IXth CONFERENCE OF EUROPEAN MEAT RESEARCH WORKERS
Budapest, September 4-11, 1963

57

335

Measurements of the dielectric properties of meat and their significance in regard to dielectric defrosting

by

N.E. Bengtsson and K. Remi

Swedish Institute for Food Preservation Research, Göteborg 16

INTRODUCTION

Over the last twenty years several reports have been published on the application of dielectric heating for defrosting frozen foods. In 1962 Jason and Sanders (1) reported promising results with continuous dielectric defrosting of fish, and Bengtsson (2) with meat and fish. Earlier, work on meat has been published by Vasiljev et. al. (3) in 1958 and by Satchell et.al. (4) in 1951. Recently the work by Jason and Sanders has resulted in practical application on an industrial scale for defrosting fish and meat in Great Britain. The process may be of considerable potential interest to the frozen food industry in general, justifying a closer study of the main variables involved.

Since the heat dissipated in a material in dielectric heating is a function of its dielectric properties as well as the frequency and voltage applied, good knowledge of these properties and their variation with temperature, frequency and rawmaterial is necessary for a proper understanding of the process. Such data being available only to a very limited extent, the present work was undertaken to determine dielectric constant and loss tangent for meat and animal fats over the temperature range from -25°C to +10°C and frequency range 10 to 200 MHz. Effect from frozen storage and variability of the rawmaterial were also investigated. Finally, the significance of the results obtained in regard to dielectric defrosting was evaluated and compared with practical experience. The work reported is part of a wider investigation on meat and fish, comprising dielectric measurements as well as practical defrosting experiments at different frequencies.

SUMMARY OF RESULTS

The dielectric properties of lean meats and animal fats over a range of temperatures and frequencies were determined, using a Boonton RX-meter and a test cell and measuring technique developed for the purpose. Results obtained showed that both dielectric constant and loss tangent increase rapidly with temperature when the melting zone is approached, but are relatively uneffected by temperature outside this region. With increasing frequency both dielectric constant and loss tangent decreased. The effects observed were much more pronounced for lean meats with their high water content than for the raw animal fats of relatively low water content. The variability of the rawmaterial between and within animals and the effect of frozen storage was found to be quite small. A Study of the data in regard to dielectric defrosting of block-shaped meat seems to confirm and explain observed tendencies towards selective heating of surface fat layers as well as the absence of pronounced selective heating of the lean meat in practical continuous defrosting experiments around 35 MHz. The data further indicated som possible advantage for increasing frequency within the frequency range studied.

DIELECTRIC MEASUREMENTS

Review

Ede and Haddow (5) reported specific conductivity data for beef, mutton, pork meat and other foods in the temperature range -30°C to +100°C and frequency range 0.2 to 20 MHz. They used a Marconi Q-meter, equipped with a thermoinsulated coaxial testcell, and measured with series connection of the test cell.

von Hippel (6) has given dielectric constant and loss tangent for bottom round steak at 25°C and 1, 10, 300 and 1000 MHz.

Oßwald (7) reported dielectric constant and conductivity for human tissues (muscle, fat etc.) at 20°C and 37°C and frequencies of 25, 50 and 100 MHz. The so called Barretter method was used, in which dielectric properties are determined through comparisons with solutions of known data.

Schwan and Li (8) reported dielectric constant and specific resistance for various human tissues as a function of frequency in the range 200 to 1000 MHz at 27°C.

Vasiljev et.al. (3) presented data on dielectric constant and loss tangent for meat, fat and bone in the temperature range -17°C to -2°C and frequency range 1-40 MHz. They used a Q-meter with special attachment. Probably the voltage over the sample and over an inductance free resistance in series with the sample was measured for amplitude and phase difference by means of a double beam oscillograph.

Experimental

Instrumentation and measuring technique

The general principle for determining dielectric properties in the frequency range concerned is to place the sample in a test cell, a kind of condenser, in which the sample is the dielectricum. The admittance of the full and the empty test cell is determined and the dielectric properties calculated.

The instrument used in our measurements was a Boonton RX-meter type 250 A, which is, in principle, a modified Schering bridge circuit, combined with oscillator and null detector. The test cell developed for our measurements is shown attached to the instrument in fig. 1. It consists of two silver plated, circular copper electrode plates with plexiglas reinforced leads of silver foil for connection to the meter. The electrodes are held at a fixed distance by a plexiglas ring and insulated on the outside by plastic discs. For good low temperature stability, thermoinsulation was improved by using very thin silver foil in the leads and by putting a box of foamplast around the cell during measurements.

The complete equivalent cirquit for the test cell can be represented as shown in fig. 2, where C_o, C_1, R_o, R_s and L_s are cell constants.

R_o is a resistance representing loss in the plexiglas covers of the cell.

R_s is the resistance in the cell leads.

$\frac{\varepsilon_0}{\varkappa \cdot C_1}$ is a resistance representing loss in the sample, where $\varkappa$ (kappa) is the conductivity of the sample and ε_0 the dielectric constant for vakuum.

C_1 is the capacitance of the empty sample compartment and

C_o the capacitance due to displacement flow through plexiglass and surrounding air.

L_s finally, is the inductance of the test cell with leads.

Through the determination of equivalent parallell capacitance and resistance on the RX-meter and with knowledge of the different cell constants, tan δ and ε could be calculated.
(Tan δ, the loss tangent, represents the dielectric lossiness of the material. For an ideal dielectric material the phase angle between voltage and current would be 90°C and its complementory angle, δ, would be zero. With increasing heat loss in the dielectric, δ and the loss tangent increase.)

The accuracy of the measurements was estimated by maximum-error calculation and by comparison with literature data for a number of materials. Precautions were taken to keep variability in measurements, caused by temperature-, sample-, test cell- and operator variability, as low as possible by using standardized procedures for sample preparation and handling, temperature adaption and actual measurement and by frequent control of empty cell data.

Table 1 lists some dielectric data reported in the literature for various materials, in comparison with own measurements. Overall the agreement seems to be quite good, considering the differences in samples, methods, operators etc.

Rawmaterial and sample preparation

Dielectric properties were determined for lean beef meat, lean pork meat and raw beef fat and pork fat. Four different lots of Swedish grade 1 cut beef meat were used with average water and fat contents of 74 % and 2.5 % respectively. Determinations were also made for some of the individual cuts used in this grade, approximately equivalent to rib, thick flank, brisket and top and bottom round cuts. Two lots of lean pork meat of 74 % water content and 3 % fat content were examined and one lot each of raw beef fat and pork fat.

Samples were minced, well mixed, frozen and stored at -30°C in sealed plastic bags. In preparation for measurement they were coldroom defrosted overnight. Up to five identical test cells were filled from the sample, adjusted to near the temperature of measurement and held in a constant temperature box til measurement, when the testcell was attached to the binding posts of the RX-meter.
The sample temperatures at the time of measurement were determined with an error of about 0.5°C.

Results and discussion

Results of measurements at different temperatures and frequencies on four different lots of grade 1 lean beef meat and more limited measurements on raw beef fat are shown in fig. 3. Results from measurements on lean pork meat and raw pork fat are not shown, since they were very close to the results for beef and beef fat.

Temperature effect

A sharp increase in dielectric constant with increasing temperature was obtained in the region of thawing, especially at the lower frequencies. Below and above this tempeature region rise in dielectric constant is slow. For loss tangent a similar increase with temperature was obtained at the lower frequencies, but less marked than for ε. Also for rawfats increases in ε and tan δ were found in the same temperature region, but of lower magnitude, in keeping with the much lower water content of the raw fats.

The observations are in good agreement with data reported by Ede et.al. as is seen from table 1. The results reported by Vasiljev (3), however, show considerable discrepancies from the other data, especially in tanδ, which is reported to decrease markedly with increasing temperature. Conductivity values calculated from Vasiljev's data show very little rise with temperature, in sharp contrast to the data by Ede and in the present report, which both showed a marked increase in conductivity with temperature between -10°C and -2°C. A possible explanation for the discrepancy in results, apart from differences in measuring technique, may be a difference of definition for tanδ.

High water content is probably the most important reason for the sharp increase observed in the thawing region. von Hippel (6) reports dielectric constants of 3.7 for ice at -12°C and 87 for water at 0°C and 10 MHz. In the present measurements differences in water content of the order of 5 % gave statistically significant differences in the ε-values.

Frequency effect

In all measurements frequency was found to have a significant effect on dielectric properties. Both ε and $\tan\delta$ decreased with increasing frequency, the effect being most evident in $\tan\delta$. This agrees with Oßwalds findings (7). For human muscle at +20°C he reported ε-values of 96, 86 and 71 at 25, 50 and 100 MHz respectively. $\tan\delta$-values calculated from his data for dielectric constant and conductivity are 4.4, 2.5 and 1.5. These data should be compared to ε-values of 83, 73 and 70 and $\tan\delta$-values of 5.0, 2.0 and 1.3 for the same frequencies in our own measurements on lean beef at +10°C.

Variability of rawmaterial

Variations in dielectric constant and loss tangent were determined between different cuts from the same animal and between identical cuts from different animals.

The results for different cuts from the same animal are shown in table 2 together with water content of the meats and the 95 % confidence limits for a single mean ($\pm 2\sigma$(sigma) limits). An analysis of variance showed no significant difference between cuts.

The averaged results from determinations on equivalent cuts (rib) from three animals are shown in table 3. At +2°C an analysis of variance showed significantly lower ε-value for a meat sample with lower water content. At -10°C the difference was nearly significant.

Variability for grade 1 cuts between and within animals was relatively low, probably because of fairly constant water content. According to Dahl (9) the total range for moisture content variation in grade 1 cut beef meat is about 71-76 %.

Effect from frozen storage

Samples of minced lean beef meat were stored at -30°C and taken out for testing after 1-2 days, 1-2 weeks and 1-3 months. The results of measurements at two temperatures and two frequencies, after different frozen storage times, are shown in table 4. An analysis of variance showed a small but significant effect in the measurements at -10°C, the dielectric properties decreasing with prolonged frozen storage.

SIGNIFICANCE OF DATA IN REGARD TO DIELECTRIC DEFROSTING

In dielectric defrosting applications regularly shaped blocks of reasonably homogenous material are usually fed with constant speed on a conveyor belt between parallell, horisontal electrodes over which is laid a high frequency field with frequencies in the range 10-50 MHz. The blocks are fed in a continuous stream, with an airgap between the product and the top electrode, and sample size, heat input, size of airgap, conveyor speed etc. are adjusted, so that the product is evenly defrosted after passing one or several electrode pairs.

The formula for the heating effect developed in a material placed between plane parallell electrodes, over which a high frequency voltage is applied is

$$P = \frac{\varepsilon \cdot \tan\delta \cdot E^2}{d^2} \cdot 5.56 \cdot f \cdot 10^{-7} \qquad (10)$$

where P is the power dissipation in watts/cm^3

ε dielectric constant of the material

δ dielectric loss angle

E voltage over the sample in volt

f frequency in MHz

The fairly small rawmaterial variations found in the dielectric properties of meat are important because it indicates that only smaller equipment resettings would be necessary between and within rawmaterial batches. The great differences found in dielectric properties between lean meat and fat and the marked increase of these properties in the thawing region suggest, however, that selective heating or runaway heating might readily occur during defrosting. With increasing frequency the product $\varepsilon \cdot \tan\delta \cdot f$ in the formula above will gradually increase suggesting that lower field strength, with reduced tendencies towards arcing and electrical discharge, could be used for a given heating effect, if-going to a higher frequency.

The much lower values of the dielectric properties for fat compared with lean meat would, on the face of it, suggest a tendency towards selective heating of the lean portion. This is however contradicted by practical experience in small scale defrosting equipment, which has shown a tendency towards selective heating of fat surface layers in meat blocks. This may partly be explained by the lower heat capacity of the fat. Another explanation is arrived at by studying the voltage distribution between air gap and the layers of surface fat and the lean meat.

For layers of different dielectric properties between flat, parallell electrodes power density in each layer can be calculated from the above formula, provided E is the voltage over the layer in question. For each layer E can be calculated as a function of dielectric constants, loss tangents and layer thicknesses for all the different layers. A calculation will then show that the field strength in a fatty surface layer will be much higher than in the lean portion, which should result in higher power dissipation in the fatty layer and an increased tendency towards selective overheating. Similarily it can be shown, with the help of the dielectric data obtained, that, should a surface layer of lean meat be heated slightly higher than the rest of the block, this will not necessarily result in runaway heating, since the field strength and power density will be much lower in the warmer surface layer.

In continuous dielectric defrosting a temperature gradient will develop in the direction of travel. If the electrodes were in direct contact with the meat, most of the heat developed would be concentrated near the exit, since the dielectric properties have much higher values for the warmer meat. When an airgap i used, however, there will be a reduction in voltage over the warmer sections, resulting in less heat dissipation there.

The reasoning above, based on the measured dielectric properties for meat and fat, seem to help explain why runaway heating has not been found a very serious problem in practical defrosting experiments with regularly shaped blocks of fairly homogenous material.

The conclusions drawn from dielectric data concerning the power dissipation in blocks heated between parallell electrodes with airgap were confirmed in limited static large scale dielectric defrosting experiments in a 20 kW equipment. Using constant airgap over the block and constant voltage over the electrodes, power dissipation (anode current) decreased with increasing product temperature. When frequency over the electrodes was increased (with otherwise maintained conditions of voltage, airgap etc) power dissipation in the block increased.

ACKNOWLEDGEMENTS

The work has been supported by a grant from the Swedish Deepfreezing Committee. The authors are further indebted to Mr J. Melin and Mr S. Söderlind, Göteborg, for their help in working out the measuring technique used.

Göteborg den 20 juni 1963

2057/63-VF

References

1. Jason, A.C. and Sanders, H.R., Dielectric thawing of fish, 1 and 2. Food Technology 1962, 16, (6), 101.
2. Bengtsson, N.E., Experiments with dielectric defrosting of meat and fish. Proceedings 1st International Congress of Food Science and Technology, London, 18-21 September, 1962, Ed.: Long, A., London.
3. Vasiljev, A.S. et al., Defrosting of meat by heating in a high frequency field. P. 55-64 in: Novyje fizitjeskije Metody Obrabotki Pistjevych Produktov, Obrabotka Pistjevych Produktov Elektritjeskim Tokom, (Gosinti) Moskva 1958.
4. Satchell, F.E. et al. High Frequency Dielectric Heating for defrosting Frozen Pork Bellies. Am. Meat Inst. Found., Chicago, Bull. No 12, 1951.
5. Ede, A.J. and Haddow, R.R., The electrical properties of food at high frequencies. Food Manufacture, 1951, 26, 156.
6. von Hippel, A.R. (ed.), Dielectric materials and applications, 1954, p. 63. N.Y., The Technology Press of M.I.T., N.Y., John Wiley & Sons, Inc.
7. Oßwald, K., Messung der Leitfähigkeit and Dielektrizitätskonstante biologischer Gewebe und Flüssigkeiten bei kurzen Wellen. Hochfrequenztechnik und Elektroakustik, 1937, 49, 40.
8. Schwan, H.P. and Li, K., Capacity and conductivity of body tissues at ultrahigh frequencies. Proceedings I.R.E. New York, 1953, 41, 1735, N.Y.
9. Dahl, O. Tillverkning av charkuterivaror med särskilt beaktande av vattenhalten. Statens Institut för Folkhälsan, Meddelande, 1948, Nr. 7, 29 p. Stockholm, Esselte AB.
10. Maddock, A.J., Dielectric heating. Journal of Scientific Instruments, 1946, 23, 165.
11. Sharma, M.N., Dielectric investigation on vegetable oils at radio frequencies. Journal of Scientific Industrial Research, 1960, 19, 5.

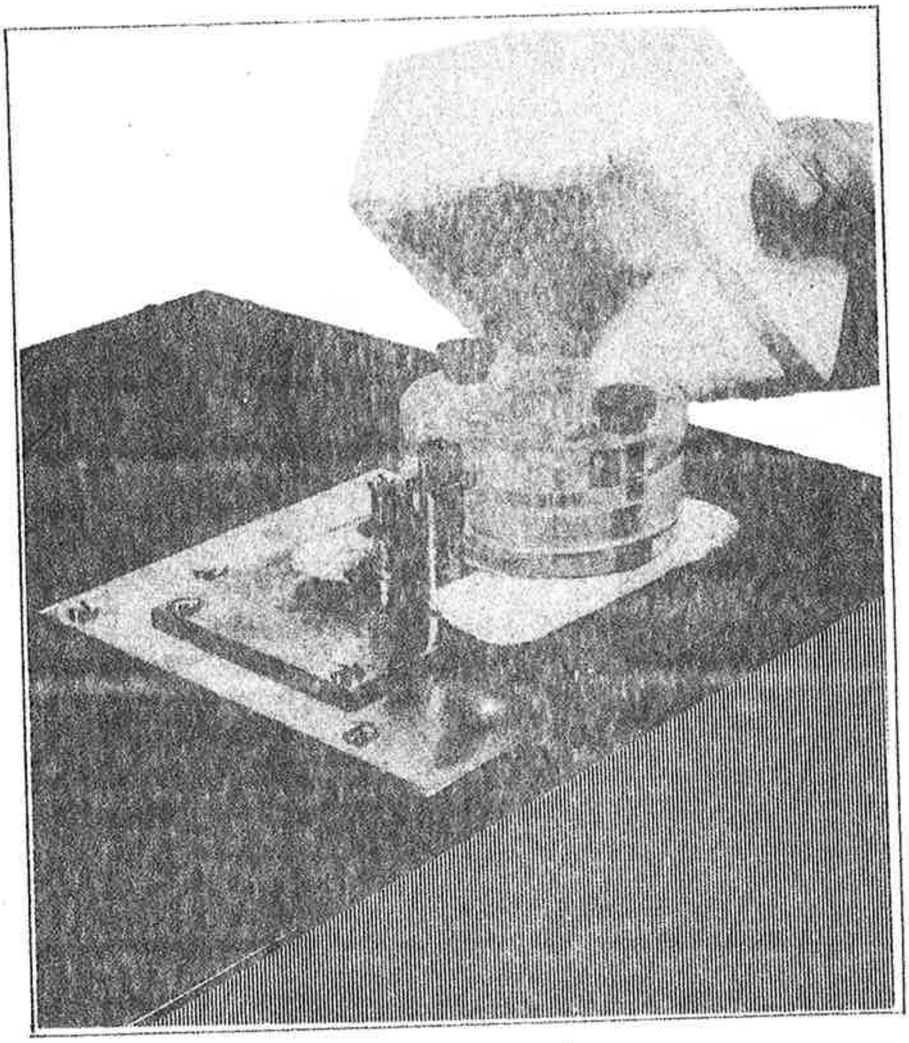

Fig.1.-Testcell attached to the Boonton RX-meter.

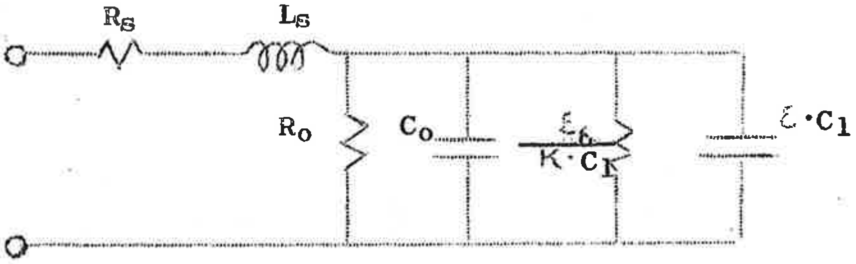

Fig.2.- Equivalent cirquit for the testcell.

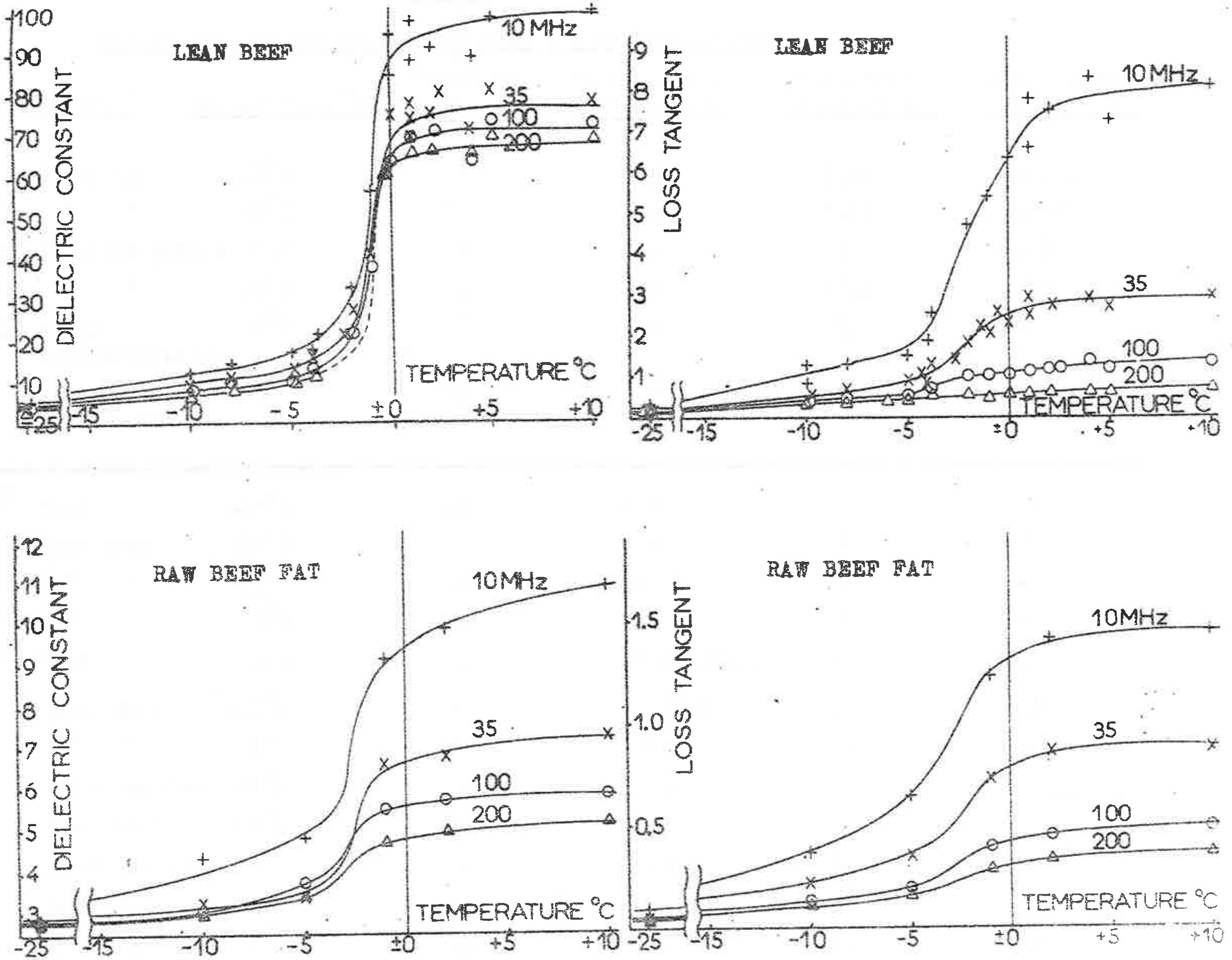

Fig. 3. Dielectric constant and loss tangent (tan δ) as function of temperature and frequency for lean beef and raw beef fat.

347

Table 1

Comparison between literature data and own measurements

Reference	Material	Temperature °C	Frequency MHz	Conductivity ohm^{-}.cm^{-}.10^{3}	Dielectric constant (ε)	Loss tangent ($\tan\delta$)
Sharma[11]	Olive oil	25°C	32	-	3.06	0.0361
own data	" "	25°C	32	-	3.12	0.045
von Hippel[6]	Ethylene glycol	25°C	1	-	41	0.03
own data	" "	25°C	1	-	37.9	0.029
von Hippel[6]	Water (conductivity)	25°C	10	-	78.2	-
own data	Water (destilled)	25°C	40	-	76.0	-
Vasiljev[3]	Meat	-17°C	10	-	9	0.5
own data	Lean beef	-15°C	10	-	8	0.5
Ede[5]	" "	-10°C	20	0.09	-	-
"	" "	0°C	20	3.	-	-
Vasiljev[3]	Meat	-9°C	20	0.17(calc.)	30	0.5
own data	Lean beef	-10°C	35	0.092	11	0.4
" "	" "	0°C	35	3.0	-	-
Osswald[7]	Human muscle	20°C	100	5-7	71	1.5(calculated)
own data	Lean beef	10°C	100	4.7	70	1.3
Schwan[8]	Human muscle	27°C	200	8.5	56	-
own data	Lean beef	10°C	200	5.6	67	-
Ede[5]	Beef fat	0°C	20	-	7.0	0.5
own data	" "	0°C	35	-	6.7	0.8

Table 2

Variability of dielectric properties between five different cuts of lean beef from the same animal at two temperatures and four frequencies

(data are averages of duplicate determinations)

Cut	Water content %	Dielectric constant ε								Loss tangent (tan δ)							
		-10°C				+2°C				-10°C				+2°C			
		10 MHz	35 MHz	100 MHz	200 MHz	10	35	100	200	10	35	100	200	10	35	100	200
Rib	75.2	13.1	9.9	8.4	7.3	90.6	74.3	68.9	64.9	1.17	0.64	0.40	0.34	7.53	2.69	1.16	0.61
Brisket	74.1	13.5	10.2	8.9	7.8	92.6	74.9	69.2	64.9	1.07	0.58	0.39	0.33	7.26	2.65	1.16	0.62
Top Round	73.5	13.1	10.2	8.8	7.9	94.0	76.3	71.1	68.5	1.19	0.58	0.39	0.33	7.50	2.71	1.17	0.59
Bottom Round	73.9	12.2	9.4	8.3	7.1	93.7	75.1	70.2	65.7	1.04	0.57	0.39	0.33	7.25	2.67	1.15	0.60
Thick Flank	73.8	12.8	9.8	8.7	7.4	92.0	74.7	69.8	66.0	1.11	0.59	0.42	0.34	7.56	2.69	1.18	0.62
Results of analysis of variance		Significant diff. between frequencies only															
95% confidence limits of a single mean		± 0.5				± 2.0				± 0.08				± 0.08			

Table 4

Variability of dielectric properties of lean beef between equivalent cuts (rib) from three different animals at two temperatures and four frequencies

(averages of triplicate determinations)

Animal	Water content %	Dielectric constant ε								Loss tangent (tan δ)							
		-10°C				+2°C				-10°C				+2°C			
		10 MHz	35 MHz	100 MHz	200 MHz	10	35	100	200	10	35	100	200	10	35	100	200
A	75.2	12.4	9.4	7.9	7.1	91.2	74.2	69.3	65.0	1.26	0.61	0.40	0.33	7.45	2.70	1.15	0.64
B	69.9	11.7	9.0	7.6	6.8	82.8	68.2	62.2	62.0	1.24	0.61	0.39	0.32	7.40	2.65	1.16	0.62
C	73.2	11.9	9.4	7.9	7.1	89.4	73.0	67.7	64.3	1.12	0.61	0.39	0.31	7.50	2.70	1.16	0.64
Results of analysis of variance		Very significant difference between frequencies															
						Sign. difference between samples				—				—			
95% confidence limits of a single mean		± 0.4				± 1.4				± 0.07				± 0.07			

Table 7

Effect from frozen storage time on dielectric properties of lean beef measured at two temperatures and two frequencies

(averages of triplicate determinations)

Frozen storage time at -30°C	Dielectric constant ε				Loss tangent (tan δ)			
	-10°C		+2°C		-10°C		+2°C	
	35 MHz	100 MHz	35 MHz	100 MHz	35 MHz	100 MHz	35 MHz	100 MHz
1 day	10.5	8.4	75.0	69.2	0.70	0.42	2.81	1.20
1 week	9.6	8.1	74.3	68.3	0.58	0.37	2.79	1.20
1 month	9.0	7.7	76.6	70.4	0.56	0.38	2.73	1.19
3 months	8.7	7.4	76.4	70.3	0.49	0.34	2.82	1.21
Results from analysis of variance	Significant effect from storage time		No significance		Significant effect from storage time		No significance	
95% confidence limits for a single mean	± 0.35		± 1.4		± 0.04		± 0.07	

Measurements of the dielectric properties of meat and their significance in regard to dielectric defrosting

by

N.E. Bengtsson and K. Remi

Swedish Institute for Food Preservation Research, Göteborg

SUMMARY

The dielectric properties of lean meats and animal fats over a range of temperatures and frequencies were determined, using a Boonton RX-meter and a test cell and measuring technique developed for the purpose. Results obtained showed that both dielectric constant and loss tangent increase rapidly with temperature when the melting zone is approached, but are relatively uneffected by temperature outside this region. With increasing frequency both dielectric constant and loss tangent decreased. The effects observed were much more pronounced for lean meats with their high water content than for the raw animal fats of relatively low water content. The variability of the raw material between and within animals and the effect of frozen storage was found to be quite small.

A study of the data in regard to dielectric defrosting of block-shaped meat seems to confirm and explain observed tendencies towards selective heating of surface fat layers as well as the absence of pronounced selective heating of the lean meat in practical continuous defrosting experiments around 35 MHz. The data further indicated some possible advantage for increasing frequency within the frequency range studied.