Modeling the Dielectric Properties of Ham as a Function of Temperature and Composition

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ABSTRACT: The dielectric properties of 19 different ham samples with different moisture (38.2% to 68.9%) and ash contents (1.78% to 6.80%) were measured at –35 to 70 °C at 2450MHz. Equations were developed as a function of temperature, moisture, and ash, and compared to literature equations. The dielectric constant decreased with ash content and increased with moisture content. It increased instead of decreasing with temperature. The dielectric loss factor increased with moisture content for moisture contents lower than 60.7%, then decreased for higher moisture contents. Ash content and temperature increased dielectric loss factor. Frozen samples had low dielectric activity that was increased by ash content above –20 to –10 °C.

Keywords: ham, meat, muscle foods, dielectric properties, dielectric constant, loss factor

Introduction

HAM IS A POPULAR MEAT PRODUCT THAT CAN BE THAWED, REHEATed, or pasteurized using microwaves. During microwave heating, the heating rate and temperature distribution within the ham are initially determined by the dielectric properties. Dielectric properties are a measure of how food interacts with electromagnetic energy during microwave processing. Complex relative permittivity is defined as $k^* = k' - jk''$, where the real part is the dielectric constant, and the imaginary part is the dielectric loss factor. The dielectric constant k' is a measure of the ability of the material to store electromagnetic energy. The loss factor k'' affects the ability of the food to dissipate electromagnetic energy into heat (Mudgett 1995). These 2 parameters are important in determining power absorption and penetration depth during microwave heating, which determine the temperature profile within the sample as it heats. The dielectric properties are strongly affected by the moisture, ash content, and temperature. Therefore, the dielectric properties of ham need to be known as a function of the composition and temperature to accurately predict the heating pattern in the microwave oven.

Dielectric constant and dielectric loss factor of ham are known to increase with temperature (Bengtsson and Risman 1971; Ohlsson and Bengtsson 1975). However, these studies did not test samples with a wide range of ash or moisture contents to develop equations to predict the effect of composition on the dielectric properties of ham. Therefore, the results can only be useful for samples with the same composition.

Several studies developed prediction equations for categories of food items. Calay and others (1995) developed equations predicting dielectric properties as a function of salt, moisture, fat content, density, temperature, and frequency for different food groups. Sun and others (1995) created equations for meats as a function of temperature, ash, and moisture content. Since ham contains more salt than most meats, it is unknown how accurately equations derived for meat will predict the dielectric properties of ham as a function of composition.

The effect of composition on the dielectric properties is complex. For example, the dielectric constant increases with moisture content for most foods (Calay and others 1995; Sun and others 1995; To and others 1974). However, studies report different trends for the dielectric loss factor. It has been reported to increase (Bircan and Barringer 1998; Nelson 1978; Nelson 1973; Van Dyke and others 1969; To and others 1974), be constant (Padua 1993; Roebuck and others 1972) or peak at a certain moisture content (Padua 1993; Roebuck and others 1972; Tulasidas and others 1995; Funebo and Ohlsson 1999; Mudgett and others 1980). The dielectric properties of ham need to be measured to be certain of the effect of composition and temperature on these values.

The dielectric properties of many foods have been reported for a range of temperatures and frequencies including meats (To and others 1974; Bengtsson and Risman 1971; Van Dyke and others 1969), fruits and vegetables (Nelson and others 1994; Funebo and Ohlsson 1999), grains (Nelson 1981, 1987), and dairy products (Green 1997; Rzepecka and Pereira 1974). However, data measured at frozen temperatures are scarce. It is known that moisture contents different by as little as 5% affect the dielectric properties of frozen meat, and that the ash content is likely to be important as well (Mudgett and others 1979; Bengtsson and others 1963).

The objective of this study is to determine the effect of moisture and ash content on dielectric properties of ham at -35 to 70 °C. Equations were generated to predict the dielectric constant and dielectric loss factor as a function of temperature (0 to 70 °C), moisture, and ash content at 2450 MHz.

Materials and Methods

NINETEEN HAM SAMPLES WERE PREPARED BY THE COMBAT Feeding Program (Natick, Mass., U.S.A.) at different moisture (38.2% to 68.9%) and ash contents (1.78% to 6.80%) (Table 1). They were prepared by 1st trimming all outside fat to expose the lean. The semimembranosus, semitendinosus, and biceps femoris were separated in order to remove intermuscular (seam) fat. The 3 muscles were chunked by mechanically grinding once through a plate with 64-mm openings using a 2 bladed knife. The chunked pork pieces were then placed in a vacuum tumbler (66 cm-Hg) with brine of the desired salt content and tumbled for 12 min. The tumbled meat was placed in plastic bags and allowed to rest for 16 h. The pork was placed into perforated collagen casings (64 mm in dia), and then cooked until a temperature probe recorded an internal temperature of 69 °C. The cooking was done at 82 °C in a conventional oven (Hobart Corp., Troy, Ohio, U.S.A.) above a water bath to maintain higher relative humidity in the oven. The process was assisted by frequent spraying with water during heating. When the desired internal temperature was reached the samples were held under a cold shower until the internal meat temperature was 16 °C.

Hams at lower moisture contents were prepared by slicing the ham, then partially drying the slices in a microwave freeze dryer that was converted from a conventional freeze dryer. Ham samples were freeze-dried in a Cober Electronics Model SF-3 Industrial Microwave Generator set at 600W, using a pressure of 0.1-mm Hg and a platen temperature of 45 °C. Moisture and ash content were determined by vacuum oven (National Appliance Co., Skokie, Ill., U.S.A.), using 16 h at 70 °C, 1-mm Hg vacuum pressure, and dry ashing at 550 °C in a muffle oven (Thermolyne, Dubuque, Iowa, U.S.A.) overnight (AOAC 1995). The samples were frozen and shipped overnight to Ohio State Univ. for the measurement of dielectric properties.

The dielectric constant and loss factor were measured using an open ended coaxial probe and a network analyzer (85070B and 8752C; Hewlett-Packard, Palo Alto, Calif., U.S.A.) interfaced with a computer. The probe lies facing upwards inside a cylindrical jacketed stainless steel sample holder, which is connected to an oil bath (RTE 140, Neslab Co., Newington, N.H., U.S.A.) that adjusts the temperature of the sample (Figure 1). The sample holder was placed between 2 steel plates and sealed using bolts. O-rings were placed between the sample holder and the plates to prevent moisture loss. A temperature probe connected to a temperature acquisition unit (HP 34970A; Hewlett-Packard) was fit permanently into the upper plate and reaches into the center of the sample. The sample holder was sealed to prevent any moisture loss as steam.

The sample (a cylinder 3 cm in height × 2.5 cm in dia) bored from the ham was initially cooled to the measurement temperature by the jacketed sample holder (for instance, 35 °C). The 1st measurement was made when the temperature reading was stable. The oil bath was then increased to 5 °C above the next temperature of measurement. When the sample reached the desired temperature, the dielectric properties were measured, and the oil temperature was increased another 5 °C. This continued until the final measurement temperature was reached (for instance, 70 °C). Thus, the temperature gradient in the sample is from the stated temperature to 5 °C warmer. Temperature range and intervals changed from sample to sample and are presented in Table 1. All reported measurements are at 2450MHz. Sixty-five percent of the data were collected in duplicates, the rest of it being in triplicates or more.

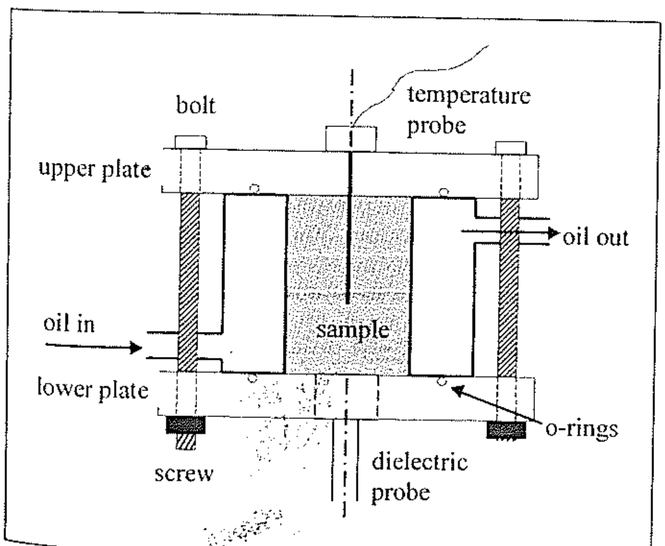

Figure 1—Sectional view of stainless steel sample holder for open-ended coaxial probe dielectric properties measurements

Table 1—The moisture, ash content (wet basis), and temperature of measurements of ham samples

% Moisture	% Ash	Temperature range (°C)	Temperature intervals (°C)
68.9	4.17	–35 to 70	10
68.6	2.17	–35 to 70	10
68.0	6.07	0 to 70	5
68.0	3.21	0 to 70	5
68.0	1.78	0 to 70	5
67.0	1.82	–35 to 70	10
66.4	3.30	0 to 70	5
65.3	2.87	0 to 70	5
63.9	6.80	0 to 65	5
63.4	2.15	0 to 70	5
62.9	4.90	0 to 70	5
59.0	3.21	0 to 70	10
55.0	4.65	0 to 65	5
52.0	2.83	0 to 70	5
48.7	1.78	0 to 70	5
45.0	4.64	0 to 70	5
43.0	1.78	0 to 70	5
41.4	3.21	0 to 70	5
38.2	2.83	0 to 70	5

Calibration was performed using a short, air, and water before every test. The sample holder was stabilized so that the probe could not be moved after calibration. The dielectric constant and loss factor were calculated from the phase shift and the magnitude of the reflected signal by the software.

The response variables, dielectric constant, and loss factor, were fit by using multiple regression from combinations of temperature, moisture content, and wet basis ash. The fitting principle was least squares, which is the most appropriate method to employ when the data are expected to exhibit significant random errors (Calay and others 1995). The models and all predictors included in the models had a significance of < 0.001. Quality of fit was assessed from adjusted coefficient of determination (R^2_{adj}) of the equation. A total of 599 data points were used to create the equations. The data were analyzed using JMPin software (SAS Inst. Inc., Cary, N.C., U.S.A.).

Results and Discussion

Dielectric constant

Increasing moisture increased the dielectric constant of ham samples (Figure 2, Eq. 1):

$$\kappa' = -25.49 + 1.063 \cdot M - 1.041 \cdot A + 0.03452 \cdot T \quad (T = 0 \text{ to } 70\ ^\circ C) \quad R^2_{adj}=0.817 \qquad (1)$$

where M is percentage of moisture, A is percentage ash, and T is temperature in °C. Water is a dipolar compound that couples electromagnetic energy at microwave frequencies more efficiently than most other components of foods; therefore, increasing moisture should increase the dielectric constant (Ryynanen 1995). Dielectric constant of both pork and ham increases with moisture content (Bengtsson and Risman 1971). Most other foods behave the same way, except low moisture foods (< 10%) for which the dielectric constant does not change much due to low dielectric activity (Mudgett and others 1980).

There is a large increase in dielectric constant values between approximately 48% and 55% moisture. Outside this range, the dielectric constant increases an average of 0.7% moisture. In this range, the increase is 2% moisture. For potato starch, a large increase in dielectric constant is seen from 20% to 40% moisture (Roebuck and others 1972, Nelson and others 1991), while for reconstituted beef it is from 20% to 45% moisture (Van Dyke and others 1969). This is likely due to an increase in the amount of free water or transition from multilayer to free water. High moisture samples contain a higher ratio of free water to bound water (Karel 1975). Free water is more dielectrically active than bound water at microwave frequencies (De Loor and Meijboom 1966).

Increasing ash content decreased the dielectric constant (Eq. 1) by binding water and restricting its freedom to rotate in response to the changing field polarity (Hasted and others 1948). Salting a product reduces the free water content and depresses the dielectric constant (Calay and others 1995). This decrease can be seen by comparing 2 samples with the same moisture content, 68.0%, but different ash contents (Figure 2). However, most samples are different in both moisture and ash content. When both change, the moisture content is the dominant effect.

Increasing temperature (-35 to 70 °C) increased the dielectric constant (Figure 2, Eq. 1). This is in disagreement with most of the literature for food samples, which indicates that dielectric constant decreases with temperature (Bircan and Barringer 2002; Ohlsson and others 1974; Ohlsson and Bengtsson 1975). However, these studies measured samples with high amounts of free water. As the ratio of bound water to free water increases, the response of dielectric constant to temperature reverses (Calay and others 1995). For example, the dielectric constant of whey protein solutions decreases with temperature for samples with 30% to 40% whey protein concentrate; however, as the concentration of whey protein increases to 50% to 60%, the dielectric constant does not change with temperature (Barringer and others 1995). Other researchers measured ham, finding its dielectric constant increases with temperature (Ohlsson and Bengtsson 1975; Bengtsson and Risman 1971). Other systems where the dielectric constant increases with temperature include: milk and whey powders (Rzepecka and Pereira 1974), potato starch and carboxymethycellulose powder (Nelson and others 1991), and yellow-dent field corn (10.5% to 18.9% moisture) (Nelson 1994). The common feature of these systems where the dielectric constant increases with temperature is that water is bound strongly, whether by salt and meat proteins for the ham or by the carbohydrate matrix for the powders and corn.

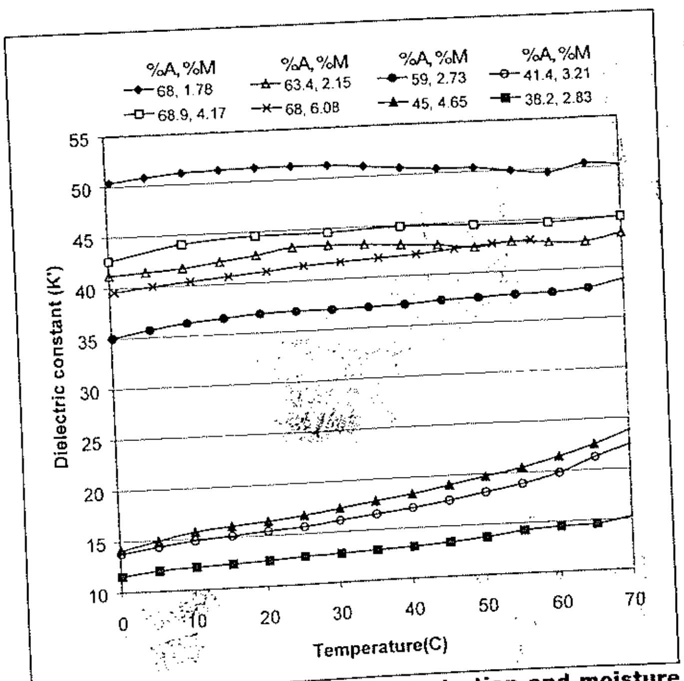

Figure 2—The effect of ash concentration and moisture on dielectric constant of ham samples at 2450MHz

In this study, we observed the beginnings of a reversal in temperature response. The dielectric constant of samples with low moisture and high ash contents (for example, 45.0% moisture, 4.65% ash) increased with temperature (Figure 2). These samples contained more bound water than samples with high moisture and low salt. The samples with more free water (for example, 68.1% moisture, 1.78% ash) did not change with temperature. Based on these trends, if the moisture content were increased further, the dielectric constant should decrease with temperature.

Our data were fit into literature equations to see how closely they predicted dielectric properties of ham (Figure 3). In general, Sun and others (1995) predicted the dielectric constant of ham higher than measured. They predicted that dielectric constant would decrease with temperature even with samples that have low moisture and high ash content, that is, water is strongly bound. This may be because the data that they used to produce their equations include meat juice in addition to data obtained measuring meat. Water is not bound strongly in meat juice. Average error of prediction was 181.3%. The predictions by Calay and others (1995) were more successful in predicting all samples, especially those with high moisture and low salt content. However, they still did not reflect the increasing trend of dielectric constant with temperature for the low moisture, high ash samples. The average error was 34.4%. The average error of prediction for Eq. 1 was 16.3%.

Dielectric loss factor

Increasing moisture content increased the dielectric loss factor of ham for moisture contents under 60.7%, while above this moisture content the dielectric loss factor decreased with moisture content (Eq. 2):

$$\kappa'' = -150.2 + 5.243 \cdot M + 6.220 \cdot A - 0.2845 \cdot T - 0.04322 \cdot M^2 - 0.4732 \cdot A^2 + 0.002245 \cdot T^2 + 0.1090 \cdot A \cdot T \quad (T = 0 \text{ to } 70\,°C) \quad R^2_{adj} = 0.852 \tag{2}$$

The moisture-dielectric loss factor relationship of food samples is complex. If ash is present with abundant free water, increasing moisture increases dielectric loss factor (Bircan and Barringer 1998; Nelson 1978; Nelson 1973; Van Dyke and others 1969; To and others 1974). This is because as the amount of moisture increases, bound salts are ionized and ions can migrate more easily with the changing electromagnetic field direction (Mudgett and others 1980).

In samples that contain no ash but abundant free water, the dielectric loss factor either stays constant or decreases with moisture content. For example, the dielectric loss factor of starch suspensions decreases with moisture (Padua 1993; Roebuck and others 1972). This occurs because these samples do not contain ions that would take advantage of the presence of more water as the moisture increases. In addition, dielectric loss factor is composed of 2 components: dipole loss and ionic loss. Dipole loss is from the motion of the water dipoles. Ionic loss is from migration of ions. In ash-free samples, the only contributor to the dielectric loss factor is the dipole loss component. The dipole loss decreases with temperature, while the ionic loss component increases with temperature.

If the water is mostly bound, either with or without ash, the dielectric loss factor 1st increases with the moisture content and then decreases, as in sucrose solutions (Padua 1993), glycerol and ethanol solutions (Roebuck and others 1972), dried grapes and sugar solutions (Tulasidas and others 1995), dried fruits and vegetables (Funebo and Ohlsson 1999), and dehydrated potatoes (Mudgett and others 1980). At low moisture, water and salts are tightly bound, resulting in low dielectric activity. As the moisture content increases, the dielectric loss factor increases rapidly with the moisture content due to increased ionization of bound ions by the free water. However, further availability of water dilutes dissolved salts and decreases the dielectric loss factor (Mudgett and others 1980). Since samples with no ash, such as carbohydrate solutions, also show this behavior there must be more to this explanation. It was theorized that water binding stabilizes the hydrogen-bonded structure of the water (Padua 1993). The stabilized structure more effectively dissipates electromagnetic energy than pure water. However, as the concentration of water binders increases, they associate with water molecules by making more than one hydrogen bond that hinders rotational freedom, decreasing the dielectric loss factor. Based on the dielectric constant, ham behaves as if the water is mostly bound. For the dielectric loss factor, our samples also fall into this category, and the loss factor increases then decreases with moisture content.

Ash increased the dielectric loss factor of ham (Figure 4, Eq 2). The ionic component of the dielectric loss factor increases as the concentration of disassociated ions increases (Mudgett 1995), thus this was expected. Dielectric loss factor also increased with temperature (Figure 4, Eq. 2). Dielectric loss factor of samples with higher ash increased more with temperature in general (Figure 4). The more dissolved ions, the greater the ionic loss component of the dielectric loss factor, and the greater the increase since the ionic loss increases with temperature (Mudgett 1995).

The loss factor was predicted with an average error of 22.5%. Literature indicates that it is more difficult to predict loss factor than dielectric constant (Sun and others 1995, Calay and others 1995). The data for dielectric loss factor were compared to equations in the literature. Equations by Sun and others (1995) produced very high dielectric loss values for high moisture, low ash samples, and negative results for low-moisture and high ash samples (Figure 3). The average error of prediction was 334%. These negative values were

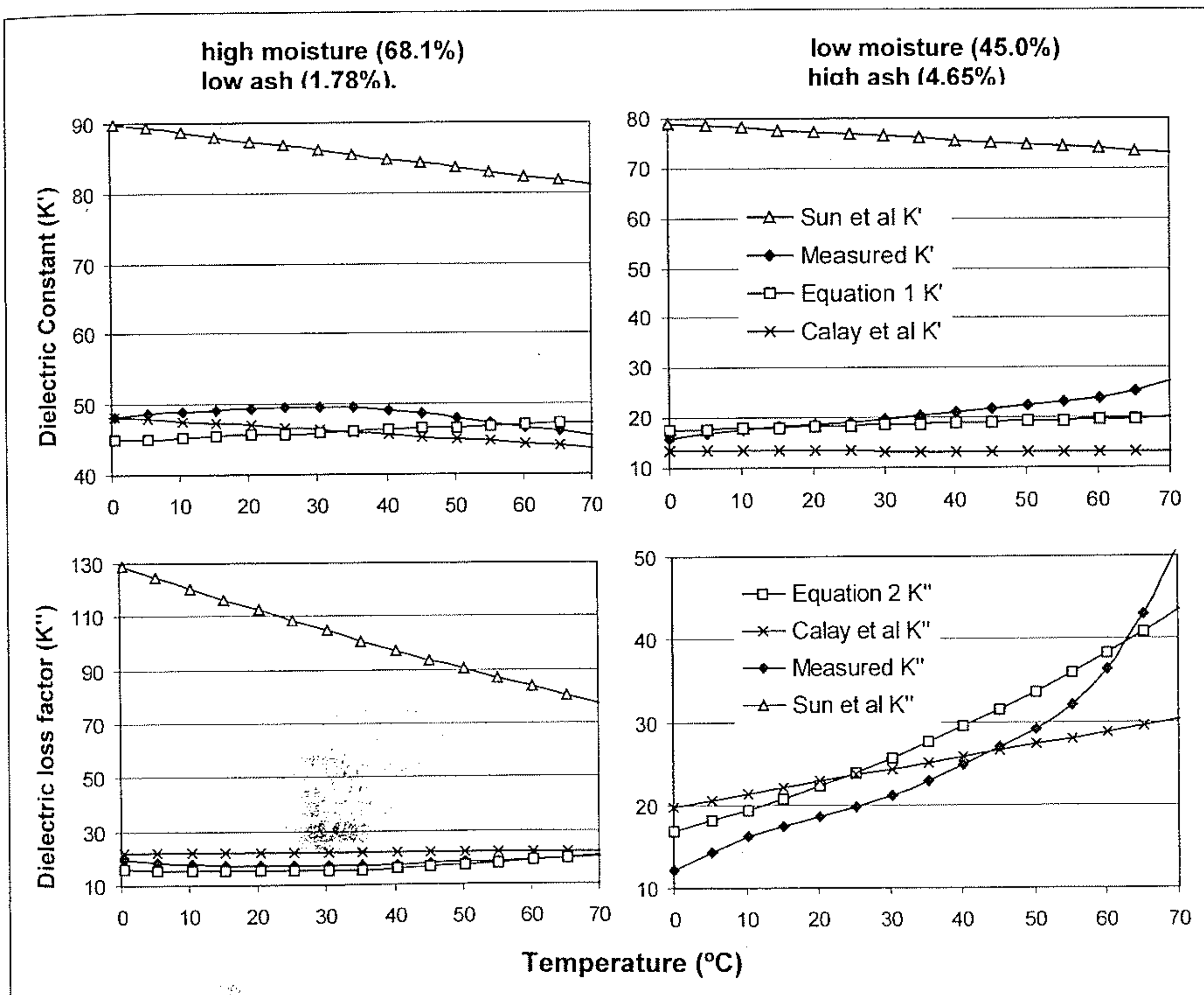

Figure 3—Comparison of measured to predicted values of the dielectric properties for ham using literature equations at 2450MHz. The x-axis is Temperature, while the y-axis is dielectric constant (top 2 graphs) or dielectric loss factor (bottom two graphs). The moisture and ash content are given above the pair of graphs.

not included in the figure since they are physically impossible. Equations of Calay and others (1995) predicted our data with an average error of 38.2%. Their predictions were higher than the measured values for high moisture, low ash samples and did not increases enough for the low moisture, high ash samples.

Dielectric properties at subzero temperatures

The dielectric properties of ham were very low up until melting started at –20 to –10 °C (Figure 5). Dielectric constant was 4 to 5, and dielectric loss factor was around 0.5. These are very close to the dielectric properties of frozen beef, pork, and chicken (Mudgett and others 1979). This temperature range was not included in regression equations because ash and moisture content had very little effect on dielectric constant and dielectric loss factor, except to determine the melting temperature. The sample with the highest ash (4.17%) melted at a lower temperature than the other samples. A difference in moisture content, on the order of 5%, is known to affect the dielectric properties of frozen samples (Bengtsson and others 1963). The differences between the moisture contents of our frozen samples were smaller than 5%. Therefore, this was not observed with our samples. The ash contents covered a wide range, 1.82% to 4.17%, but no effect was seen on the dielectric properties until melting occurred.

Conclusions

Dielectric constant of ham increased with moisture and temperature and decreased with ash content. Increase of dielectric constant with temperature was a result of high amounts of bound water.

Dielectric loss factor increased with temperature and ash content. It increased with moisture content for moisture contents lower than 60.7%, and decreased for moisture content above 60.7%. The increase was caused by increased mobility of ions due to increased moisture content, and the decrease was caused by dilution of ions due to further addition of water. Equations were developed to predict the dielectric properties as a function of temperature and composition, and the results compared to equations in literature.

The dielectric properties of frozen ham are very low. Ash content affects dielectric properties of frozen ham by decreasing the melting temperature.

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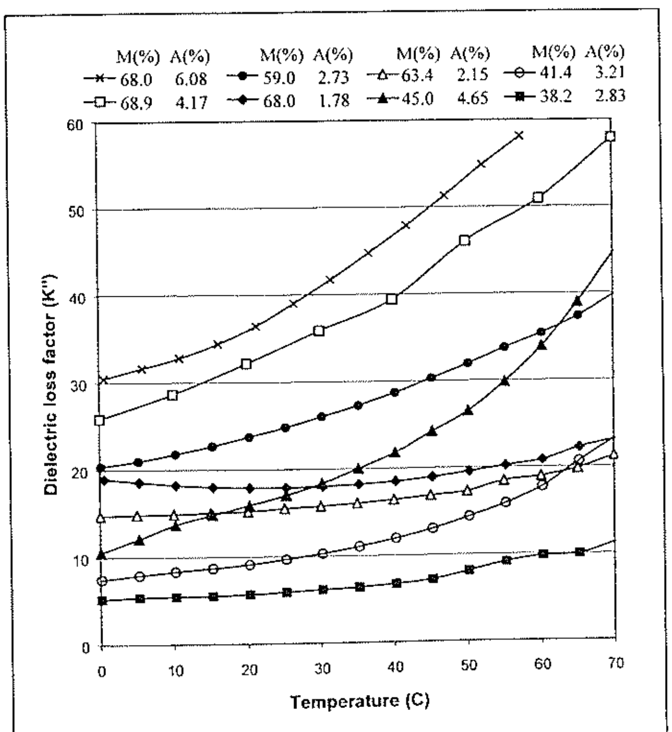

Figure 4—The effect of moisture and ash concentration on dielectric loss factor of ham samples at 2450MHz

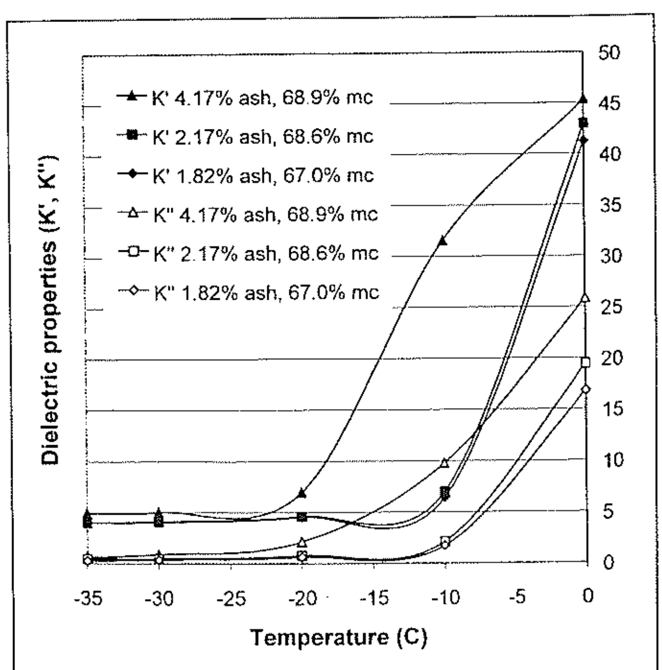

Figure 5—The effect of moisture and ash concentration on dielectric properties of ham samples between -35 and 0 °C at 2450MHz

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