Permittivity of Meat Fish and their Components at UHF RFID Frequencies and Industry Relevant Temperatures

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ABSTRACT

Permittivity values of lean beef, pork, fish, poultry, and values for other components from these sources (i.e. fat, marrow and bone) were measured at selected industry-relevant temperatures – 18 °C, - 12 °C, - 5 °C, 0 °C, 7 °C, 25 °C, 40 °C and UHF RFID relevant frequencies of 868 MHz, 915 MHZ, 950 MHz and 2450 MHz. Muscle fibre orientation in relation to probe placement was also investigated. Increases in temperature generally led to increases in the dielectric constant (ε') and loss factor (ε'') of all test samples while the opposite trend was observed with increases in frequency (i.e. ε' and ε'' decreased). These trends were clearly evident for samples of lean beef, pork, poultry and fish. The dielectric properties of other non-lean components also varied with temperature and frequency. ε' and ε'' values of fat and marrow were significantly lower than those of lean while for fibrous tissues muscle fibre orientation only had a significant influence in the case of poultry ($p \leq 0.05$) and not in the case of beef or pork ($p \geq 0.05$). Results of this study can serve as basic data for the design and/or application of RFID inlays.

keywords: Ultra High Frequency Radio Frequency Identification (UHF RFID), Coupling, Permittivity, Dielectric properties, Muscle fibre, Ireland.

1. INTRODUCTION

Over the last decade there has been a growing interest in radio frequency identification (RFID) as a method of real time tracking and identification of any object either living or inanimate. One outstanding feature of RFID technology is the use of radio waves eliminating the need for a direct line-of-sight between transponder and reader antennae. To date RFID has proven to be an ideal method of warehouse inventory in the supply chain (Chow et al., 2006), access control, points of sale and public transport (Wu et al., 2006) payment. A basic RFID system consists of a tag (transponder) which possesses the ability to store information regarding the item to which it is attached, and a reader (transceiver) which is connected to a data management system (Finkenzeller, 2003). The reader is responsible for communicating wirelessly with transponders to power and/or identify them.

Transponders may be passive (i.e., contain no method of self power and rely on the interrogation wave coming from the reader as a source of power); active (i.e., complete with on-board power source) or semi-passive / semi-active (i.e., are equipped with a power source to provide the tag circuitry with energy to operate, yet rely on the interrogation wave for communicating with the reader antenna) (Glover & Himanshu, 2006). Transponders are also available in a variety of shapes, sizes and functional properties. Active and semi-active RFID tags offer additional capability to record processing, storage and/or transportation conditions such as temperature and relative humidity (Lahiri, 2006), thus ensuring a safe hygienic final product.

RFID frequency standards vary considerably with each variation suited to a particular application. For instance, 134.0 KHz has been allocated to animal identification (Kampers et al., 1999) according to ISO Standards 11784, 11785 and 14223 (advanced transponders) (Lahiri, 2006); and both 13.56 MHz high frequency (HF) followed by 860 – 960 MHz (UHF) ultra high frequency. (ISM) industrial, scientific and medical frequency bands have been allocated for RFID item level tracking according to ISO Standards 14443, 15693 and 18000, respectively. The 2450 MHz RFID band is also governed by the ISO / IEC 18000 Part 4, Mode 1 Standard (Intermec, 2007). Compared to their lower frequency counterparts, RFID systems in the UHF and the microwave (2.45 GHz) bands have the advantage of operating at their electromagnetic far field regions at relatively smaller distances from the tag, thereby enhancing their range of detection (Glidden et al., 2004). Ultra high frequency (UHF) radio frequency identification (RFID) operates at different frequency bands governed by geographical regions throughout the world; 865.6 – 867.6 MHz (in selected countries in Europe), and 902 – 928 MHz in the USA (Lehpamer, 2008).

UHF RFID is not without its disadvantages; the coupling between a UHF tag and a reader is greatly reduced in the presence of metals and water due to reflection and attenuation of the propagating electromagnetic wave, respectively (Lahiri, 2006). It has also been reported that UHF RFID applications have been less successful compared to HF RFID in the pharmaceutical industry due to losses in biomaterials (Philips Semiconductors, 2004). Previous work has also shown that meat samples with bone have demonstrated better coupling capabilities between transponder and transceiver, than similar masses of meat without bone (Ayalew et al., 2006; Mc Carthy et al., 2009b). Another drawback associated with the coupling capabilities of UHF RFID relates to tag detuning due to materials different from those at design in the immediate environment of the transponder (Sweeney, 2007; Mc Carthy et al., 2009a)

Permittivity of meat at these particular frequencies is missing from the literature, as UHF RFID tracking is an area of active research and development, and even more so in its applications in food in general and meat in particular (Ayalew et al., 2006). Therefore, the determination of permittivity values for meat and its constituents will be useful in the design of RFID tag inlays with specific applications to meat and derivative products.

The dependence of permittivity of substances on temperature is an established phenomenon which Ramo et al. (1984) attribute mainly to the decrease, with increased temperature, of viscous damping of the permanent dipole contribution to polarisability. Zhang et al. (2004), in a study conducted on a variety of meat batters; and Sipahioglu et al. (2003), in a study on ham; reported that temperature had a significant effect on the dielectric properties of meat. This phenomenon is important in relation to meat traceability in that meat must be kept at a temperature of not more than 4 ºC (poultry) and 7 ºC (all other meats) during cutting, boning, trimming and packaging; and stored frozen to -18 ºC under EU regulation (European Commission, 2004). Other temperatures may be imposed due to plant-specific HACCP plans. Accordingly, the study of permittivity at relevant temperatures would be of importance in the application of RFID to meat along the supply chain.

The effects of orientation of muscle fibres in relation to the electromagnetic fields is also of interest as dielectric dispersion depends on membrane effects (Kuang & Nelson, 1997). This may also prove to be an important operational characteristic in terms of tag location in relation to muscle fibre orientation during RFID system coupling.

The composition of meat varies according to anatomical location (Shirsat et al., 2004). Although it would be practically impossible to determine, composition in real time, permittivity data on constituents of meat should be useful to serve as a rough guide to the permittivity of a portion of meat given a particular cut.

This study aimed at the examination of dielectric properties of meat and its constituents at temperatures of practical interest at RFID related frequencies. The effect of muscle fibre orientation in relation to the electric field will also be investigated.

2. MATERIALS AND METHODS

2.1 Samples

Commercially available samples were used for all trials. Meat types included beef loin (BF), pork loin (PK), salmon (FS) and chicken breast (PT). Constituents were designated as muscle (M), bone marrow (MW) and fat (FT). Fat samples were derived from beef and pork samples only. Marrow samples were collected from a beef source only. All visible fat was removed form all muscle samples prior to freezing and permittivity measurements. Fat samples were obtained from both bovine and swine sources. Marrow samples were manually extracted from a bovine source for analysis.

2.2 Instrumentation

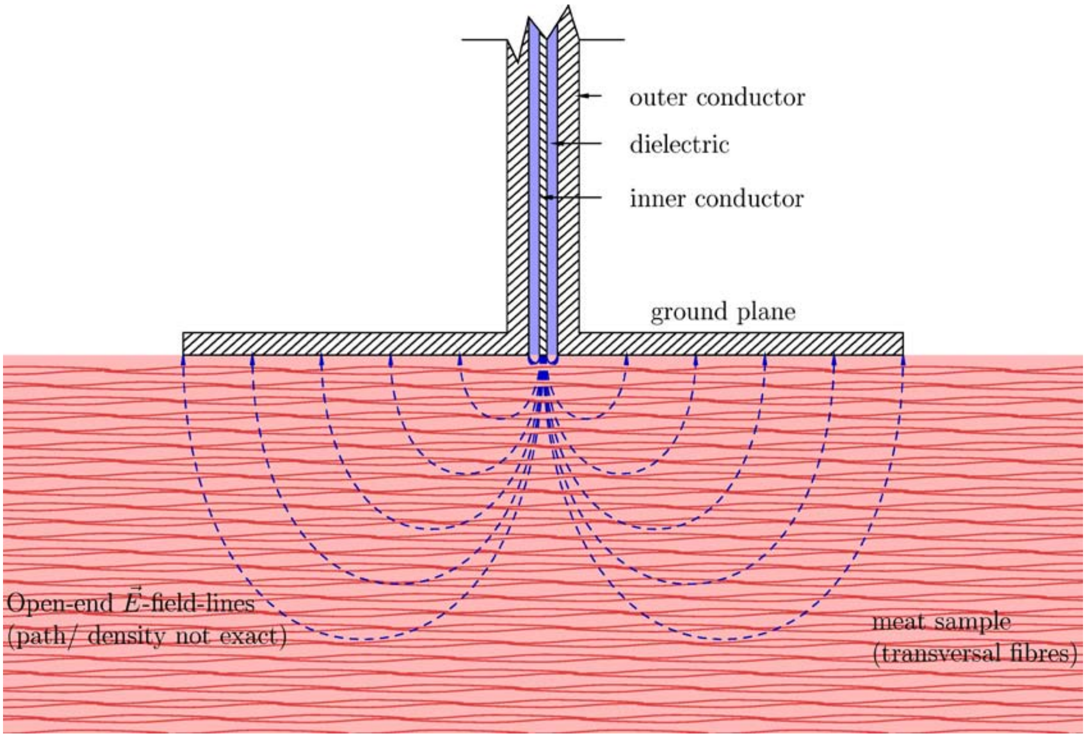
Permittivity measurements were made using a Hewlett-Packard network analyser (Model 8714 ET, Agilent Technologies, California, USA) in conjunction with Agilent Technologies open ended co-axial probe (Model 85070C) between 0.3 and 3.0 GHz. Calibration of the system was carried out at regular intervals during data acquisition, as per manual. Data was acquired with the aid of an Agilent Technologies 85070C software package. All Statistical analyses were carried out using Minitab Version 13 (Minitab, UK), using p-values of t-Stat at 95 % confidence level in all cases.

2.3 Measurment Procedure

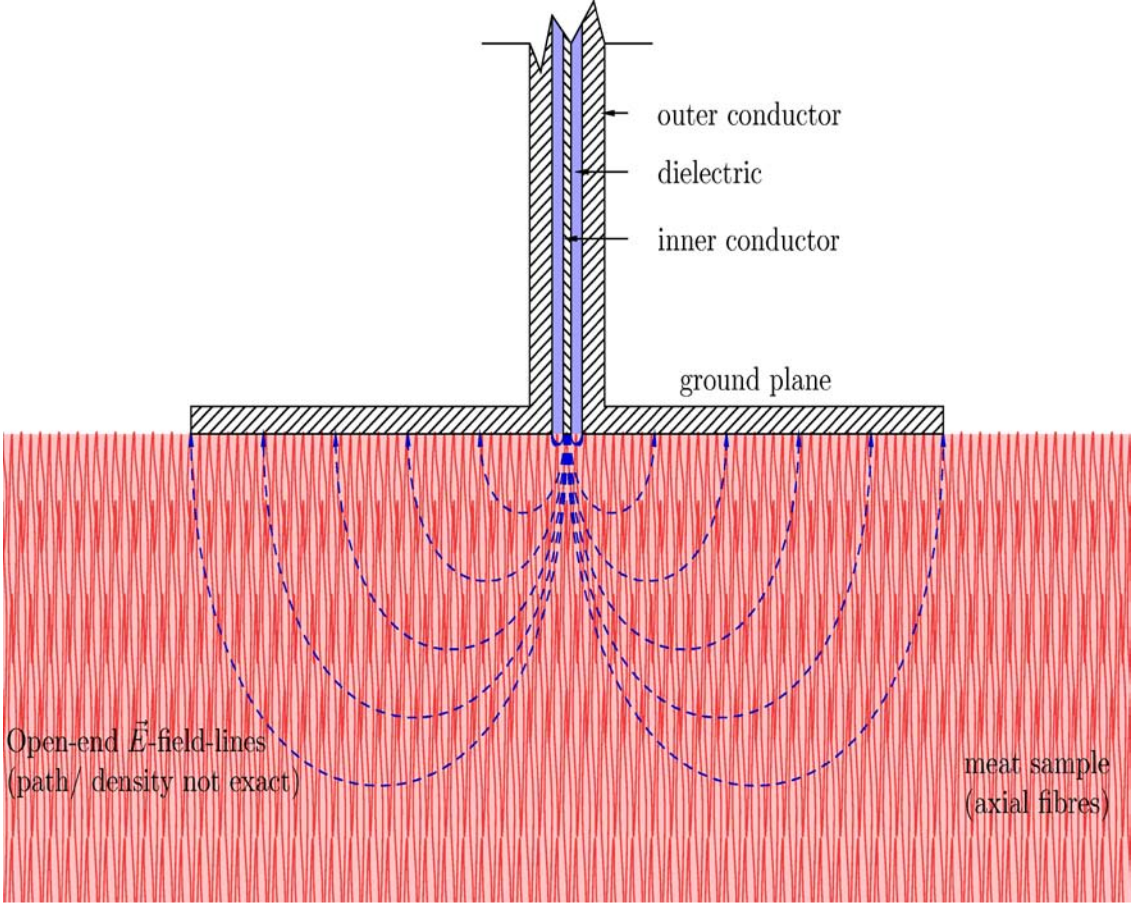
All test samples were contained to fill 140 ml plastic (King Ireland, Dublin Ireland) sample cups immediately after purchase. Samples were initially frozen to – 18 ºC in a sub-zero water-bath (Grant Instruments (Cambridge) LTD; Shepreth Cambridgeshire SG8 6GB, England). Temperatures of up to 40 ^{o}C were achieved in a commercially available water bath. Once placed in the water bath all samples were allotted a temperature equilibrium period of 8 hours. Each water bath was covered with a purpose built styrofoam lid to minimize temperature fluctuations. Dielectric measurements were carried out as per Zhang et al. (2004) in a controlled temperature laboratory to ensure accuracy. Samples were kept in shape using a custom built clamping system to ensure one single side of the sample remained perfectly flat thus ensuring full contact with the co-axial probe during data acquisition.

Permittivity measurements were made at 868, 915, 950 and 2450 MHz. Measurements were taken at five randomly selected sites on a single sample face. Each sample was stored in the water bath prior to and immediately after analysis to minimise temperature fluctuations. Beef, pork and poultry samples were also analysed for meat fibre orientation. Each muscle sample was placed either transversely (TR) or axially (AX) in relation to the axis of the co-axial probe determined through visual inspection of the sample - visually depicted in Figure 1a and Figure 1b respectively.

The above procedure was repeated for each of the following temperatures - 18, - 12, - 5, 0, 7, 25 and 40 ºC. While - 18, and 7 ºC are due to processing and storage related regulations, 40 ºC was selected to approximate body temperature at the point of kill. This was to monitor any changes that may occur in the dielectric properties between initial body temperature and specific processing temperatures. 25 ºC was selected as it is generally accepted to be room temperature. 0 ºC was included as it represents the freezing temperature of water. – 12 and - 5 ºC were selected to monitor sub-zero changes in the dielectric properties of test samples which may be useful to UHF RFID application in the case of frozen meat. Each sample was prepared and analysed in duplicate.



(a)



(b)

Figure 1 Meat fibre orientation (a) transverse (b) axial.

3. RESULTS

The mean dielectric constants of all test samples are plotted as functions of RFID relevant frequencies and at a temperature of 7 ºC in Figure 2. Figure 3 shows the plot of the corresponding mean loss factor values plotted in figure 2. The mean dielectric constant of beef and its components at 868, 915, 950 and 2450 MHz are plotted in Figure 4 as functions of temperature with corresponding loss factor values plotted in Figure 5. Figure 6 shows the mean dielectric constants of all test samples at 868 MHz as functions of temperature with corresponding loss factor values plotted in Figure 7. The plots of similar quantities for other meat types (pork, poultry and salmon) also exhibited similar trends, but not presented to save space. In Figures 4 and 6 the maximum value of the dielectric constant of marrow has not been included in the plot area, to aid clarity. Their respective values have been included in their relevant legends. Table 1 lists the p-values obtained during muscle fiber orientation trials of beef, pork and poultry samples. Table 2 lists p-values of all the paired t-Statistics comparison of all test samples at each frequency.

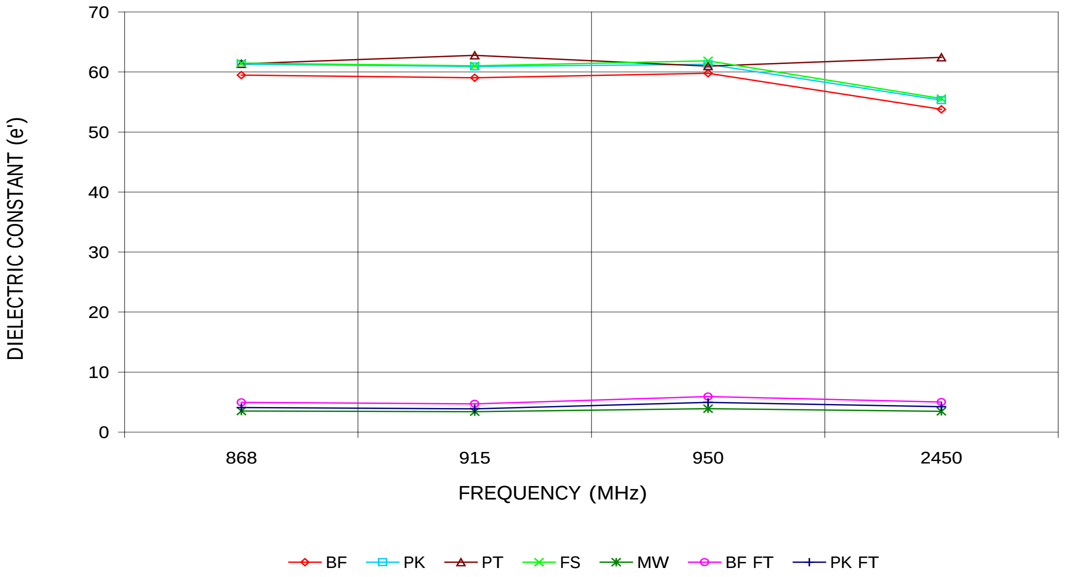


Figure 2 Mean dielectric constants of all test samples at 7 ºC as functions of RFID relevant frequencies.

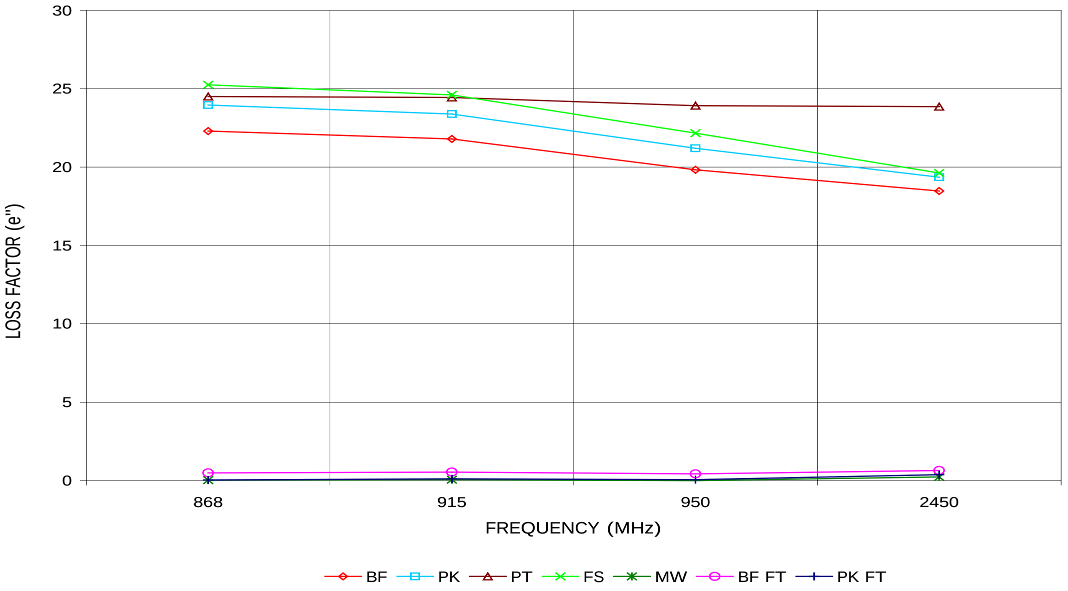


Figure 3 Mean dielectric loss factors of all test samples at 7 ºC as functions of RFID relevant frequencies.

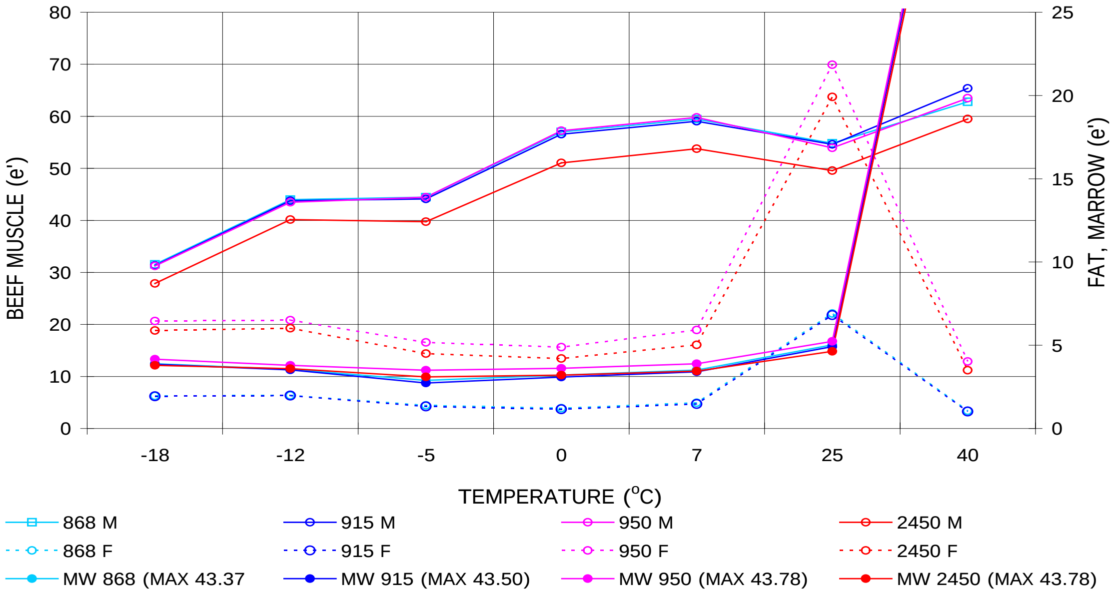


Figure 4 Mean dielectric constants of beef and its components at 868, 915, 950 and 2450 MHz as functions of temperature.

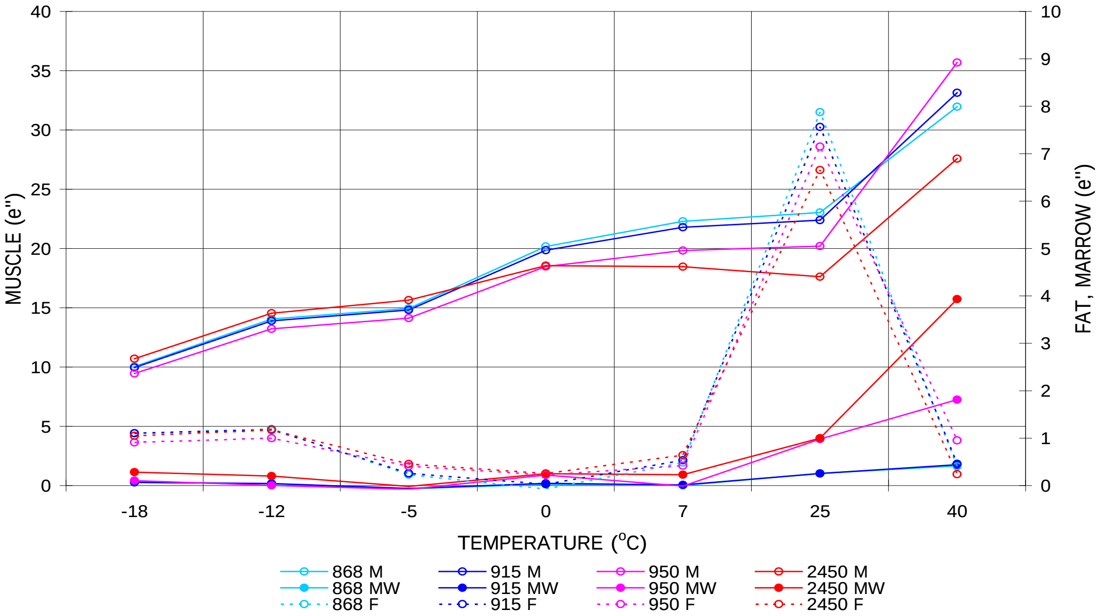


Figure 5 Mean dielectric loss factors of beef and its components at 868, 915, 950 and 2450 MHz as functions of temperature.

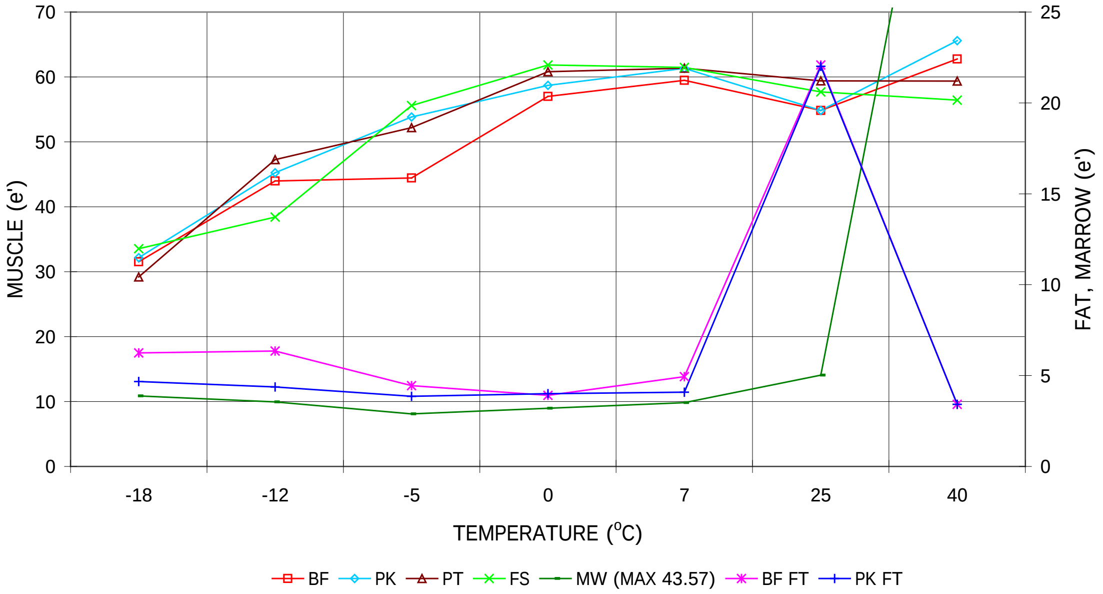


Figure 6 Mean dielectric constants of all test samples at 868 MHz as functions of temperature.

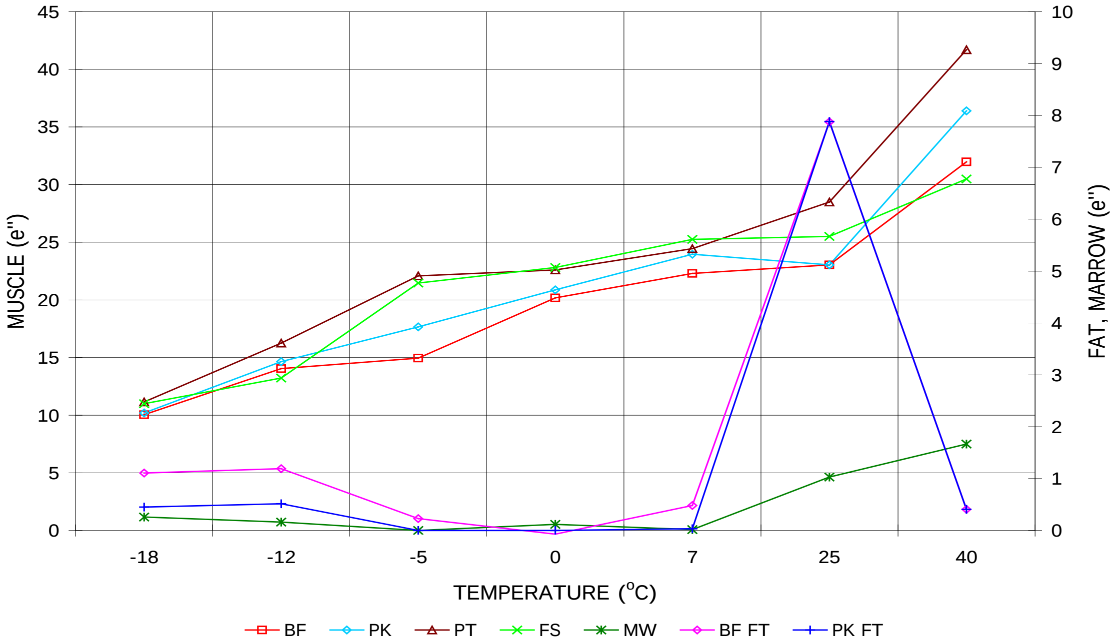


Figure 7 Mean dielectric loss factors of all test samples at 868 MHz as functions of temperature.

Table 1. Average p-values of a t-Statistic analysis of comparison of muscle fibre orientation axially and transversally orientated meat fibres in relation to probe axis.

FREQUENCY (MHz)	DIELECTRIC CONSTANT			DIELECTRIC LOSS FACTOR		
	BEEF	PORK	POULTRY	BEEF	PORK	POULTRY
868	0.088	0.150	0.003	0.010	0.354	0.002
915	0.267	0.100	0.003	0.041	0.208	0.002
950	0.137	0.123	0.003	0.346	0.165	0.002
2450	0.234	0.104	0.002	0.346	0.055	0.002

4. DISCUSSION

4.1 Frequency Dependence of Permittivity

Referring to Figures 2 and 3, the dielectric constant and the loss factor decreased gradually with frequency for all meat muscle samples with the exception of poultry, which showed slight variations in dielectric constant and a slight decrease in loss factor. The fact that permittivity decreased gradually with frequency in this band is in agreement with the results of Brunton et al. (2006). Similar to muscle samples, loss factor values of fat and marrow samples also decreased with a frequency increase for the spectrum studied although the decrease in dielectric constant is less notable. Fat constitutes non-polar molecules, therefore, inhibiting the ability of fat to bond with a polar molecule like water (Feiner, 2006), therefore decreasing its dielectric polarisability.

These findings are again in agreement with the findings of Smith & Foster (1985), who examined fat and bone marrow from a bovine, canine and equine sources at 25 ^{o}C at frequencies of between 1 KHz and 1 GHz.

Results of t-Statistic comparison for paired samples of meat and constituents of meat over all temperatures at RFID relevant frequencies are summarized in Table 2. As is evident from the table, more significant differences in permittivity values occurred (i.e. low p-value) generally at farther apart frequencies. Similar trends have been reported by Lyng et al. (2005), who conducted trials on meat and meat ingredients including pork and pork fat at 27.12, 915 and 2450 MHz and Shirsat et al (2004) who studied the conductivity of pork samples; and Smith & Foster (1985) who used a co-axial transmission line on low moisture content tissues of bovine, canine and equine sources between the frequencies of 1 KHz and 1 GHz. Trabelsi & Nelson (2006) in another study noted that moisture plays a major role in dielectric properties during characterization of shelled peanuts through a non-destructive method of determining bulk density and moisture at frequencies ranging from 7 to 12 GHz at 24 ºC. This may be noted from the graphs that the dielectric constants of lean meat muscle tissue being made up of a large percentage (between 70 and 75 %) water Feiner (2006) are in the range of 30 – 65, that of water being $\varepsilon = 79 - j3.8$ at 915 MHz at ambient temperature (Fletcher et al., 2005).

The loss factors on the other hand are higher than that of water ranging between 10 - 37 perhaps due to relaxation contribution by other constituents of the muscle tissue than water alone. This hypothesis is also supported by the works of Venkatesh & Raghavan (2004), in a review paper of microwave processing of agricultural and food materials. A variation in the dielectric constant and loss factor evident from figures 2 and 3 indicate that the frequency at which an RFID system operates is crucial to its coupling capabilities.

4.2 Temperature Dependence of Permittivity

Referring to Figures 6 and 7 there is a steady increase in the dielectric constant of muscle over the given temperatures. Fat and marrow on the other hand decrease in value between – 12 ºC and 7 ºC and then increase sharply. A similar trend is observed for the corresponding loss factor in Figure 7. Generally the dielectric constant (Figures 4 and 6) and loss factor (Figures 5 and 7) increased with temperature for muscle and marrow, the latter significantly above 25 ºC. The rate of increase of the loss factor for muscle was greater at higher temperatures. Fat, however, exhibited a peak at 25 ºC with a subsequent decrease to a lesser value at 40 ºC than those at lower temperatures. This increase at 25 ºC and subsequent decrease in both dielectric constant and loss factor of fat samples may be partially explained through the change of phase fat undergoes at about 20 ºC (Tocci & Mascheroni, 1998; Grisham & Barnett, 1973). This trend is less evident in the loss factor values (Figures 5 and 7). The increase is less accentuated in the Tocci and Mascheroni trial as the temperature ranged from – 40 to + 40 ºC which differs from the present trial of – 18 to + 40 ºC. The pattern of increase in dielectric constant and loss factor agree with the findings of Sipahioglu et al (2003) in trials conducted on ham and also reinforced by Ryynänen (1995) in a review of the electromagnetic properties of food materials.

4.3 Fibre Orientation Dependence of Permittivity

Table 1 provides the summary of comparison of t-Statistic for paired samples of the dielectric constants and loss factors of samples in relation to fibre orientation, at different frequencies. The effect of fibre orientation was observed to be insignificant in a majority of cases ($p \geq 0.05$) in beef and pork samples perhaps due to the pattern of fields near the open ended probe whereby regardless of the general orientation of meat muscle fibers, part of the electric field lines pass partially along the axes and partially perpendicular to the axes of the fibres. Poultry on the other hand exhibited statistically significant effects of fiber orientation ($p \leq 1$ %), and the effect of the electric fields passing through both modes of orientation seems negligible. Results of Brunton et al (2006) who conducted fibre orientation trials on beef biceps femoris muscle during cooking from 5 – 85 ºC at 27.12, 915 and 2450 MHz found beef muscle orientation to be insignificant similar in most part to the findings of this trial. Bircan & Barringer (2002), stated significant differences do exist in relation to fibre orientation in beef and pork through trials conducted on beef, chicken, salmon and perch using an open ended coaxial probe. Bodakian & Hart (1994) conducted trials on beef and chicken using a low frequency (1 Hz to 1 MHz) impedance analyzer and observed orientation significance. Further studies of the effect of orientation on permittivity is required to conclusively determine the effect of fibre orientation, perhaps using other permittivity measurement techniques such as a rectangular resonant cavity.

4.4 Compositional Dependence of Permittivity

Moisture content is one of the main factors affecting the dielectric properties of food followed by fat content (Bircan & Barringer, 2002). It can be seen in Figures 2 and 3 that there is an obvious difference in the dielectric values of muscle and fat and this trend is also visible from Table 2. Carcass fat contains 80 – 85 % triacylglycerol fat, 5 – 10 % moisture and around 10 % connective tissue, by weight. Pork has a high fat content 9 – 11 % compared to beef with 4.8 % and chicken containing 4.7 %. Fat is composed of non-polar molecules, therefore, inhibiting the ability of fat to bond with polar molecules like water Feiner (2006), hence keeping its dielectric properties low in value. Figures 2 and 3 show a clear difference between the dielectric properties of muscle compared to that of either fat or marrow. Table 2 confirms that significant differences exist in terms of dielectric constant and dielectric loss factor values between muscle and either fat or marrow irrespective of frequency used. This may be due to the considerable difference in moisture between muscle Price & Schweigert (1971) and fat (Feiner, 2006). Marrow may contain up to 93 % fat (Gerrard, 1977) which may lead to the assumption that fat content of a substance has a crucial role to play in its dielectric properties as it will inhibit its water binding capabilities, and as a result, its water content.

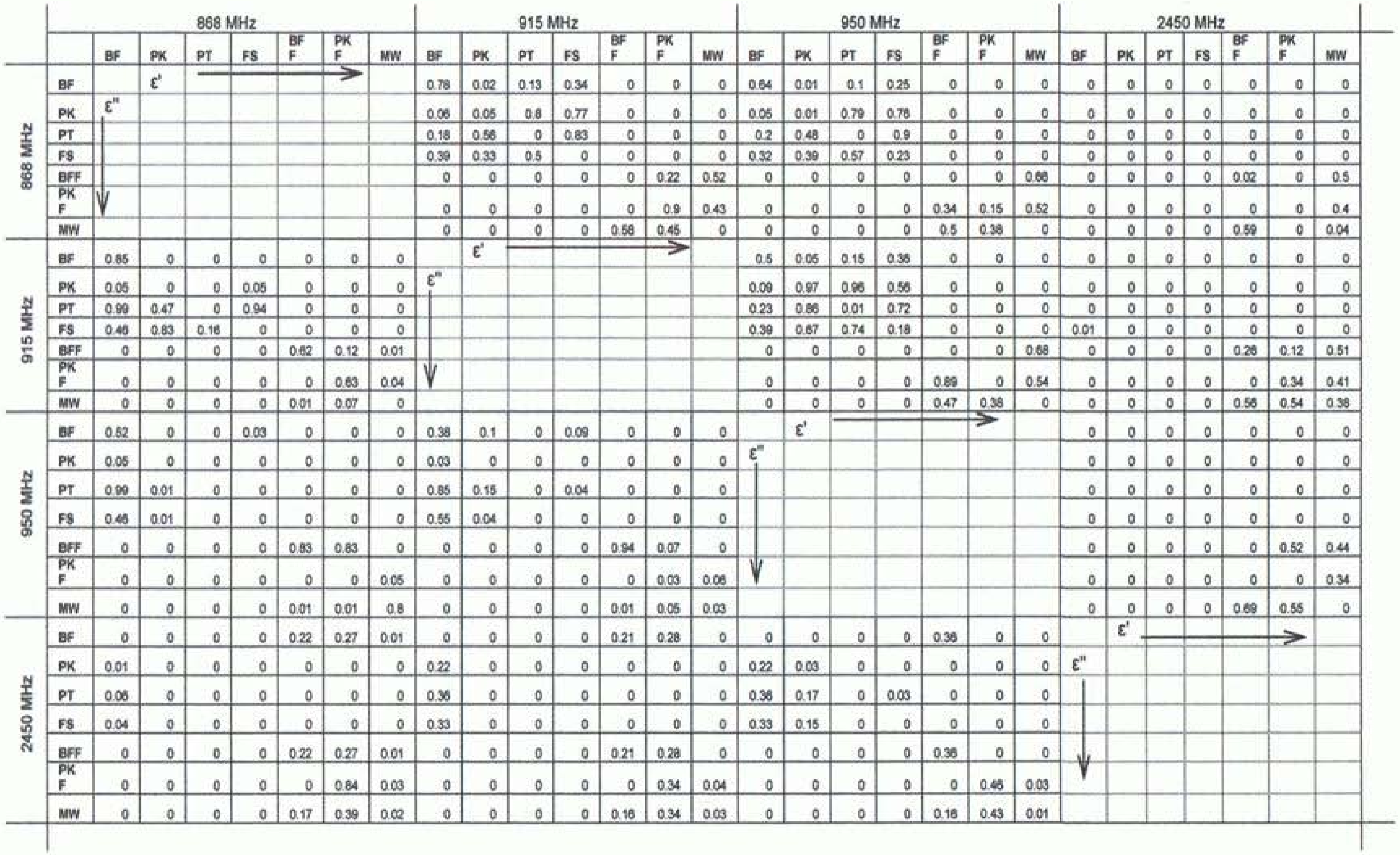
The naturally occurring protein contents of beef, pork and poultry lean muscle are 20 – 22 %, 19 – 20 % and 20 – 23 %, respectively, by weight (Varnam & Sutherland, 1995). Moisture, like protein is directly comparable in samples of beef, pork and poultry as 70 – 73 %, 68 – 70 % and 73 %, respectively, by weight. There is a clear difference between the fat content of pork muscle compared to beef and poultry yet these muscle samples contain similar moisture content to that of pork. Although it has been stated that both moisture and fat have an important role to play in dielectrics it can be seen that moisture is a dominant factor as beef, pork and poultry contain similar moisture contents yet differing fat contents resulting in closely clustered dielectric properties.

5. CONCLUSION

The permittivity of meat and its components is affected by a number of different factors including frequency, temperature, sample composition and in some cases muscle fibre orientation. These findings lead to the conclusion that at typical temperatures during processing the variation in the dielectric properties of meat will lead to a theoretical variation in the coupling capabilities of a UHF RFID system. A variation in the composition of a particular sample (muscle:fat:bone) will also vary the tag-to-reader coupling capabilities and it is believed that the data presented will be useful for the design and/or application of tag inlays in the and be an aid to the traceability of meat along the supply chain.

Future research will incorporate the use of a UHF RFID system to determine the readability of RFID tags on actual packaged meat samples, and non-parametric comparison with computer simulated detectability using dielectric properties reported in this work.

Table 2. Mean p-values of paired sample t-statistic comparison over all temperatures of dielectric constant and loss factor of meat constituents at RFID relevant frequencies



		868 MHz							915 MHz							950 MHz							2450 MHz						
		BF	PK	PT	FS	BF F	PK F	MW	BF	PK	PT	FS	BF F	PK F	MW	BF	PK	PT	FS	BF F	PK F	MW	BF	PK	PT	FS	BF F	PK F	MW
868 MHz	BF		ε' →						0.78	0.02	0.13	0.34	0	0	0	0.64	0.01	0.1	0.25	0	0	0	0	0	0	0	0	0	0
	PK	ε'' ↓							0.06	0.05	0.8	0.77	0	0	0	0.05	0.01	0.79	0.76	0	0	0	0	0	0	0	0	0	0
	PT								0.18	0.56	0	0.83	0	0	0	0.2	0.48	0	0.9	0	0	0	0	0	0	0	0	0	0
	FS								0.39	0.33	0.5	0	0	0	0	0.32	0.39	0.57	0.23	0	0	0	0	0	0	0	0	0	0
	BFF								0	0	0	0	0	0.22	0.52	0	0	0	0	0	0	0.66	0	0	0	0	0.02	0	0.5
	PK F								0	0	0	0	0	0.9	0.43	0	0	0	0	0.34	0.15	0.52	0	0	0	0	0	0	0.4
	MW								0	0	0	0	0.58	0.45	0	0	0	0	0	0.5	0.38	0	0	0	0	0	0.59	0	0.04
915 MHz	BF	0.65	0	0	0	0	0	0		ε' →						0.5	0.05	0.15	0.36	0	0	0	0	0	0	0	0	0	0
	PK	0.05	0	0	0.05	0	0	0	ε'' ↓							0.09	0.97	0.96	0.56	0	0	0	0	0	0	0	0	0	0
	PT	0.99	0.47	0	0.94	0	0	0								0.23	0.86	0.01	0.72	0	0	0	0	0	0	0	0	0	0
	FS	0.46	0.83	0.16	0	0	0	0								0.39	0.67	0.74	0.18	0	0	0	0.01	0	0	0	0	0	0
	BFF	0	0	0	0	0.62	0.12	0.01								0	0	0	0	0	0	0.68	0	0	0	0	0.26	0.12	0.51
	PK F	0	0	0	0	0	0.63	0.04								0	0	0	0	0.89	0	0.54	0	0	0	0	0	0.34	0.41
	MW	0	0	0	0	0.01	0.07	0								0	0	0	0	0.47	0.38	0	0	0	0	0	0.56	0.54	0.38
950 MHz	BF	0.52	0	0	0.03	0	0	0	0.38	0.1	0	0.09	0	0	0		ε' →						0	0	0	0	0	0	0
	PK	0.05	0	0	0	0	0	0	0.03	0	0	0	0	0	0	ε'' ↓							0	0	0	0	0	0	0
	PT	0.99	0.01	0	0	0	0	0	0.85	0.15	0	0.04	0	0	0								0	0	0	0	0	0	0
	FS	0.46	0.01	0	0	0	0	0	0.55	0.04	0	0	0	0	0								0	0	0	0	0	0	0
	BFF	0	0	0	0	0.83	0.83	0	0	0	0	0	0.94	0.07	0								0	0	0	0	0	0.52	0.44
	PK F	0	0	0	0	0	0	0.05	0	0	0	0	0	0.03	0.06								0	0	0	0	0	0	0.34
	MW	0	0	0	0	0.01	0.01	0.8	0	0	0	0	0.01	0.05	0.03								0	0	0	0	0.69	0.55	0
2450 MHz	BF	0	0	0	0	0.22	0.27	0.01	0	0	0	0	0.21	0.28	0	0	0	0	0	0.36	0	0		ε' →					
	PK	0.01	0	0	0	0	0	0	0.22	0	0	0	0	0	0	0.22	0.03	0	0	0	0	0	ε'' ↓						
	PT	0.06	0	0	0	0	0	0	0.36	0	0	0	0	0	0	0.36	0.17	0	0.03	0	0	0							
	FS	0.04	0	0	0	0	0	0	0.33	0	0	0	0	0	0	0.33	0.15	0	0	0	0	0							
	BFF	0	0	0	0	0.22	0.27	0.01	0	0	0	0	0.21	0.28	0	0	0	0	0	0.36	0	0							
	PK F	0	0	0	0	0	0.84	0.03	0	0	0	0	0	0.34	0.04	0	0	0	0	0	0.46	0.03							
	MW	0	0	0	0	0.17	0.39	0.02	0	0	0	0	0.16	0.34	0.03	0	0	0	0	0.16	0.43	0.01							

6. ACKNOWLEDGEMENTS

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