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Modeling the electrical conductivity value of the model solution

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Abstract: The ohmic heating process is one of the novel electrical heating methods that are considered as fast, homogeneous and efficient heating. In this study, the details of the relationship between electrical conductivity (EC)-Temperature (Temp) and EC-pH-Temp at different Total Soluble Solid Content (TSSC) and different pH values were examined. Especially, the study explains details of the electrical conductivity value due to pH change (2, 2.5, 3, 3.5) and expressing EC change depending on the pH value of fruit and vegetable juices. At constant pH, EC values decrease with increasing TSSC values (10%, 20%, 30%, 40%, 50%, 60%) and decrease with increasing pH at constant TSSC value. When the relationship between Temp-EC is analyzed that the EC value increases as Temp increases in all cases and this increase is linear. It was found that the Temp-EC relationship was in high compatibility with an R^2 value above 0.97. Also, in the Temp-EC-pH relationship, the R^2 value was found to be an acceptable value above 0.95.

Key words: Ohmic heating, electrical conductivity, pH, TSSC, mathematical model.

INTRODUCTİON

In the ohmic heating process (OHP), also known as Joule heating and electrical resistance heating, alternating current is passed through the food material (solid/liquid) between the two electrodes. OHP is based on the principle of heating by the generation of heat in the food material due to its resistance to the flow of electric current. In addition to being expressed as homogeneous heating due to its homogeneous current flow especially in liquid applications, it has been reported as fast heating with high energy efficiency (Icier 2012, Kaur & Singh 2016).

Although OHP was first used for the pasteurization of dairy products in the 19th century, it was not used for a long time due to the technology was not fully developed, and electricity prices were high in those years. However, it seems that its usage has increased gradually since the second half of the 20th century, due to technological developments and decreasing electricity costs (Icier 2012).

In the literature reviewed on OHP, there is a tendency on system development/design, and electrical conductivity at the beginning (de Alwis & Fryer 1992, Qihua et al. 1993, Roberts et al. 1998). However, after 2000, the studies were on the examination of EC value especially on liquid food applications (Icier & Ilicali 2004, 2005a, b). In the following years, food engineering applications increased and the applications were distillation (Tunç & Koca 2019), drying (Lebovka et al. 2006), extraction (Aamir & Jittanit 2017), thawing (Cevik & Icier 2018) dairy products (Kuriya et al. 2020, Rocha et al. 2020a), food safety (Barros et al. 2020, Rocha et al. 2020b, Pires et al. 2021) and evaporation (Icier et al. 2017). In this sense, not only the studies carried out are mostly on electrical conductivity, but also quality properties and performance analyses attract attention.

It is known that one of the most important parameters for OHP is electrical conductivity change during the process (Icier 2012, Kaur & Singh 2016). In the literature review, the electrical conductivity change was mostly depending on the relationship between voltage gradient and temperature. It has been reported in many studies that the electrical conductivity value increases due to the increase in voltage gradient. The molecular mobility increases due to the increase in temperature and the relation usually are linear (Castro et al. 2004, Halden et al. 2007, Assawarachan 2010, Gomathy et al. 2015, Sabanci & Icier 2017).

There are several studies on the relationship between EC and increased TSSC values. In this sense, studies for different juices and concentrates have been reported that electrical conductivity increases up to certain content of TSSC and then tends to decrease (Castro et al. 2003a, Icier & Ilicali 2004, Icier & Ilicali 2005b). Besides, in ohmic evaporation studies (under vacuum and atmospheric conditions), the electrical conductivity value for the different liquid applications (tomato, seawater, pomegranate juice, sour cherry water, etc.) increases up to the critical TSSC value and then decreases after the evaporation begins (Assiry et al. 2010, Hosainpour et al. 2014, Icier et al. 2017, Sabanci & Icier 2017).

The current study aims to heat the model solutions, which are at different pH (2-3.5) and TSSC (10-60%), by using the ohmic system from 15 °C to 95 °C. The study focuses on the effect of some influencing parameters (TSS, pH, and Temperature) on the EC of the model solution.

Abbreviations

EC → Electrical Conductivity
Temp → Temperature
TSSC → Total Soluble Solid Content
OHP → Ohmic Heating Process

MATERIALS AND METHODS

Materials

Glucose syrup was prepared as the model solution for OHP. In the study, glucose syrup with 80% TSSC content was adjusted to 10%, 20%, 30%, 40%, 50%, 60% and 0.15% (w/v) NaCl solution was added to provide sufficient ionic mobility. The TSSC adjustments were made by a Digital refractometer (Hanna, Romania). The pH (2, 2.5, 3, 3.5) values of the model solution were adjusted with citric acid, which is the dominant acid in fruit juices. After that, the solutions were placed in the refrigerator for preservation.

Methods

Ohmic heating

In OHP, a laboratory-scale special design system is consisting of a power supply (360V-50 Hz), isolated transformer, microprocessor unit, computer connection, and test cell (6×7×8 cm) (Figure 1). The test cell used in ohmic heating is made of polyoxymethylene and the electrodes (60×150×1 mm) are made of stainless steel. The applied voltage gradient was 20 V/cm and the solution was subjected to heating from 15 °C to the target temperature of 95 °C. Temperature, current, and voltage values are recorded every second by using a specially designed microprocessor. In the extraction process, the solution temperature data was recorded by an isolated T-type thermocouple (Cole- Parmer, UK).

Electrical conductivity

Electrical conductivity values are calculated by using equation (1) in the unit of S/m (Icier & Ilicali 2004).

Electrical conductivity value (S/m)

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

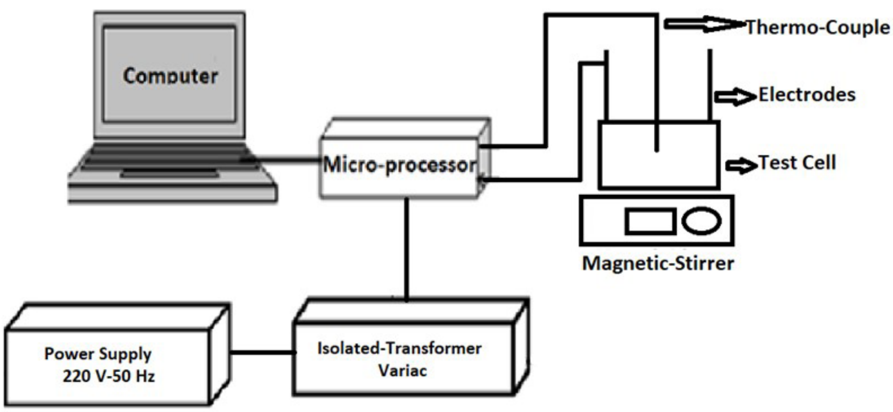

Figure 1. **Schematic representation of the ohmic heating system.**

where L represents the distance (m) between two electrodes, V voltage (volts), I current (amps), and A represents the liquid contact area (m^2) of the electrode.

Electrical conductivity model

Temp-EC relation between 15-95 °C was determined with the help of equation (2). The relationship was examined by non-linear regression analysis, and electrical conductivity was taken as a dependent, and the temperature was taken as an independent variable in the model expression.

$$= a \times T + b \quad (2)$$

Here, σ refers to electrical conductivity (S/m), T (°C) temperature value, and a (S/m×°C) and b (S/m) equation constants.

Equation 3 was determined as the most suitable model by nonlinear regression analysis by testing pH and temperature in different combinations to express the relationship between EC, Temperature, and pH. The relationship was examined by non-linear regression analysis, and electrical conductivity was taken as a dependent, and temperature and pH values were taken as independent variables in the model expression.

$$\sigma = a \times T + pH^n + b \quad (3)$$

Here, σ represents the electrical conductivity (S/m), T (°C) temperature value, a (S/m×°C), b (S/m) and n value represent the equation constants.

Statistical evaluation

SPSS 16.0 (IBM, USA) package program was used in the statistical evaluation of the results (heating time, EC). Completely determined by one-way variance (Post-Hoc Duncan test) analyses. The effect of TSSC and pH on the heating time was examined with the Duncan test and a one-way analysis of variance Confidence level was taken as 95% ($p = 0.05$). If p values are less than 0.05, it means that there is a statistically significant difference. Also, non-linear regression analysis was used with SPSS 16.0 (IBM, USA) for model experiments.

RESULTS AND DISCUSSION

For this reason, in the present study, the prepared model solution at different TSSC (10-60%) and different pH values (2-3.5) was heated from 15 °C to 95 °C, and the details of EC-TEMP and EC-TEMP-pH relationships were examined in following parts.

The heating time of the model solution

The processing time required for the model solution having different TSSC and different pH values to reach from 15 °C to 95 °C with ohmic heating is given in Table I. It has been determined that the concentration and ionic mobility of the model solution affected the heating time during OHP. In this sense, especially molecular mobility affects the electrical conductivity, and accordingly, the processing time is longer as the pH value increases at the same TSSC value. Increasing the pH value means a decrease in the molecular concentration of [H^+] in the solution. For this reason, the higher pH value of the solution has negatively affected the warm-up time when it reaches 95 °C in the process.

Similarly, at the same pH values, it was observed that the processing time increased due to the increase in TSSC value. For instance, the warm-up of pH 2 solution with 10% TSSC value to reach 95 ° C is 176s but at the same pH (pH 2), 1831s was measured for 60% TSSC and this value was found to increase approximately 10 times than 10% TSSC ($p<0.05$). Similarly, it was figured out that the time to reach 95 °C increased between 8-10 times due to the increase of TSSC at different pH values ($p<0.05$). The warm-up time varies depending on the content of the product used in the ohmic heating process. In particular, ionic mobility and molecular mobility are important variables on electrical conductivity. In the study conducted with sour cherry juice and apple juice, the warm-up time is shorter at the sample that has a lower pH value and higher ionic activity (Icier & Ilicali 2004). Similarly, in a study conducted with strawberries and products, it was found that the gel structure, which significantly restricts molecular mobility, extends the processing time (Castro et al. 2004). As a result, it has been determined that the decreasing pH value affects the mobility in the product and causes the processing time to be shortened. Therefore, the pH value has an effect on the processing time in the current study. Besides, the change in the TSSC value affected the processing time and the processing time was negatively affected due to the increased TSSC value.

Change of electrical conductivity (EC) of the model solution

The electrical conductivity change during the heating of the model solution having different TSSC and pH values from 15 °C to 95 °C is given in Figure 2. It was determined that increasing TSSC value negatively affects EC values at the same pH value (Figure 2) ($p<0.05$). The main reason for this is the increasing TSSC value is thought to limit molecular mobility. Intramolecular forces and water-soluble substances limit molecular motion and therefore electrical conductivity is affected. These forces depend on intermolecular

Table I. Process times (s) required for solutions having different pH and different pH values to reach from 15 °C to 95 °C.

TSSC	pH 2	pH 2.5	pH 3	pH 3.5
10%	176.0±1.7	246.0±4.4	282.0±2.7	293.0±1.0
20%	221.3±1.5	290.3±6.7	336.3±4.0	346.3±4.9
30%	340.0±2.7	447.3±5.5	500.6±9.1	506.7±14.6
40%	513.3±9.9	645.0±22.3	734.6±14.0	722.0±12.1
50%	838.0±54.2	1064.3±37.6	1094.5±14.9	1181.5±62.9
60%	1831.0±36.6	2283.5±55.9	2348.5±21.9	2465.0±43.8

spaces and the resistance of the hydrogen bond. Therefore, with the increase of TSSC, an increase in a hydrogen bond with hydroxyl groups can occur and is thought to increase viscosity value and restrict mobility due to a decrease in molecules in the solute liquid state (Constenla et al. 1989). Similarly, Giangiacomo, (2006) examined the water-sugar interactions in different concentrations of sugar solutions (glucose, fructose, and sucrose) using the NIR spectroscopy method. In the study, the low concentrations of sugars acted like a breaker of the water cluster, and that they acted as structure makers at higher concentrations. As a result, he reported that this structure restricted molecular mobility. In the same TSSC value, the increasing pH value negatively affects ionic mobility this time and accordingly negatively affects its electrical conductivity ($p<0.05$). In their study, Icier & Ilicali (2004) heated cherry and apple juice at different concentrations reported that cherry juice with a lower pH value warms faster and the EC value is higher compared to all other concentrations (Icier & Ilicali 2004). In general, the electrical conductivity value was affected depending on the temperature, pH, and TSSC value and the EC value increased as the temperature value increased. Also, at the same TSSC value, the EC value decreased as the pH value decreased. Also, when the pH value was kept constant, the EC values increased with the decrease of the TSSC values. Therefore, EC values were positively affected by decreasing pH and TSSC values and increasing temperature.

The electrical conductivity change of the model solution depending on the temperature change at different pH and TSSC values is given in Figure 2. Depending on the increasing temperature value, it was found that the electrical conductivity value increased for all TSSC values. From the literature review, a similar trend was found for different juices. For example,

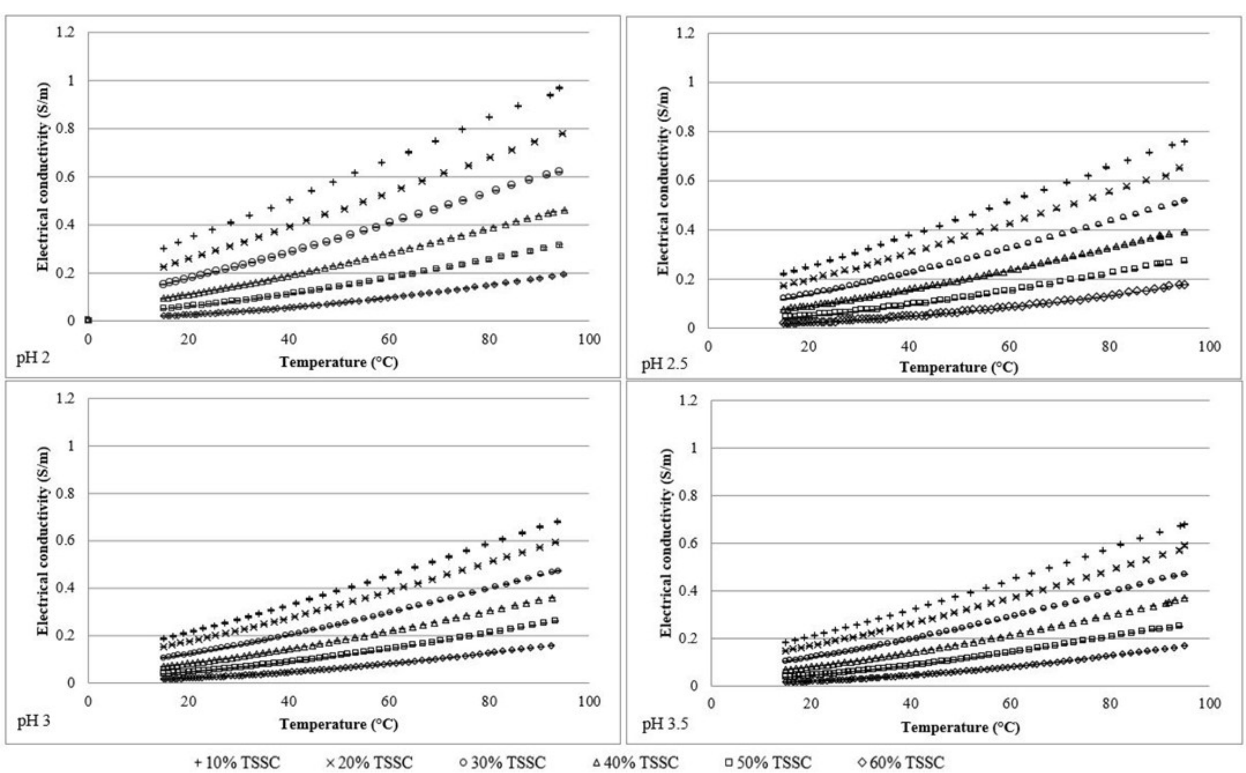

Figure 2. Temp-EC change of the solutions that have different TSSC and pH values.

the electrical conductivity value is 0.8-1.6 S/m for cherry juice (20-60V/cm; 20-60 % TSSC; 30-75 °C) (Icier & Ilicali 2004), 0.35-1.00 S/m for apple juice (20-60V/cm; 20-60% TSSC; 30-75 °C) (Icier & Ilicali 2004), 0.16-1.16 S/m for orange juice (20-60V/cm; 20-60% TSSC; 30-75 °C) (Icier & Ilicali 2005b), 0.2-0.5 S/m for strawberry pulp (32-90V/cm; 14-59.5% TSSC; 20-85 °C)(Castro et al. 2003b), 0.41-1.02 S/m for lemon juice (30-55V/cm; 20-74 °C) (Darvishi et al. 2011), 3.1-8.5 S/m for tomato juice (6-14 V/cm; 9.1%; 25-100 °C) (Torkian Boldaji et al. 2015), 0.40-1.11 S/m for red grape juice (10-15 V/cm; 10.5-14.5% TSSC; 25-80 °C) (Assawarachan 2010), 0.40-0.76 S/m for grape juice (20-40 V/cm; 30-80 °C) (Icier et al. 2008) and 0.21-1.10 S/m for pomegranate juice (30-55 V/cm; 20-85 °C) (Darvishi et al. 2013). It has been reported that molecular mobility increases due to the

Table II. **Equations expressing the relationship between electrical conductivity and temperature during the heating of the model solution at different TSSC and different pH values.**

TSSC	pH	Equation	R^2
10%	2	σ= 0.008xT + 0.174	0.999
	2.5	σ = 0.006xT + 0.104	0.999
	3	σ = 0.006xT + 0.081	0.998
	3.5	σ = 0.006xT + 0.077	0.998
20%	2	σ = 0.007xT + 0.113	0.999
	2.5	σ = 0.006xT + 0.069	0.998
	3	σ = 0.005xT + 0.054	0,997
	3.5	σ = 0.005xT + 0.053	0,996
30%	2	σ = 0.006xT + 0.051	0.998
	2.5	σ = 0.005xT + 0.029	0.996
	3	σ = 0.004xT + 0.021	0,996
	3.5	σ = 0.004xT + 0.019	0,995
40%	2	σ = 0.004xT + 0.009	0.995
	2.5	σ = 0.004xT + 0.002	0.994
	3	σ = 0.003xT + 0.000	0,993
	3.5	σ = 0.003xT + 0.001	0,993
	4	σ = 0.003xT + 0.000	0.993
50%	2	σ = 0.003xT + 0.014	0.990
	2.5	σ = 0.002xT + 0.016	0.989
	3	σ = 0.002xT + 0.016	0,987
	3.5	σ = 0.002xT + 0.015	0,988
	4	σ = 0.002xT + 0.015	0.987
60%	2	σ = 0.002xT + 0.021	0.981
	2.5	σ = 0.001xT + 0.020	0.978
	3	σ = 0.001xT + 0.020	0,979
	3.5	σ = 0.001xT + 0.021	0,977

increasing temperature value and the electrical conductivity value increase accordingly. It has been reported that molecular mobility increases due to the increasing temperature value and the electrical conductivity value increase accordingly.

The EC-Temperature relationship (Figure 2) may be fitted by a linear expression. The equations and the regression coefficients of the linear relationship obtained at different pH and TSSC values are given in Table II. It has been generally demonstrated that model constants decrease with the increase in TSSC at the same pH values. In the same way, the model constants decreased as the pH value increased with the same TSSC value. Regarding the model compatibility that the regression coefficient is over 0.97. It has been reported in many studies that the temperature-electrical conductivity relationship is linear for juices. Besides, some different equations have been reported for other fruit pulp such as apricot, peach, and papaya pulp (Icier & Ilicali 2005a, Gomathy et al. 2015).

Table III. **Equations showing the temperature-pH-electrical conductivity relationship of different TSSC values.**

TSSC	Electrical Conductivity (S/m)	R^2
%10	$\sigma=0.0066xT+pH^{-0.3258}-0.5910$	0.956
%20	$\sigma=0.0061xT+pH^{-0.4964}-0.5576$	0.986
%30	$\sigma=0.0050xT+pH^{-0.2099}-0.7796$	0.975
%40	$\sigma=0.0040xT+pH^{-0.1099}-0.8925$	0.981
%50	$\sigma=0.0029xT+pH^{-0.0458}-0.9696$	0.982
%60	$\sigma=0.0018xT+pH^{-0.024}-0.9971$	0.973

TSSC: Total soluble solid content.

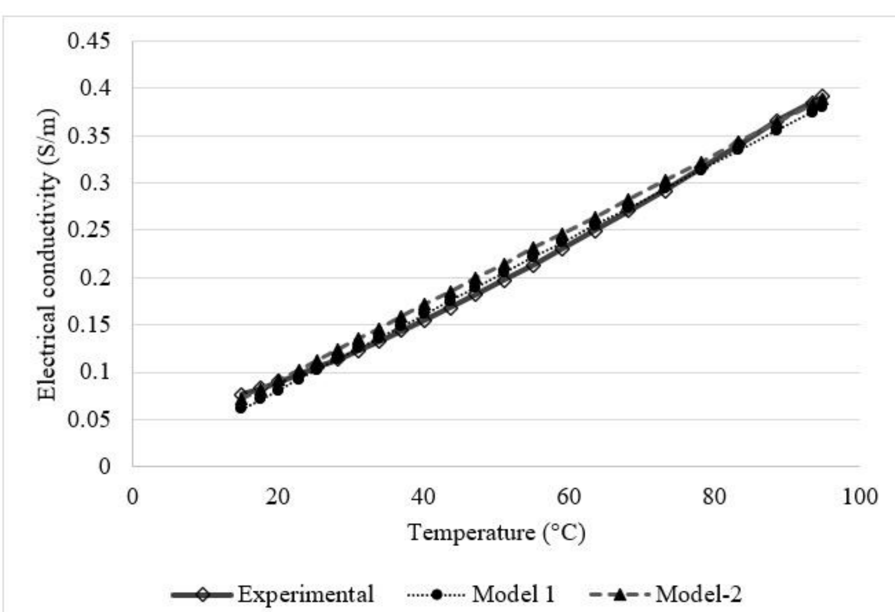

Figure 3. **Temperature change of experimental and model electrical conductivity value at 40% TSSC and pH 2.5 Model 1: EC-Temp; Model 2: EC-pH-Temp.**

Temperature-pH-Electrical Conductivity Relationship

In this study, it has been found that there is a relationship between temperature-pH-electrical conductivity. Model equations and regression coefficients belonging to different TSSC values are given in Table III. It was found that the effect of pH on the electrical conductivity is not linear and has a negative effect in contrast to the effect of temperature.

The EC value obtained for the 40% TSSC and pH 2.5 model solution heated from 15 to 95 °C by OHP and the EC values obtained from both EC-Temperature and EC-pH-Temperature models are given in Figure 3. In the literature review, no model equation expressing the electrical conductivity change due to pH value was found in model solutions for different TSSC values. Different models were tried to express the relationship between EC-Temperature-TSSC and EC-Temperature-pH-TSSC, but it was determined that the R^2 value ranged between 0.90-0.93 and it was found insufficient to express these relationships. In particular, electrical conductivity may differ depending on the content of the product. Therefore, it is recommended to examine pH changes with different sugar types.

CONCLUSION

The model solutions with different TSSC and different pH values were heated from 15 °C to 95 °C and it was determined that the increased TSSC and pH value on the total time during warming had a negative effect on the EC of the solution. The EC value increased in all heated model solutions due to the increasing temperature value. Also, since the increase in pH value decreases ion mobility, it negatively affects the EC value and the restriction of molecular mobility in the increased TSSC value. Besides, the electrical conductivity temperature relationship was found to be linear. Also, there is a relationship between EC-pH-Temp, and equations expressing this relation are acceptable over 95% of model compatibility. Especially, it is envisaged that the determination of EC-pH-Temp relationship may be data and source for model ohmic designs. However, it is recommended to determine the effect of ohmic heating in different model sugar solutions and to determine different relationships.

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Serdal Sabancı: Conceptualization, Software, Methodology, Investigation, Writing & Editting, Visualization; Kübra Kaya: Investigation, Methodology, Visualization; Ali Goksu: Software, Methodology, Investigation, Writing & Editting, Visualization.