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Evaluation of electrical conductivity of maize flour by ohmic heating

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ABSTRACT

Electrical conductivity of foods is key component in the design of an ohmic heater. Electrical conductivities of maize flour of three particle sizes (0.6 mm, 1.0 mm and 1.4 mm) at different moisture contents (40%, 35% , 30% and 25%) and applied voltage gradient (55V/cm, 45V/cm, 35V/cm and 25V/cm) were determined, the samples were heated for 90 seconds. In general maize flour at 40% moisture content was more conductive than samples prepared with 35%, 30% and 25% moisture content. The effect of applied voltage gradient was significant at all the four moisture contents. At 40% moisture content, conductivity was highest for 55V/cm and minimum for 25V/cm. The effects of applied voltage were considerable for samples with 35% and 30% moisture content but for 25% the effect was least significant. Samples with smaller particle size were more conductive than larger particle size flour at all the voltage and moisture content combinations. In all cases, electrical conductivities increased linearly with temperature till the gelatinization temperature.

Key words: Maize flour, Moisture content, Votage gradient

Ohmic heating is an advanced thermal processing method in which heat is internally generated within foods by passing an alternating electric current through them (Zhu *et al*. 2010). Most foods contain ionic species such as moisture, salts and acids, enabling the electric current to pass through the food and generate heat inside (Palaniappan and Sastry 1991). Ohmic heating is also called electrical resistance heating, Joule heating, or electro-heating. Ohmic heating can volumetrically heat the entire mass of a food system, resulting in faster heating, better quality and less energy consumption than conventional heating or processing system. Due to the faster and uniform heating minimum structural, nutritional or organoleptic changes occur in ohmically heated food (Rahman 1999). Ohmic heating includes other advantages like enhancing drying rates (Lima and Sastry 1999, Wang and Sastry 2000, Zhong and Lima 2003) and extraction yields (Lima and Sastry 1999, Wang and Sastry 2002, Halden *et al.* 1990) in certain fruits and vegetables and preparation of pre-gelatinized starches (Fernando *et al*. 2005)

Electrical conductivity, particle type, size, concentration, shape and moisture content are some of factors affecting the heating rate in ohmic system (Legrand *et al*. 2007, Marcotte 1999, McKenna *et al*. 2006, Roberts *et al*. 1998). The electrical conductivity of foods is a key parameter of ohmic heating system. The design of an effective ohmic heating system depends on the electrical conductivities of foods (Sarang *et al*. 2008).

There is evidence of the work being conducted on the electrical conductivity of liquid fruit products like juices and purees (Palaniappan and Sastry 1991, Icer and Ilicali 2005, Castro *et al*. 2004). Mitchell and de Alwis (1989) measured electrical conductivity of pear and apple at 25°C. Castro *et al.* (2003) reported electrical conductivity of fresh strawberry over a 25–100°C temperature range. Electrical properties of meat have also been investigated in recent years (Saif *et al*. 2004). But the investigation on electrical conductivity of flours is very limited.

The aim of the study was to measure the electrical conductivity of maize flour of different particle sizes at different voltages gradients and moisture contents.

MATERIALS AND METHODS

Maize var. J 1006 was procured from farms of Punjab Agricultural University, Ludhiana and maize flour was obtained by dry milling of maize with hammer mill at CIPHET, Ludhiana. Different particle sizes were obtained using sieve analyzer, MAC (Macro Scientific Works Pvt Ltd). Initial moisture content was determined by hot air oven method by AACC (2000). 50 g of flour sample was taken and moisture content was adjusted to 40%, 35%, 30% and 25% wet basis.

The heater system used consisted of a cylindrical plastic tube of 4.0 cm total length and 2.0 cm inside diameter. A thermometer opening was provided in the center of the cylindrical ohmic heating cell. Two stainless steel electrodes were placed at each end of the tube. Samples were heated

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Table 1 ANOVA table for effect of moisture content, voltage and time on electrical conductivity and temperature of maize flour (0.6, 1.0 and 1.4 mm particle size)

Source	0.6 mm particle size		1.0 mm particle size		1.4 mm particle size	
	Electrical Conductivity (F-Value)	Temperature (F-Value)	Electrical Conductivity (F-Value)	Temperature (F-Value)	Electrical Conductivity (F-Value)	Temperature (F-Value)
Moisture(M)	1.517*	6.956*	6.125*	2.90*	3.075*	5.261*
Voltage(V)	315.303*	2.520*	7.325*	5.323*	4.097*	7.316*
Time(T)	447.586*	1.893*	841.499*	2.423*	1.3053*	4.132*
M X V	1.904*	371.582*	2.208*	1.230*	2.285*	667.465*
V X T	163.201*	82.122*	127.494*	220.195*	53.500*	330.436*
M X T	49.846*	136.496*	236.049*	160.649*	216.273*	131.225*
M X V X T	383.211*	100.494*	129.199*	78.808*	39.731*	40.583*
R^2	0.998	0.996	0.998	0.997	0.997	0.997

*Significant at $P \leq 0.05$

using an alternating current source, of 50 Hz, with different voltages, i.e 100 V, 140 V, 180 V and 220 V (or voltage gradients from 25 to 55 V/cm). Temperatures were monitored using pen shape multi-stem thermometer. Voltage and current were analyzed using voltmeter and ammeter. The circuit was completed after filling the samples and fixing the electrodes in the cell.

Electrical conductivity was calculated using the formula:

$$\sigma = \frac{LI}{AV}$$

where, L, Interval between electrodes (m); I, current (Ampere); A, inner cross-sectional area of ohmic heater (m^2); V, voltage (Volts); σ, electrical conductivity (S/m).

A set of experiments was conducted to determine the effect of voltage gradient on the electrical conductivity changes during ohmic heating. The maize flour samples (with varying moisture contents, i e 40%, 35%, 30% and 25%) were heated for 90 seconds using four different voltage gradients (from 25 to 55 V/cm) with a 4 cm gap between electrodes.

Each experiment was replicated thrice. All the results were statistically analyzed to estimate the difference between moisture content and applied voltage on the basis of electrical conductivity and temperature. The analysis was done using univariate analysis of variance (uni-anova) in general linear model using SPSS $^{16.0}$ (Statistical method for social sciences). Means were computed and least square difference (LSD) was calculated at 5% of significance ($P \leq 0.05$).

RESULTS AND DISCUSSION

Table 2 describes the electrical conductivity changes of maize flour (0.6 mm particle size) with varying voltage gradient obtained at 40%, 35% 30% and 25% moisture content on wet basis respectively. The conductivity changes of maize flour at different moisture content (40%, 35% 30% and 25%) and voltage gradients (25V/cm to 55 V/cm) of maize flour with 1.2 mm and 1.4 mm particle size are shown in Table 3 and Table 4 respectively. Table 2 clearly illustrates that for 0.6 mm particle size, the maximum electrical conductivity was obtained with 40% moisture content and 55 V/cm voltage gradient, where electrical conductivity reached up to 0.1717 S/m in 30 sec and later it decreased due to gelatinization. During gelatinization, the starch swells after heating in water and forms gel. This gel type structure inhibts the passage of electric current which results in decrease in electrical conductivity. For 1.0 mm and 1.4 mm sized flour samples, the combination of 40% moisture content and 55 V/cm voltage gradient increased electrical conductivity to the maximum, i e 0.21452 S/m and 0.20717 S/m in 60 sec and 70 sec respectively (Table 3 and 4). It is evident from Table 2 to Table 4, that the electrical conductivity increases with the temperature and decreases with starch gelatinization. The results of the present study are in agreement with the previous findings of Wang and Sastry (1997) who stated that increase in electrical conductivity is attributed to the structural changes and decrease is due to an increase in bound water due to gelatinization. Results clearly show that in all the particle sizes and moisture contents, the electrical conductivity increases with the increase in applied voltage. The presence of moisture in product has a critical importance to obtain an efficient heating process as an increase in water molecules resulted in proportional increase in ion solvation and thus higher ionic mobility and higher flow of electric current (Dhingra *et al.* 2012). The voltage gradient application results in increasing fluid motion through the capillaries, which is directly proportional to electrical conductivity (Halden *et al.* 1990). The heating process causes membrane destruction and consequently the free water content increases (Bean *et al.* 1960, Halden *et al.*1990, Sasson and Monselise 1977). Whereas the decrease in electrical conductivity in later stages, with higher moisture content and greater applied voltage, may be attributed to the presence of starch which change their properties (namely, the viscosity) during heating, therefore increasing the drag forces of the medium, reducing the mobility of the fluid and of the ionic components present (Castro *et al.* 2003).

Table 2 also represents the temperature rise during ohmic heating of maize flour (0.6 mm) at 40%, 35%, 30%

Table 2 Electrical conductivity and temperature variation of maize (0.6 mm particle size) at different moisture contents (25%, 30%, 35%, 40%) and voltage gradients (25V/cm, 35 V/cm, 40 V/cm, 55 V/cm)

Voltage gradient (V/cm)	Time(S)	Moisture content (%) 25		30		35		40	
	Time(S)	EC(S/m)	Temp(°C)	EC(S/m)	Temp(°C)	EC(S/m)	Temp(°C)	EC(S/m)	Temp(°C)
25	10	0.005091	27.9	0.02551	27	0.032272	35.7	0.062929	30.7
	20	0.005091	27.9	0.029013	28.1	0.033546	36.5	0.074596	36.5
	30	0.005091	27.9	0.036019	29.8	0.03482	37.2	0.091566	43.0
	40	0.005091	27.9	0.039523	30.2	0.036093	37.9	0.108535	49.5
	50	0.005091	27.9	0.043026	31.6	0.036093	38.6	0.138232	54.2
	60	0.005091	27.9	0.050032	34.8	0.037367	39.2	0.15202	58.7
	70	0.005091	27.9	0.055287	38.5	0.038641	40.0	0.162626	62.5
	80	0.005091	27.9	0.05879	41.2	0.038641	40.8	0.177475	66.3
	90	0.005091	27.9	0.064045	43.3	0.039915	41.7	0.18596	69.9
35	10	0.003636	28.1	0.03303	27.5	0.05303	32.1	0.085836	39.5
	20	0.003636	28.1	0.037576	29.6	0.064061	33.3	0.098574	43.2
	30	0.003636	28.1	0.041818	31.8	0.063212	34.5	0.104034	46.6
	40	0.003636	28.1	0.044545	33.9	0.076364	36.5	0.113133	50.3
	50	0.003636	28.1	0.048788	36.9	0.074667	38.4	0.123142	54.8
	60	0.003636	28.1	0.052727	39.8	0.078485	39.5	0.134061	60.5
	70	0.003636	28.1	0.056061	42.9	0.092909	41.4	0.14498	65.1
	80	0.003636	28.1	0.063636	44.4	0.092485	43.1	0.154079	70.2
	90	0.003636	28.1	0.067273	46.9	0.103939	45.8	0.163179	75.2
45	10	0.008013	30.8	0.038653	27.3	0.042935	30.3	0.08037	31.0
	20	0.009192	32.5	0.041481	30.6	0.047181	36.3	0.090976	35.6
	30	0.010135	33.1	0.041246	33.2	0.052135	44.6	0.106296	43.8
	40	0.011077	33.7	0.048552	35.5	0.057089	52.4	0.124209	50.4
	50	0.011549	34.3	0.050673	38.9	0.062043	57.7	0.145421	59.5
	60	0.012727	35.0	0.05633	42.2	0.069828	63.5	0.166397	68.8
	70	0.012963	35.9	0.058451	45.9	0.072659	67.1	0.180067	78.7
	80	0.01367	36.6	0.061279	49.0	0.077613	71.6	0.154848	90.9
	90	0.014377	37.5	0.061751	53.1	0.08469	77.1	0.1433	94.2
55	10	0.006271	27.8	0.042055	28.7	0.064928	27.8	0.129604	47.2
	20	0.006456	29.0	0.044822	32.1	0.067694	31.83	0.162836	59.7
	30	0.007563	30.2	0.048696	35.1	0.074335	38.3	0.171698	76.1
	40	0.008116	31.2	0.052569	38.9	0.077655	45.6	0.111327	88.9
	50	0.008854	31.8	0.055889	44.7	0.092042	54.5	0.068679	89.8
	60	0.009223	33.5	0.059763	48.7	0.11307	65.1	0.049294	88.1
	70	0.009592	34.9	0.06419	55.4	0.123584	76.8	0.031016	86.8
	80	0.010329	35.8	0.069723	63	0.128564	89.4	0.012739	82.8
	90	0.011067	37.2	0.073043	66	0.136311	93.5	0.006092	79.2

Table 3 Electrical conductivity and temperature variation of maize (1 mm particle size) at different moisture contents (25%, 30%, 35%, 40%) and voltage gradients (25V/cm, 35 V/cm, 40 V/cm, 55 V/cm)

Voltage gradient (V/cm)	Time(S)	Moisture content (%) 25		30		35		40	
		EC(S/m)	Temp(°C)	EC(S/m)	Temp(°C)	EC(S/m)	Temp(°C)	EC(S/m)	Temp(°C)
25	10	0.005091	27.7	0.023333	32.9	0.028424	26.8	0.049212	29.1
	20	0.005091	27.7	0.024606	35.2	0.03097	29.1	0.056848	30.6
	30	0.005091	27.7	0.028424	38.8	0.032667	30.8	0.060667	33.4
	40	0.005091	27.7	0.03097	41.3	0.034788	31.7	0.06703	36.8
	50	0.005091	27.7	0.033515	43.7	0.037333	32.2	0.070848	40.1
	60	0.005091	27.7	0.036061	45.8	0.040303	33.2	0.08103	44.8
	70	0.005091	27.7	0.038606	48.3	0.041576	34.7	0.088667	48.7

Contd.

Table 3 *Contd.*

Voltage gradient (V/cm)	Time(S)	Moisture content (%)							
		25		30		35		40	
		EC(S/m)	Temp(°C)	EC(S/m)	Temp(°C)	EC(S/m)	Temp(°C)	EC(S/m)	Temp(°C)
	80	0.005091	27.7	0.039879	49.7	0.044121	35.9	0.100121	52.1
	90	0.005091	27.7	0.042424	51.6	0.045394	36.7	0.112848	56.4
35	10	0.003636	28.4	0.02697	35.2	0.040303	28.8	0.091212	30
	20	0.003636	28.4	0.029394	36.7	0.042848	32.5	0.101111	32.2
	30	0.003636	28.4	0.031515	38.3	0.045394	35.9	0.110657	35.9
	40	0.003636	28.4	0.032424	40.4	0.049212	39	0.121263	40.3
	50	0.003636	28.4	0.034545	43	0.05303	42.3	0.136111	45.7
	60	0.003636	28.4	0.036667	45.2	0.056848	47.6	0.144596	49.7
	70	0.003636	28.4	0.038182	47.3	0.059394	49.7	0.15803	55.4
	80	0.003636	28.4	0.039091	48.7	0.061939	52.8	0.172172	61.5
	90	0.003636	28.4	0.040606	49.9	0.065758	54.3	0.18101	66.7
45	10	0.002828	27.9	0.028283	33.4	0.045017	30.0	0.10229	31.5
	20	0.002828	27.9	0.030168	35.3	0.047138	34.1	0.120909	37.2
	30	0.002828	27.9	0.031818	37.7	0.048552	39.8	0.153434	44.7
	40	0.002828	27.9	0.032997	41.5	0.05138	45.1	0.180539	54.8
	50	0.002828	27.9	0.034646	45.3	0.054209	50.7	0.203401	63.4
	60	0.002828	27.9	0.036532	47.1	0.05633	55.2	0.197273	78.6
	70	0.002828	27.9	0.038418	50.4	0.059158	60.7	0.180303	86.3
	80	0.002828	27.9	0.041717	55.0	0.061279	64.5	0.17064	92.6
	90	0.002828	27.9	0.04596	61.1	0.063401	69.4	0.148249	98.8
55	10	0.006825	24.6	0.039473	31.8	0.044453	32.1	0.123973	33.9
	20	0.007378	25.7	0.042793	33.9	0.051462	37.0	0.141414	47.4
	30	0.007931	28.6	0.04722	36.7	0.06419	47.6	0.15697	58.4
	40	0.008116	30.2	0.05054	40	0.082266	60.0	0.179596	68.3
	50	0.008485	31.0	0.053307	44	0.089091	70.3	0.214242	90.2
	60	0.009038	31.7	0.054967	47.4	0.094809	80.4	0.19303	100.2
	70	0.009223	33.3	0.058287	51.2	0.100527	93.8	0.164747	94.3
	80	0.009776	34.2	0.060501	55.5	0.092042	100.0	0.136465	90.5
	90	0.010145	34.6	0.062714	60.3	0.085586	98.5	0.122323	77.9

and 25% moisture content, whereas the heating rates of maize flour 1.0 mm and 1.4 mm are depicted in Table 3 and Table 4 respectively. Analyzing the above mentioned data, for 0.6 mm particle sized flour at 40% MC, it is evident that heating rates are maximum in samples ohmically heated with 55V/cm where it took 50 sec to reach temperature up to 90°C, whereas with 45V/cm, 35V/cm and 25V/cm in 50 sec temperatures reached up to 60°C, 55°C and 54°C. Similarly for 35% and 30% moisture contents heating was fastest for samples heated with 55V/cm applied voltage and slowest for 25V/cm applied voltage. For 1.0 mm and 1.4 mm sized flour at all the ranges of moisture content (40%, 35% and 30%), fastest heating was attained with 55V/cm and minimum with 25V/cm. The statistical analysis support the fact that the electrical conductivity and temperature were significantly ($P \leq 0.05$) affected by the moisture content, voltage and time of treatment, the effect of interaction term was significantly higher. Table 1 shows that R^2 value in all the experiments ranged from 0.996 to 0.998, which justifies the fact that the regression line approximates the real data points and electrical conductivity and temperature are significantly related to voltage gradient and moisture content.

It was concluded from the experiment that during ohmic heating the relationship between the electrical conductivity and temperature of flour was linear before and after starch gelatinization. In all the moisture content (25%, 30%, 35% and 40%) and applied voltage gradients (25V/cm, 35 V/cm, 45V/cm and 55 V/cm), electrical conductivity increased with temperature and decreased as the gelatinization starts. Thus change in electrical conductivity helps in determining starch gelatinization temperature. For all the four moisture content, the applied voltage or voltage gradient directly affect the electrical conductivity. The applied voltage directly affects electrical conductivities and temperature of the maize flours of all three particles (0.6 mm, 1.0 mm and 1.4 mm). The electrical conductivity and temperature of smallest particle size flour samples (0.6mm) were more considerably affected by applied voltage and moisture content than samples with 1.0 mm and 1.4 mm particle size. Fastest heating and change in electrical conductivity was obtained using 55 V/cm and 40% moisture content, which results in

Table 4 Electrical conductivity and temperature variation of maize (1.4 mm particle size) at different moisture contents (25%, 30%, 35% , 40%) and voltage gradients (25V/cm, 35 V/cm, 40 V/cm, 55 V/cm)

Voltage gradient (V/cm)	Time(S)	Moisture content (%)							
		25		30		35		40	
		EC(S/m)	Temp(°C)	EC(S/m)	Temp(°C)	EC(S/m)	Temp(°C)	EC(S/m)	Temp(°C)
25	10	0.005091	27.1	0.027929	28.1	0.041152	26.3	0.046667	32.0
	20	0.005091	27.1	0.02899	29.7	0.046242	28.0	0.050485	33.4
	30	0.005091	27.1	0.030758	30.9	0.050061	30.7	0.054303	35.3
	40	0.005091	27.1	0.031818	32.1	0.053879	33.1	0.060667	36.9
	50	0.005091	27.1	0.032879	33.5	0.057697	34.7	0.065758	38.0
	60	0.005091	27.1	0.033232	34.6	0.061515	36.2	0.069576	39.3
	70	0.005091	27.1	0.034293	36.2	0.065333	38.4	0.078485	41.3
	80	0.005091	27.1	0.035	37.6	0.070424	40.1	0.086121	43.1
	90	0.005091	27.1	0.035707	38.8	0.074242	42.2	0.093758	45.3
35	10	0.003636	27.9	0.029697	28.1	0.045394	25.7	0.073535	30.5
	20	0.003636	27.9	0.031818	29.9	0.049212	26.9	0.078838	34.1
	30	0.003636	27.9	0.034242	32.9	0.054303	29.6	0.084848	38.1
	40	0.003636	27.9	0.03697	36.2	0.059394	32	0.092273	42.6
	50	0.003636	27.9	0.039394	38.4	0.063212	35.6	0.096869	44.8
	60	0.003636	27.9	0.041515	41.3	0.068303	38.5	0.101818	48.1
	70	0.003636	27.9	0.045152	44.4	0.072121	41.3	0.108535	51.8
	80	0.003636	27.9	0.04697	48.7	0.077212	44.5	0.114192	58.6
	90	0.003636	27.9	0.049697	51.3	0.08103	48.7	0.120202	59.3
45	10	0.002828	27.7	0.032054	26.8	0.047845	29.3	0.076364	30.1
	20	0.002828	27.7	0.033704	29.5	0.049966	33.3	0.086498	34.1
	30	0.002828	27.7	0.037475	31.6	0.052088	37.7	0.096633	40.4
	40	0.002828	27.7	0.040303	34.3	0.054916	42.4	0.115017	49.0
	50	0.002828	27.7	0.043131	36.4	0.057037	46.7	0.129394	55.5
	60	0.002828	27.7	0.04596	40.3	0.059865	50.5	0.139057	63.4
	70	0.002828	27.7	0.048316	44.4	0.063401	54.1	0.150606	73.4
	80	0.002828	27.7	0.050909	47.3	0.066936	59.3	0.1367	81.3
	90	0.002828	27.7	0.053737	50.9	0.074007	63.3	0.130808	90.4
55	10	0.002121	28.2	0.034493	28.8	0.051831	30.2	0.09404	31.7
	20	0.002121	28.2	0.036153	32.5	0.053491	35.1	0.116667	43.2
	30	0.002121	28.2	0.040026	36.7	0.055705	40.4	0.136465	54.8
	40	0.002121	28.2	0.045007	41.1	0.058472	46.6	0.151313	63.5
	50	0.002121	28.2	0.051094	46.7	0.061792	53.9	0.167576	74.4
	60	0.002121	28.2	0.056627	51.8	0.065112	60.7	0.190909	86.0
	70	0.002121	28.2	0.063267	57.7	0.068986	68	0.207172	94.3
	80	0.002121	28.2	0.049433	63.3	0.073412	74.8	0.183838	101.0
	90	0.002121	28.2	0.045007	69.7	0.077839	77.6	0.149899	92.0

enery saving. Statistically, the variation in electrical conductivity and temperature with change in voltage and moisture content, was significant, for all three particle sizes (0.6 mm, 1.0 mm and 1.4 mm)

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