest values of the correlation coefficient (R^2), and lowest χ^2 and *RMSE*.   The established model confirmed its good accuracy.   Figure 6 presents the comparison between predicted values and actual electrical conductivity of red grape juice using mathematical models at 15 V/cm.   The validation of the suitability of this mathematical model for predicting electrical conductivity of red grape juice at 11.5°Brix at a temperature range of 25-80℃ and a constant voltage gradient (15 V/cm).   The linear nature of the curve, at 45℃ slope from the origin indicates that the predicted model is a good fit for the actual electrical conductivity changeable data.   The accuracy of the established model was confirmed by comparing the data of the predicted mathematical model and observed experiment.   The predicted data is banded around the straight line which
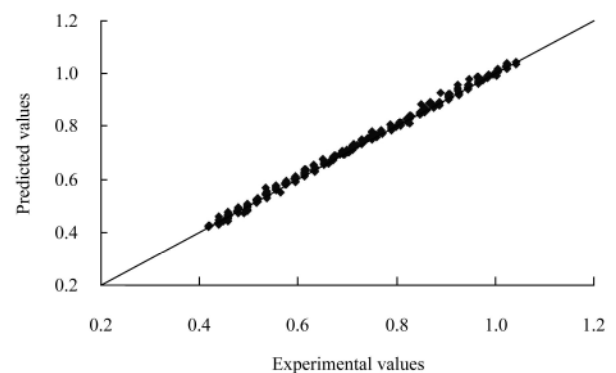

Figure 6   Experimental and predicted electrical conductivity values for red grape juice (*TSS* =11.5°Brix) at 15 V/cm

shows the best suitability for the mathematical model. These results showed the suitability of this mathematical model in describing electrical conductivity that changed the behavior of red grape juice.

4 Conclusions

Electrical conductivity of red grape juice was found to be increased linearly with the increase of both total soluble solids and temperature. The electrical conductivity values obtained from the experiment were in the range of 0.4-1.15 S/m, where the temperature values were in the range of 25-80℃ and concentration 10.5-14.5°Brix. In the ohmic heating process, voltage gradient directly affects the heating rate, but it does not influence electrical conductivity properties of food specimens. All models gave the highest values of R^2 in the range between 0.9975-0.9992 and the lowest values of χ^2 and *RMSE* values between 0.0003 to 0.0051 and 0.0173 to 0.0538, respectively. As the results, multiple linear regressions on the coefficients of the mathematical model of electrical conductivity prediction have given the highest values of the correlation coefficient (R^2) and the lowest χ^2 and *RMSE* so the established model was confirmed for its good accuracy.

Acknowledgements

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