APPLICATION OF MICROWAVE SENSORS TO POTATO PRODUCTS

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Chapter 8

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List of Abbreviations and Symbols

ε'	Dielectric constant
ε''	Dielectric loss
ε_s	Static Permittivity
ε_∞	Infinity Permittivity
τ	Relaxation Time
f_c	Critical Frequency/Relaxation Frequency
ε_0	Electric constant of free space (8.854 x 10^{-12} farad(F)/m)
k	Boltzmann constant.
σ_s	Static conductivity
$\varepsilon_{s\gamma}$	Static Permittivity of free water
$\varepsilon_{s\delta}$	Static Permittivity of bound water
α	A measure of the spread of the relaxations time
ρ	Density
S11	Input Reflection Coefficient
S12	Reverse Transmission Coefficient
S21	Forward Reflection Coefficient
S22	Forward Transmission Coefficient
ε_i''	Dielectric loss of ionic solution
ε_d''	Dipole loss
ε_σ''	Ionic loss

Y	Normalised admittance
Γ	Reflection coefficient
μ_0	Permeability of the free space (4 x 10^{-7} H/m)
J_0	Bessel Function
ε^*	Relative Complex Permittivity
G	Normalised conductance
S	Normalised susceptance.
β	Phase Shift
α	Signal Attenuation
γ	Propagation Constant
τ_0	Transmission Coefficient in the Haigh Thompson & Gibson Equations
ρ_0	Reflection Coefficient in the Haigh Thompson & Gibson Equations
λ_0	Wavelength of free space
λ_c	Cut off wavelength.
Q	Q factor of resonant system
ν	viscosity
E_a	Activation energy
R	Universal gas constant
ω	Radian frequency

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Abstract

The first microwave measurement techniques uses an open ended coaxial probe with a purposely built sample holder to measure the dielectric properties of potato products from 500 MHz to 1 GHz. The second system utilises a waveguide cell with a purposely built sample holder to characterise potato products from 2.4 to 3.5 GHz. Common British varieties of raw potatoes such as Estima, King Edward and Maris Piper are used in this study. The two microwave measurement techniques are also used to measure the dielectric properties of potato products at elevated temperatures for these frequency ranges. Both measurement techniques are also used to study the effect of storage temperature on the dielectric properties of Saturna raw potato. For this part of study, it is concluded that the microwave measurement techniques are unable to discriminate between potatoes that had a storage history of different temperature profiles. On the other hand, waveguide cells and open ended coaxial probes are able to measure the dielectric properties of raw potato, partial cooked fried potato and fried potato at the 500 MHz to 1 GHz and 2.4 GHz to 3.5 GHz frequency range. The measurement results show that both dielectric constant and loss values of fried potatoes decreased with frying time, due to the reduced moisture content during the frying process. Furthermore, the dielectric loss behaviour of raw and fried potatoes is dominated by the effect of the ionic conductivity at frequencies lower than 1 GHz. An apparatus has been designed and built in order to measure the dielectric properties of potato for both frequency ranges as a function of temperature. In the subsequent measurements it is found that the dielectric properties of potato products at elevated temperatures also depend on frequency and moisture content. For high moisture content potato (~> 70 %), at 2.45 GHz both the dielectric constant and loss are found to decrease with temperature, whereas at 915 MHz the dielectric constant decreases but the loss increases for the moisture content above 30%. For the intermediate moisture content (10%<MC<70%), all dielectric properties increase with temperature at the microwave heating frequencies 2.45GHz, whereas at 915 MHz all the dielectric properties increase with temperature for the moisture content range 10% to 30%. The increase in dielectric properties with temperature is small and marginal for fried potatoes with low moisture content (< 10 %). It is therefore apparent that moisture content is the primary factor in detecting the complex permittivity of potato products.

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Chapter 1

Introduction

1.1 **Brief overview of work**.

Recent developments in food processing and agriculture processes have heightened the need for sensing to monitor the online quality of food and agriculture products. Traditional methods such as chemical analysis are time consuming and this type of analysis is considered as invasive and destructive. Microwave measurement techniques are non-hazardous, non destructive and also non-invasive and therefore may be preferred in the food industry. In industrial applications, infrared and microwave methods are the modality most commonly used but due to the short wave length, the penetration depth of infrared is only several millimetre inside the sample and hence limited to the surface of the sample. On the other hand, microwave sensors have a longer wavelength and potentially higher penetration depth than infrared extending the measurement to the core of the sample. Hence it is a suitable method to do bulk measurements.

Before the microwave sensors can be used to measure the food composition, it is necessary to establish the dielectric properties of that particular food product as a function of frequency, temperature, density and food composition. This data will be used to do the characterisation of the specific food and agriculture product. In this study various microwave techniques are developed in conjunction with temperature control apparatus to fully characterise foodstuff. The particular foodstuff of interest to this project is raw potatoes and fried potatoes. This project was partially supported by Pepsico Ltd who manufactures crisps using radio frequency and microwave drying and they have a particular need to know the material properties in the potatoes in all states of drying and frying. So far, however, there are limited studies on the microwave measurement techniques and the characterisation of the dielectric properties for the raw, partial cooked and cooked fried potatoes, particularly for the common potato varieties like Saturna, Estima, King Edward and Maris Piper. The dielectric properties of the raw, partial cooked and cooked fried potatoes are important to determine the microwave depth penetration, microwave power dissipation and heat distribution in the potato samples from raw potato to the finished fried potato products in the microwave heating system. There are several previous studies conducted on the frying of fried potatoes using microwave heating technique but these studies do not evaluate the complex permittivity of the potato. These papers discuss how microwave heating offers several advantages over the conventional heating system using a heating element.

Estima, King Edward and Maris Piper are the best known and popular varieties on sale in UK. They are widely grown across the country, so the stocks are always available for the commercial production of crisp. So these varieties of potato, Estima, King Edward and Maris Piper were selected in this PhD study.

The other focus of the research presented here is to evaluate the possibility of using microwave measurement techniques to discriminate the effect of the storage temperature on the dielectric properties of the raw Saturna potatoes. The measurement method is based on the transmission line and open ended coaxial probe measurement techniques within the frequency range 500 MHz to 1 GHz and 2.4 GHz to 3.5 GHz.

The bulk of the study presented here involved using open ended coaxial probe and waveguide cell techniques for characterising potato slices in various stages of cooking. This technique was used to extract complex permittivity of the food products mainly at 915 MHz and 2.45 GHz, which are the drying and heating frequency used in industry. The general result found from this study was that as the potato is cooked, the moisture content of material reduced and hence the complex permittivity reduces with cooking time. Furthermore when studied with temperature at 2.45 GHz both the dielectric constant and loss for high moisture content were found to decrease with increasing temperature, where as at 915 MHz the dielectric constant reduced but the loss increased with temperature. The dielectric properties of intermediate moisture content potato samples were found to increase with temperature at 2.45GHz and 9.15 MHz. For low moisture content potatoes, the dielectric properties were largely invariable at 2.45 GHz and 915 MHz.

Finally the microwave technique was investigated as a method of detecting temperature shock. In this case the microwave methods were unable to discriminate between shocked and non-shocked potato.

The objective of this PhD study is to evaluate the effectiveness of using microwave techniques to discriminate the effect of storage temperature on the dielectric properties of the raw Saturna potato, to characterise the complex permittivity of raw, partial cooked and cooked fried potatoes at the frequency range 500 MHz to 1 GHz and 2.4 GHz to 3.5 GHz and then to provide a knowledge and understanding of how the complex permittivity of potato slices change as they are heated and fried

Estima, King Edward and Maris Piper are the best known and popular varieties on sale in UK. They are widely grown across the country, so the stocks are always available for the commercial production of crisp. So these varieties of potato, Estima, King Edward and Maris Piper were chosen in this PhD study.

1.2 Brief overview of Thesis.

Chapter 1 describes the scope and background of the PhD research study. It also provides the significance of conducting the research study to the commercial food processing sector. On top of that, this chapter provides the brief overview of the other chapters in the thesis.

Chapter 2 reviews the previous research on microwave measurement of moisture content and ionic conduction for food and agriculture products. A brief review on the dielectric properties behaviour of food products against temperature at the microwave frequencies is also discussed in this chapter. There then follows a review of microwave application for the potato products

Chapter 3 discusses the overview of the microwave measurement techniques. This chapter provides the information on the most commonly used microwave measurement techniques to measure the dielectric properties of the food and agricultural products include open ended coaxial probe, transmission line method, resonant cavity method and free space methods. This chapter also reviews the advantages and disadvantages these measurement techniques for the various type of food products and in the area of dielectric properties measurement.

Chapter 4 describes the detailed overview of the dielectric properties of food products. This chapter outlines the brief information on the theoretical background and factors affecting the dielectric properties of the food products.

Chapter 5 is concerned with the theory of the microwave measurement technique used for this study. This covers the calibration, theory and measurement techniques for the open ended coaxial probe and waveguide cell.

Chapter 6 reports the measured dielectric properties of the Saturna potato stored in different temperature storage. The detailed discussion highlighted the possibility of using the microwave measurement techniques to measure the effect of the storage temperature on the dielectric properties of the Saturna potato.

Chapter 7 present the finding of the research study on the dielectric properties of the raw, partial cooked fried potato and cooked fried potato. The brief discussion on the result and conclusion for the dielectric properties of samples at the frequency measurement range 500 MHz to 1 GHz and 2.4 GHz to 3.5 GHz is presented in this chapter.

Chapter 8 concludes the research conducted in this PhD study. The detailed discussion and suggestion are presented here to improve the work in the future work study.

Chapter 2

Literature Review

2.0 Introduction

The development of improved microwave sensor devices for control and automation in the food processing industry needs a better understanding of the dielectric properties of food materials and the microwave techniques to measure these properties. Therefore, this literature review will discuss the role of dielectric properties and its correlation with food composition and the application of various microwave measuring techniques and their development for measuring food composition.

2.1 Microwave measurement techniques for dielectric properties of food materials.

The most commonly used techniques for dielectric properties measurement at microwave frequencies include open-ended probe methods, transmission line methods, resonant cavity methods and free space methods using horn waveguides. Each of these measurement techniques can be designed to operate in a specific microwave frequency range. The measurement techniques appropriate for any particular application depend upon the dielectric properties of the materials to be measured, the physical state of the materials (solid, semi-solid or liquid), the frequency range and the degree of accuracy required. This literature review will briefly describe methods that have been reported in the previous study for the use of measuring the dielectric properties of different types of food and agricultural products.

2.1.1 Microwave measurement of moisture content and moisture related parameters in bulk food samples.

In many situations, especially where moisture is involved, the measurement of moisture content can be based on microwave techniques [1 - 4]. Water has a dominant effect on the permittivity measurement of food in the microwave spectrum. Free water has a high value of static permittivity, which is around 80 at 22 C. Furthermore, water has a wide range of dielectric constant with frequency: at low frequencies the real part is asymptotic to the static dielectric constant (~ 80) but as the frequency varies through the microwave and millimetre wave band this real part reduces to around 4. The imaginary part of the water permittivity peaks at around 40 in the microwave frequency band. The maximum dispersion of free water occurs at around 18 GHz at 22 C. This high sensitivity will make water detectable and contributes a major portion of dielectric reading for food composition in the microwave frequency spectrum.

Some of the parameters such as the maturity index of fruit, water activity and texture in the food and fruit in particular have a close relationship with moisture content. One study reported that there is a close relationship between the oil content and moisture content during the fruit development for palm oil [5]. In addition water activity which is related to moisture content is important in food processing to determine microbial growth, browning effect, enzyme reaction, oxidation process and texture of food products [6,7].

The water content and soluble solid content of water melon were investigated with the correlation to its permittivity reading by Nelson[8]. The open ended probe was used to measure the complex permittivity of water melon. Moisture content and soluble solid content of water melon were used as a quality factor for the correlation with the dielectric properties. A high correlation was obtained between the dielectric constant divided by solid soluble content and dielectrics loss divided by solid soluble content.

Dielectric properties of an apple after 10 weeks of storage were measured using the open ended probe technique at radio and microwave frequencies [9]. The dielectric constant and loss of the external and internal tissues of an apple were correlated with the moisture content, firmness, solid soluble content (SSC) and pH of juices from the internal and external tissue. They found no high correlation between the dielectric reading and moisture content, SSC, firmness and pH. On the other hand, when real permittivity divided by SSC and imaginary permittivity divided by SSC is plotted in the complex plane a high correlation was obtained from the graph.

Furthermore, water related parameters such as the maturity index of fruit and water activity in the food products have been investigated to see whether there is a good correlation between these parameters [10]. The water content in the certain type of fruit like durian has a correlation with the maturity index. For example microwave techniques are also used generally to characterise the moisture content of material. Water activity measurement by microwave technique in coated paper using resonant cavity waveguide has been studied by Henrya [11]. They used the relaxation time parameter of free water and bound water to quantify the value of water activity during adsorption and desorption of water vapour on the surface of solid materials.

2.1.2 Microwave Measurements of Food Particulates.

Nelson, Kraszewki and Trabelsi have conducted a number of research projects on the determination of moisture content in food and agriculture products. Most of their work is related towards the investigation of microwave techniques on particulate materials like wheat grain. They developed a microwave method for online determination of bulk density and moisture content of particulate materials [12]. The moisture content measurement of particulate materials is independent of bulk density effect but exclusively dependent on the dielectric properties. They used an Argand diagram of the normalised effective permittivity for wheat grain at two extreme frequencies and three temperatures to develop a new density-independent function for predicting the moisture content.

Trabelsi and Nelson also conducted another study using free space methods to measure the moisture content of cereal grain and oil seed [13]. They developed a moisture calibration function which is based on the permittivity measurement at the single frequency and independent from the effect of density parameter and type of materials. The new universal calibration method in the microwave moisture sensing method will help to develop the online microwave measuring method for the moisture content of cereal grain and other granular materials.

A microwave resonator technique has been used by Kraszewski and Stuart Nelson to investigate the methods of measuring the moisture and mass simultaneously for the single soybean seed [14]. The moisture and mass of individual soybean seed are determined by the measurement of the resonant frequency shift and change in the transmission characteristic when the single soybean seed is inserted into the empty resonant cavity waveguide. The uncertainty of the measurement for the determination of moisture is less than 1 % and for mass is 3 %. A similar method was developed by Chua et al for single wheat grain kernels. A rectangular waveguide resonant cavity with the corn kernel is positioned in a plastic tube at the center of the cavity was used to measure the moisture content of the single kernel grain with arbitrary shape [15].

Another study that has been reported in the literature was to improve the use of a waveguide cell in measuring the dielectric properties of granular and liquid samples. The four boundary cell sample holder for the waveguide cell is designed to contain the granular materials or liquids [16]. This type of measurement can be used to measure the permittivity of granular and liquid forms of the food and agricultural products. In addition this four boundary sample holder in the waveguide cell can be used to determine the moisture content of food products. One of the problems with this type of measurement is the interface problem between the Perspex window and the granular material [17].

The microwave measurement system for single kernel wheat grain moisture content was developed using a cylinder cavity using the resonant TM_{010} loaded by a single wheat grain kernel with an automatic loading mechanism [17]. The density and volume of the single wheat grain are determined by a calibrated gas displacement pressure transducer. In a separate experiment, the complex permittivity of compressed wheat was measured using rectangular wave guide 10 and this data was used together with the final element method to design the microwave cavity. The compressed mechanism was used in this study to minimize the interface problem between the wheat grains and the Perspex window. The relationship correlation between grain volume and density has been established.

Andrzej Kraszewski and Stuart Nelson presented the principles of using resonant cavity wave guide to measure the single seeds and grain kernels such as peanuts, corn, soybeans, wheat rice and grape seed [18,19]. The cavity parameters that are related to the dielectric properties of seeds and kernel grains are determined by measuring the shift in the resonant frequency and the change in the Q factor when a sample is inserted into the cavity. The other dependence parameters are the volume of the cavity, sample volume, sample shape, location of sample inside cavity and mode operation of cavity.

The results of the study show the potential of using this technique for measuring the moisture content in the uniform shape of kernels and seeds and independent of size of sample.

2.1.3 Microwave Measurements on Food Pastes and Liquids

An open ended probe and water jacket with another temperature control equipment were used to measure the temperature dependence and frequency dependence of the dielectric properties for the liquid, semisolid and pulverised food materials [20]. The dielectric properties were measured over a wide range frequency and can be used to explain the influence of the other forms of water, eg: free water, bound water, rotationally hindered and dielectric relaxation mechanisms.

The horn free space waveguide with spot focusing lens was used to determine the complex permittivity of methanol at frequency range 8-40 GHz. This method is useful to measure chemical active reagent, which requires non contact measurement[21].

Another study was conducted on dielectric properties measurement of liquid whole egg and egg white at the microwave frequencies 915 MHz and 1.8 GHz. This study provides data of the dielectric properties of egg for the microwave heating application[22].

A portable microwave fat meter for the estimation of the fat content of fish has been studied for the use of measuring the fat content in beef mince, lamb mince, pork mince and turkey mince [23]. The fish fat meter operates at frequency 2 GHz and uses the moisture reading to estimate the fat content of fish. So it is possible for this equipment to use a similar concept to measure the fat content in minced meat. Beef mince (high fat), steak mince (medium to low fat) and lean mince (low fat) were prepared into 53 samples for the fat content measurement. The laboratory analysis such as oven drying was used to determine water content at the temperature 105 ^{o} C for 24 hours. Fat contents were determined by Fosslet apparatus. Protein content was determined according to the method of Kjeldahl. Ash was determined by heating drying sample at 550 ^{o} C in a furnace and weighing the residue. The result of microwave meter measurement showed that it was not accurate compared to results of the laboratory based method.

Microwave and millimetre methods were used to measure the complex permittivity of added fat in meat paste[24]. The optimum frequency measurement range from 8 GHz to 20 GHz was selected from the results of these two measurement methods. Then a rectangular wave guide cell was designed and fabricated for this frequency measurement range. The dielectric loss reading showed the better accuracy of determining the fat content than by using dielectric constant. The accuracy, robustness and repeatability of the measurement result were not much influenced by temperature and density of sample. Mixture model method was used to predict the fat content from the complex permittivity reading. A study on dielectric properties of lean, fat and meat blend was conducted to improve the understanding of the interaction between meat products and microwave radiation [25]. The complex permittivity of lean, fat and meat blend were measured at the frequency 915 MHz and 2450 MHz. The results showed that frequency and composition have an effect on the dielectric properties and the dielectric properties of pork meat fat were lower than lean meat (chicken(breast), lamb(leg) and turkey(breast)). The effect of composition change on the dielectric properties was higher in the microwave band measurement than the radio wave band measurement. The correlation between the dielectric properties and temperature was not accurate when the higher and lower dielectric activity ingredients were mixed into lean meat.

Another study was conducted on the effect of added water on the dielectric properties of pork products from UK retailers [26]. An open ended probe was used to measure the complex permittivity of the pork products at the frequency range between 130 MHz to 18 GHz. The partial least squares or principal component analysis was used to correlate between the dielectric spectra with the amount of added water and also other compositional variables such as protein, fat, salt and water in the pork products. The standard error of prediction for the added water in the pork products was ± 1.5%.

The structure of aging muscle for meat and freezing fish was evaluated using microwave sensing techniques [27]. Free space horn and rectangular waveguide probes were used to measure the dielectric properties of the fish and meat muscle at the frequency range 8.2 GHz to 12.4 GHz and 16 GHz to 24 GHz. The changing of dielectric anisotropy ratio was used to determine the freshness of the aging meat and fish during freezing-thawing cycle and storage.

Guided microwave spectroscopy GMS (Epsilon Industrial Inc, Austin, TX*)* was used to measure the soluble and total solids/total moisture in continuous processing of apple, grape, peal; apple-cherry and apple-banana juices in a pilot scale processing unit [28]. The microwave measurement equipment operated at frequency range 0.25 GHz to 3.2 GHz and temperature between 21 C to 65 C. GMS is equipped with measurement chamber having a well defined cut off frequency response characteristic. The cut-off frequency is defined by the geometry size of the measurement chamber and electromagnetic properties of the sample. The dielectric constant is determined based on the cut-off frequency and dielectric loss is determined from the slope of the cut-off curve. Guided microwave epsilon spectrometer was able to give a good result for the measurement of soluble and total solid in the fruit juice.

2.1.4 Microwave measurement to study the effect of temperature on complex permittivity

The frequency and temperature dependence of the dielectric properties of a few fruit and vegetables have been studied by Stuart Nelson at the frequency between 10 MHz to 1.8 GHz and temperature between 5 to 95 ^{o} C [29]. The permittivity measurement was conducted in the microwave and radio wave spectrum using an open-ended coaxial probe, an impedance analyser, temperature controlled stainless steel sample cup and water jacket assembly, built and designed for the probe. The dielectric constant reading at the temperature from 5 ^{o} C to 95 ^{o} C and frequency range from 10MHz to 1.8 GHz for the 9 different fresh cut fruit and vegetables increased at the lower frequency and decreased at the higher frequency. Furthermore, the dielectric loss generally increased with increasing temperature. This information on the frequency and temperature dependence of the fruit and vegetable dielectric properties is useful for the dielectric heating and quality sensing applications.

There are number of research papers that discuss the measurement of the dielectric properties of food or agriculture products as a whole and are not measuring single composition such as moisture, fat, protein and others. This research was conducted to study the effect on the dielectric properties with the change of frequency, temperature and density.

The dielectric data for the whole composition of food product such as mashed potato, ham, potato puree and others is important to determine the power penetration depth of microwave energy for designing the microwave heating system. The relation between power penetration depth and the dielectric properties of food products is described as follow.

$$\delta_p = \frac{\lambda_0}{2\pi\sqrt{2\varepsilon'}} \times \left(\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2} - 1 \right)^{1/2}$$

where λ_0 is wavelength of the microwave in free space.

A microwave heating study on salmon fish and sturgeon caviar was conducted by Murad Al Holay at the frequency of 915 MHz between temperature 20 ^{o} C to 80 ^{o} C [30]. They found that power penetration depth tended to decrease as temperature increased. On the other hand, power penetration depth is higher for unsalted salmon and sturgeon caviar compared to salted salmon and sturgeon caviar.

In another development, the dielectric properties of UHT milk were studied over the frequency 1 to 20 GHz and at temperature 17 ^{o} C to 20 ^{o} C [31]. The dielectric properties of fresh UHT milk and spoiled UHT milk were measured and the Cole-Cole parameter and ionic conductivity were extracted from the dielectric spectra to see the possibility to distinguish between fresh and spoiled UHT milk.

A microwave heating study at the frequency 915 MHz was conducted on pickled asparagus for developing short-time microwave pasteurization system on the food product which is sensitive to thermal heating [32]. The texture quality of pickled asparagus under microwave pasteurization treatment was compared with the conventional hot-water pasteurization method. The textural quality of asparagus was evaluated in shear tests and the C-value was used to assess the impact of different processes. They found that microwave method resulted in a uniform heating and it reduced a process time and thermal degradation on asparagus.

Stuart Nelson conducted a microwave measurement study using the open ended probe with sample temperature control equipment to measure the complex permittivity of solid, semi solid and pulverized food materials [33]. Dielectric properties of macaroni, ground whole wheat flour, apple juice and cheese were presented as a function of frequency and temperature. The result shows the high dependence of dielectric properties of food material on the frequency and temperature.

A research project was conducted to study the effect of short time exposure of the microwave radiation on contaminated chicken with bacteria *Escherichia coli* K12 and *Campylobacter jejuni* (5-6 log10 cfu cm-2) [34]. A microwave oven with frequency 2450 MHz and power 1138.8 W was used to radiate the electromagnetic field to the sample for 10, 20 and 30 second. The result of this study showed that short time exposure to microwave field did not significantly affect the microbial growth and increase the shelf life of the treated chicken with microwave radiation.

Another study was conducted on the microwave heat pasteurization technique for controlling the pathogenic microbes like *Salmonella enteritidis* in egg [35]. Laboratory microwave oven operating at frequency 2450 MHz and different power density (0.7, 1 and 2 W/g) was used in this study. The heating time for every power density was determined from the heating curve. The effect of microwave heating was compared with the normal water bath heating on the physical properties and dielectric properties of the yolk and albumen of egg. The result showed no significant changes of physical properties of egg compared with pasteurization of egg using water bath heating technique.

2.1.5 Microwave measurement to determine the salt or ionic conductivity of materials.

Salt or sodium chloride and other ionic conductivity material such as mono sodium glutamate, sodium nitrate, sodium nitrite and others are ingredients that can be found in food and agriculture products. These compounds are added during the food processing of the food products or it is already available in the fruit and agriculture product. The determination of salt content in food product is important because salt content will affect the flavour of food, it is used in the some of food processing techniques such as cucumber pickles and for the dietary aspect of food products such as low sodium diets. The variations of salt concentrations have an effect on the dielectric properties of food at frequencies lower than 2 GHz. This frequency range can be used to determine the salt content in the food and agriculture products.

The microwave transmission technique has been used to determine the salt content in a butter making process [36]. The result of the study indicated that the salt had a greater influence on the attenuation on the microwave transmitted through the butter than the phase shift at the frequency below than 3 GHz. The best microwave frequency for detecting the salt content in butter is below 3 GHz.

Another study was made by Chin to characterise bread dough with different densities, salt contents and water levels using microwave transmission method [37]. The microwave measurement was conducted between frequencies 0.3 MHz to 6 GHz but the analysis of measurement was reported at the frequency of 3.5 GHz. They found that dough with higher salt content showed a significant increase in the attenuation. This study shows that the microwave frequency measurement of salt content in the dough is around 3.5GHz.

Open ended rectangular wave guide or microwave reflectometer system has been used to monitor water quality [38]. The measurement system uses the dielectric properties of water to indicate the quality parameters of waste in the river or other reservoir. The dielectric properties of different salinities were measured and used as one of the indicators for the determination of water quality. They suggested to carry out the future research works on the investigation of the capability of this microwave reflectometer system for measuring the other type of impurity matters in water such as organic matters.

2.2 Previous research on the microwave application for potato's products.

As mentioned in the previous section, the dielectric properties can be used to measure the food composition such as moisture content, fat content, solid soluble content and others. There are a number of food products used in the previous studies to determine their composition by correlating with its dielectric properties. But there was limited studies conducted on the dielectric properties of fried potato. Most of the microwave research studies conducted on the drying or frying potato chips are on the advantage of using microwave frying or drying over conventional frying or drying method. Here this section will outline the research study conducted on the potato product especially pertaining to the microwave application and its dielectric properties.

M.H Oztop conducted the study on the effect of microwave frying on the quality of potato chips such as moisture content, hardness, colour and oil absorption [39]. He found that the optimum condition for microwave frying is 550 W microwave power levels for 2.5 min frying time in sunflower cooking oil. This optimum condition will give less oil content in the potato chips as compared to conventional frying. He also found that moisture content decreased but oil content, hardness and colour of potato increased as the frying time and microwave power level were increased.

A comparative study between microwave drying, combined convective and microwave drying, and convective drying was conducted on the drying rate and effective moisture diffusivity profiles of drying process for the potato chips [40]. The drying duration and diffusivity were decreased in microwave drying.

A fluidised bed dryer with the assistance of microwave application reduced the drying time by 85 percent as compared to that without microwave application [41]. The potato quality parameter of potato slices such as colour remains similar between conventional the fluidised bed dryer and the fluidised bed dryer with the microwave application.

Microwave finish frying of potato chips containing 0.5 % higher glucose content will make the colour quality of the finished potato chips more acceptable to consumer[42]. The oil content of microwave finish-dried potato chips is 5.7 % lower than conventional fried potato chips.

The other research studies were conducted on the dielectric properties of potato products at the microwave heating frequency, in order to see the dielectric properties profile of the potato products for use in microwave heating applications. This study was conducted to study the use of microwave heating systems to thaw frozen mashed potatoes [43]. Regier et al investigated the effect of temperature (-17 C to 80 C) and preparation procedure on the dielectric properties of mashed potatoes. They found that the dielectric properties were not much affected by the temperature at 2.45 GHz above the freezing temperature. However, there was a sharp increase of the dielectric properties above the melting temperature.

Mladek and Komarek conducted the comparison study between the dielectric properties of potato and wheat starches containing up to 40% water [44]. They found that at 10 GHz, the value for dielectric constant of potato starch is higher than wheat starch. On the other hand, the value for dielectric loss of potato starch is lower. The dielectric loss is contributed by the relaxation of hydroxyl groups in a dry starch molecule.

2.3 Conclusion.

In this literature review, the main papers on the microwave measurement techniques and dielectric properties of food materials has been discussed and reviewed. Different microwave measurement techniques used to measure dielectric properties of various types of food products were reviewed. It also discusses the correlation between the dielectric properties and food composition such as moisture, salt and other moisture related parameters. The research paper on the application of microwave frying and drying on the potato products have been enlisted in this chapter. The research study described in these literatures is used to support the new research presented in this thesis.

Chapter 3.

Microwave Measurement Techniques.

3.1 Introduction.

The microwave electromagnetic radiation spectrum lies within a frequency range from 10^8 up to 10^{11} Hz with the wavelengths of 0.3–300 cm. More specifically, the microwave frequency range is typically considered to range from 1GHz to 30GHz. Example bands within that range include: 800 MHz-1.8 GHz (mobile phone), 2.45 GHz (microwave oven), 1GHz-40 GHz (Radar). An important parameter associated with electromagnetic propagation is the complex permittivity of the propagating medium. The permittivity of the medium affects how the signal will be reflected, attenuated and transmitted between a source and receiver. For example, the permittivity of space and the environment including weather conditions is important for communications signal transmission and radar. The permittivity of sea-water is important for marine radar and subsea communications. Similarly, the complex permittivity of foodstuffs is important for microwave cooking as in the microwave range (around 2 GHz) both the dielectric constant and dielectric loss of water are maximised and its interaction with high power microwaves is utilised to produce heating of the foodstuff. That is why, it is important that foodstuffs in microwave ovens do not become totally dehydrated in the heating process. Of course, microwave signals interact differently with different food materials such as water, salt water, protein, carbohydrate and fat and that is one reason that regions within food packages heat at different rates. In general this is a problem for microwave engineers when designing heating equipment and there have been several solutions including mode scatterers and turntables. However, the fact that microwaves interact differently with different food materials can be used to advantage when microwave techniques are adapted as sensors to determine content. For example, as protein contains a large proportion of water microwaves techniques provide a very robust approach to determining the fat content of meat samples. Similarly, the ionic conduction of salt solutions is readily determined at low microwave frequencies via the imaginary part of the complex permittivity.

The most commonly used techniques for permittivity measurement at the microwave frequencies include open-ended probe methods, transmission line methods, resonant cavity methods and free space methods using horn waveguides. Each of these measurement techniques can be designed to operate in a specific microwave frequency range. These methods have been reported in the literature for the use of measuring the permittivity of different types of food and agricultural products. In this introduction, a brief overview of these methods is presented.

3.2 Open ended probe method.

There are a number of authors in the literature who have described open ended coaxial probes as a sensor that can be used to measure the dielectric properties of materials in the microwave frequency range [45-49]. Open ended probe measurements are considered non destructive and can provide broadband information[45]. In its simple form, the open ended probe consists of a truncated section of the coaxial line with the optional extension of a ground plane. The probe is connected to a vector network analyser through a coaxial cable to determine the reflection coefficient. The material under test is placed at the end of the probe and the permittivity of the sample under test is determined from the reflection coefficient and admittance of the probe[5]. The admittance of the probe and the permittivity of the sample are calculated by using a lumped equivalent circuit and the point-matching method[50, 51].

The open ended probe measurement has advantages that include ease of sample preparation and small size of sample needed for the measurement. It provides good accuracy for the measurement of complex permittivity for high loss materials but is less accurate for low loss materials[52]. An important consideration is the selection of the calibration material and its match with the type of material to be characterised. For example, distilled water is often used as the calibration material for the measurement of high dielectric constant materials.

On the other hand, for low loss materials, silicone oil or cyclohexane is recommended to be a reference liquid

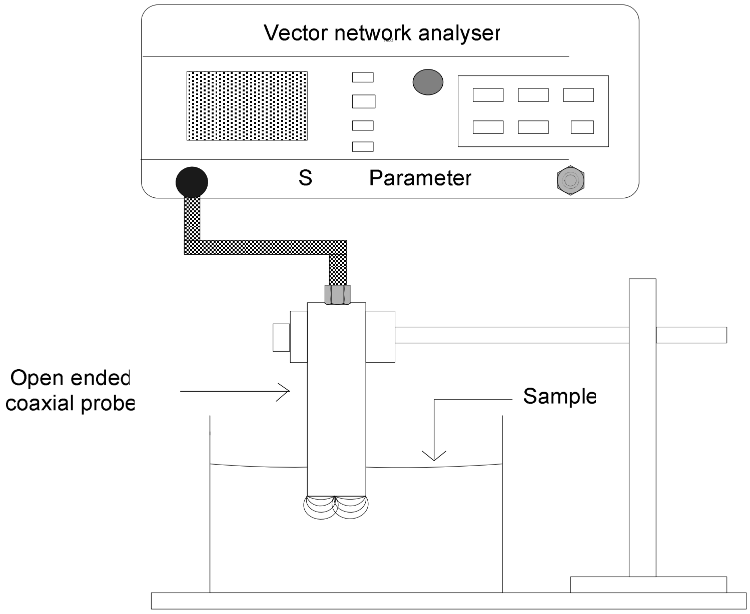


Figure 3.1 : Schematic diagram of the open ended probe measurement.

The coaxial probe method is an open technique where the probe can be brought to the material under test, and as such it can provide very quick measurements. It is particularly useful for characterising liquids where the probe can be easily inserted into the sample. It is very important to ensure that there are no air bubbles on the interface between the coaxial probe surface and the liquid. This method only measures the local permittivity of the liquid as the electromagnetic field only propagates a fraction of a wavelength into the liquid. Therefore, it is important that the liquid or sample is homogeneous. Sometimes the method can be used to characterise pastes, but it is not so useful for solids or particulates. It is a broadband technique such as that information can be extracted from RF frequencies right through to millimetre-wave frequencies. In this way, the coaxial probe method is very useful for determining the frequency of maximum sensitivity as a preamble to designing sensors. For example, ionic conductivity has a large dependency below 2 GHz and the dipolar effect of water is maximised between 10 GHz to 20 GHz; these effects can be quickly measured and visualised using the open probe technique.

3.3 Transmission line method.

The transmission line is an ordinary method to determine the complex permittivity for solid, particulate and liquid materials. The measurement is restricted to the dominant mode and frequency range. Therefore, it is very important to make sure that higher order modes are not supported as this would cause an erroneous derivation of the complex permittivity of the sample. Using this technique, the sample is inserted into the waveguide transmission line sample holder, sometimes known as the waveguide cell. The sample holder is in the form of rectangular or coaxial cross-section. When the microwave signal is sent to sample, some of the signal is reflected from the sample and the rest is absorbed by the sample or passes through it. This signal is measured by a vector network analyser in the form of scattering (S) parameters. The characteristic equation for the boundary value problem is a function of the cell geometry and the complex permittivity of the sample. Using the S parameters as data input an iterative algorithm is employed to extract the complex permittivity of the sample. If the material under test is a solid then it is possible to model the boundary value problem as a two boundary problem. This problem was first dealt with by Tischer, who developed a formulation in terms of the reflection and transmission coefficients[53]. Using this transcendental equation and the measured S-parameters the complex permittivity of the sample can be extracted for each frequency of measurement in the waveguide band. In the case of liquids and particulate materials the two layer boundary formulation is not practical, and it becomes necessary to introduce low-loss windows that can seal the cell and create a holder for the liquid or particulate material under test. This problem is a three layer boundary value problem typically consisting of a Perspex window, followed by the sample material and bounded by a second Perspex window. This three layer is a four boundary cell problem that has been formulated by a number of authors in the literature [16, 54].

This algorithm describes how to derive the reflection and transmission equation of the 4 boundary rectangular wave guide cell with 2 perspex windows and 1 space cell for the sample. The cell and 2 perspex windows are typically inserted into a rectangular waveguide transmission line of the chosen frequency band. The transmission coefficient for the whole cell is derived and then the complex permittivity of sample is calculated using the Newton–Raphson approximation method. Before the measurement, the network analyser and waveguide are calibrated and error corrected by a full 2 port calibration process.

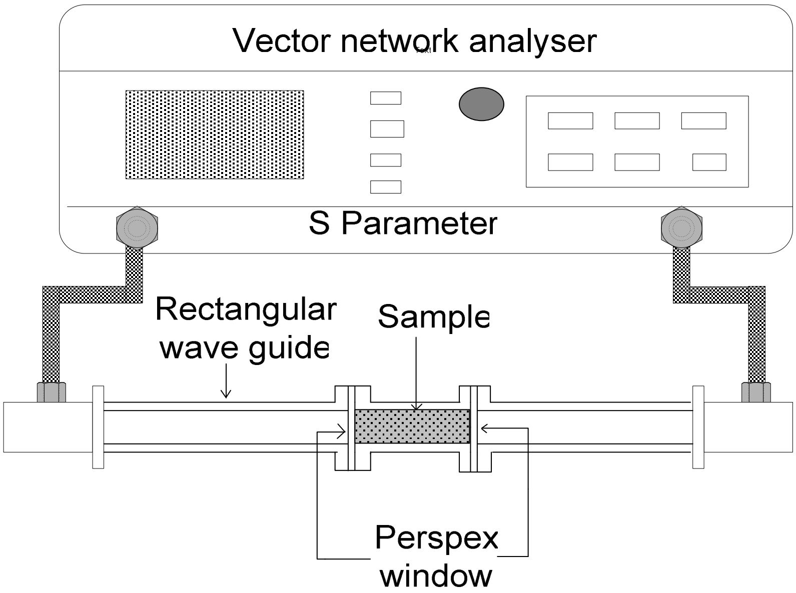


Figure 3.2: Schematic diagram of the transmission line measurement

Unlike the coaxial probe technique, the waveguide cell approach is enclosed inside a waveguide and this means that the sample preparation, loading and measurement can take some time. Furthermore, when measuring liquids it is very important not to capture air on the surface of the Perspex windows or within the cell. Surface contact between the windows and particulate materials can also lead to irregularities in the measurement process[17]. However, the waveguide cell method is more accurate than the coaxial measurement, but it is taken over a narrower frequency band. In order to obtain broadband information using this method requires the use of several waveguide sizes and considerable sample preparation and experimental effort. This method is also suited to the computer control and automated derivation of the complex permittivity by downloading the S parameter data from the VNA.

3.4 Resonant cavity method.

The coaxial line reflection method and the transmission cell method previously discussed are undertaken over relatively high frequency bands and rely on accurate models to determine the complex permittivity. On the other hand, a resonant cavity could be constructed and loaded with a relatively low loss, small scale sample. The resonant frequency and Q of the cavity will be perturbed by the complex permittivity of the sample. Resonant cavities are constructed from coaxial, circular and rectangular waveguides depending on the application. The cavity has an external Q associated with the coupling and this could be an aperture, electric probe or magnetic loop depending on the connecting waveguide and the field distribution of the desired resonant mode. As the cavity is so sensitive to load variations then it requires careful sample preparation[18]. This technique is recommended to measure the complex permittivity of a low loss material [18]. For example, a cylindrical resonant cavity has been used to determine the moisture content of single grain kernels placed in the centre of the structure and used to perturb the TM_{010} mode.

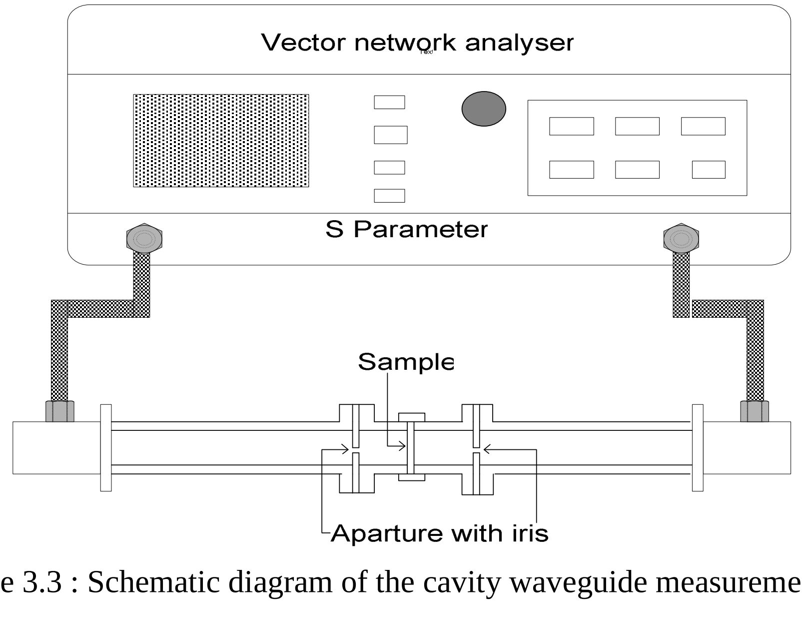


Figure 3.3 : Schematic diagram of the cavity waveguide measurement

This approach is calibrated to determine the microwave properties of the material by measuring the shift of resonant frequency and the change of Q factor of the cavity when material is inserted into the cavity[19]. The complex permittivity of the sample can be determined from the resonant frequency and Q factor of empty and filled cavity, the volume of sample and empty cavity[55]. The resonant cavity technique is not suited to on-line measurements as the sample has to be prepared and carefully loaded into the resonator structure. It is most useful when trying to detect very small changes in the sample such as the level of moisture content in fairly dehydrated samples.

3.5 Free space method using horn wave guide.

Free space techniques are non destructive and has no contact with the sample. The sample preparation does not require fixing to any shape. As a result, it is suitable for the high temperature measurement and inhomogeneous dielectric[56]. The sample will be placed between the transmitting and receiving the horn wave guide, and then the attenuation and phase shift are measured.

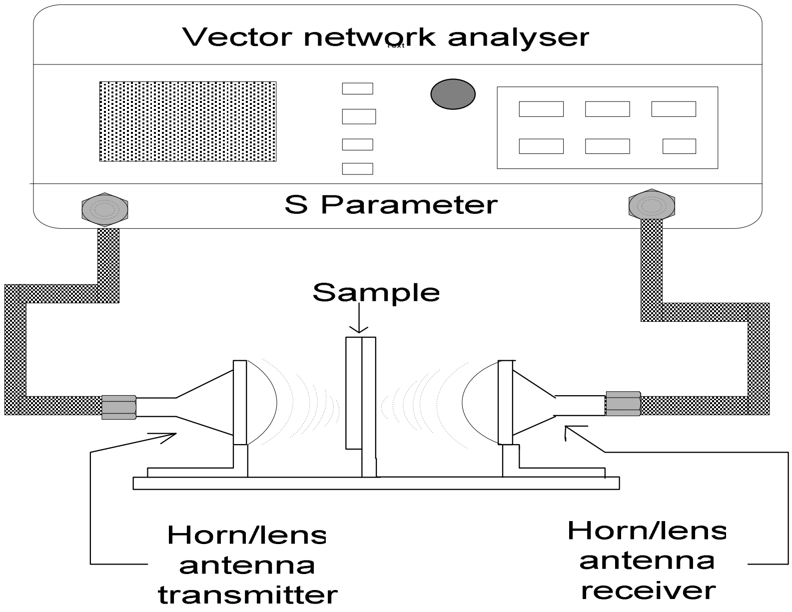


Figure 3.4: Schematic diagram of the free space waveguide measurement

The complex permittivity of the sample can be derived from the value of transmission and reflection coefficients. In this measurement, error occurs from mismatches, multiple reflection and diffraction at the sample edges and parasitic interference from the immediate environment. The accuracy of measurement depends on the choice of radiating element, the design of the sample holder, sample thickness and the position of the sample in between of two radiating elements[56].

3.6 Comparison of microwave measurement techniques.

Many factors such as the frequency measurement, accuracy, convenience, and the material shape and form are important in selecting the most appropriate measurement technique. The features and advantages of each microwave measurement techniques are summarised in the table 3.1.

Table 3.1 : The features of microwave measurement techniques

Technique / Features	Open ended probe	Transmission line	Resonant cavity	Free space using horn waveguide
Usable Band (GHz)	Broadband 0.1 to 50 GHz frequency.	Restricted to waveguide bands.	Single frequency	Restricted to waveguide bands
Sample preparation	Non destructive / easy	Destructive/ precise sample shape to fit into the waveguide.	Destructive/ small	Non destructive and hard
Type of sample	Liquid or semi solid	Liquid, semisolid, particulate, granular material	Best for low loss material and small sample	Best for flat sheet, powder and high temperature measurement. Not contacting with sample.
Measurement at different temperatures	Easy	Hard	Hard	Easy
Inline field measurement	Easy	Hard	Hard	Medium
Accuracy low loss	Bad	Reasonable	Good	Reasonable
Accuracy high loss	Good	Very good	Poor	Good

3.7 Conclusion.

The common complex permittivity measuring techniques such as the coaxial probe, waveguide cell, cavity waveguide and free space waveguide are discussed in this chapter. The advantages and disadvantages of each waveguide are given. This will provide knowledge on the selection of measuring technique for specific application or foodstuff.

Chapter 4.

Dielectric properties of food products.

4.1 Introduction

Dielectric properties can be categorised into two parameters, dielectric constant ($\varepsilon^{'}$) and dielectric loss factor ($\varepsilon^{''}$). Dielectric constant is the ability of a material to store microwave energy and dielectric loss factor describes the ability of a material to dissipate microwave energy into heat. The dielectric properties can be used to determine the interaction of microwaves with food and agricultural products. The complex permittivity can be expressed in mathematical form as:

$$\varepsilon^{*} = \varepsilon' - j\varepsilon'' \tag{4.1}$$

where $\varepsilon^{'}$ is dielectric constant and $\varepsilon^{''}$ is dielectric loss.

The dielectric properties of food and agricultural product can be divided into polar and non polar. Polar materials have a distribution of positive and negative charges in their molecules. Normally polar materials do not have symmetrical charge molecules and they exhibit a dipole moment. When it is exposed to the microwave field, it will experience a rotational force attempting to orient them in the direction of the field. The electric charges in the material tend to separate, the negative charges moving to the positive electric field and the positive charges toward negative electric field. Non polar materials do not have dipole moments and relaxation process in the microwave region. It does not have the characteristic of polar material when it is exposed to the electric field.

For a polar material with a single relaxation time, its complex permittivity can be expressed with the Debye equation.

$$\varepsilon^* = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j\omega\tau} \tag{4.2}$$

where ε_∞ is the infinity permittivity, ε_s is static permittivity and τ is the relaxation time.

The relaxation time is a measure of the time taken for the dipoles to return to a random distribution of orientations through exchange of angular momentum by collision by other molecules. Then relaxation time is dependent on the temperature of material. The complex permittivity of food composition which is frequency dependent has the characteristic of a polar material. It has a static permittivity ε_s at the low frequency and infinity permittivity ε_∞ at the higher frequency. The graph of real permittivity and imaginary permittivity which is frequency dependent is shown in Fig. 4.1 for a typical polar dielectric.

The peak of dielectric loss occurs at the relaxation time or critical frequency given by

$$\mathrm{f_c} = \frac{1}{2\pi\tau} \tag{4.3}$$

Water is a good example of a polar material. Each molecule has two positive charges of hydrogen and one negative charge of oxygen. The dielectric dispersion of water at room temperature is quite a large magnitude. Its static permittivity at the room temperature is 80 and infinity permittivity is approximately 5. The relaxation time or maximum peak of dielectric loss occurs at around 17 GHz. All these factors make water responsive to microwave frequencies.

4.2 Parameters affecting the dielectric properties of food materials.

The dielectric properties of food and agriculture products depend on the frequency of the applied electromagnetic field, its temperature, composition and density.

4.2.1 Frequency dependence.

The dielectric properties of the polar materials vary with frequency. It is due to the polarisation of molecule and their effort to reorient under the influence of a changing electric field. Debye describes this process with the high value of static dielectric constant at zero frequency and the dielectric constant at the very high frequency where molecular orientation is not affected by polarisation. In between of these two permittivities, the dielectric constant and loss change with frequency of the applied electromagnetic field. In the microwave spectrum dipolar materials like water have a high value of dielectric loss and constant. Most food and agriculture products contain a lot of water whereby its dielectric properties vary with frequency. Some non polar food material such as cooking oil has very low dielectric loss and low dielectric constant. The dielectric properties of cooking oil are not dependent on frequency. At the microwave frequency above, 1 GHz, dipolar polarisation is the dominant effect. The dipolar polarisation in the microwave frequency is the contributing factor of the dielectric loss in the food materials which is due to the orientation of water molecule with the imposed electric field.

Debye has developed the dielectric model to describe the interaction between dielectric properties of pure polar material such as water with frequency and this is given in the form

$$\varepsilon^{*} = \varepsilon_{\infty} + \frac{\varepsilon_{s} - \varepsilon_{\infty}}{1 + j\omega\tau} \tag{4.4}$$

where ε_{∞} is the infinity permittivity, ε_{s} is static permittivity and τ is the relaxation time.

The relationship of the Debye equation is illustrated in the figure 4.1 for water.

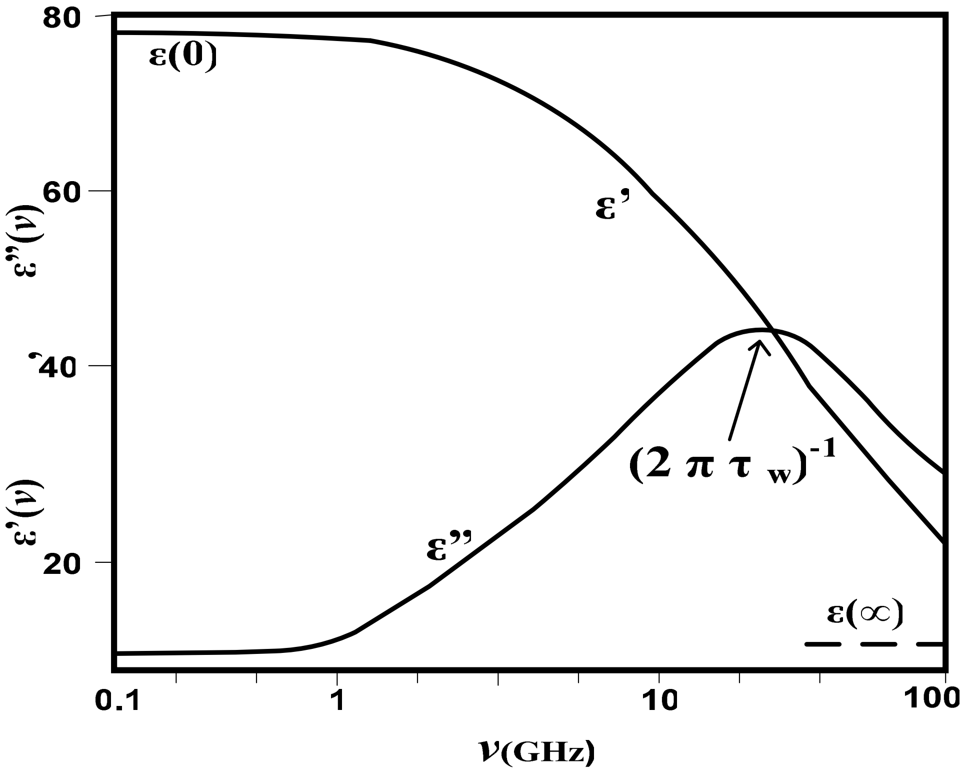


Figure 4.1. Real permittivity (ε') and imaginary permittivity (ε'') for water at 25 ^{o}C. Microwave permittivity data for water is taken from the literature[56]

ω is the angular frequency where f is the frequency of the electric field. From the Debye dielectric model, the permittivity of polar material is varied with the frequency in the intermediate frequencies region between static permittivity and infinity permittivity as shown in the figure 4.1. The dielectric constant undergoes dispersion from the static permittivity to the infinity permittivity. But the dielectric loss has the maximum peak loss due the dissipation of the electric field. This phenomena occurs at the relaxation frequency $\omega = 1/\tau$.

The dielectric data can be presented graphically in the complex plane ε' and ε " which is known as a Cole-Cole diagram.

4.2.2 Temperature dependence.

The dielectric properties of materials also depend on the temperature. When the temperature of a material is increased, their molecules will distance themselves from each other, and then it has short time to return to their normal orientation. In the influence of electromagnetic field, a material at a high temperature will have low relaxation time (τ) and then the peak of dielectric loss will shift to the higher frequency ($\omega = 1/ \tau$). Dielectric constant will increase and dielectric loss will decrease or increase depending whether the operating frequency is lower or higher than the relaxation frequency. Free and bound water and ionic conductivity affect the rate of change of dielectric constant and loss with temperature[57]. If bound water is present, the increase in temperature will increase the dielectric properties. But in the presence of free water, the increase of temperature will decrease the dielectric properties.

In general the food composition consists of dipolar and ionic materials and their dielectric loss compose of dipolar loss and ionic loss. The increase in temperature will decrease the dipolar dielectric loss but in the case of ionic loss, dielectric loss will increase if the temperature increases[57]. As a result, for food materials containing both dipolar and ionic components, it is possible to observe first a decrease and then an increase in dielectric loss with temperature.

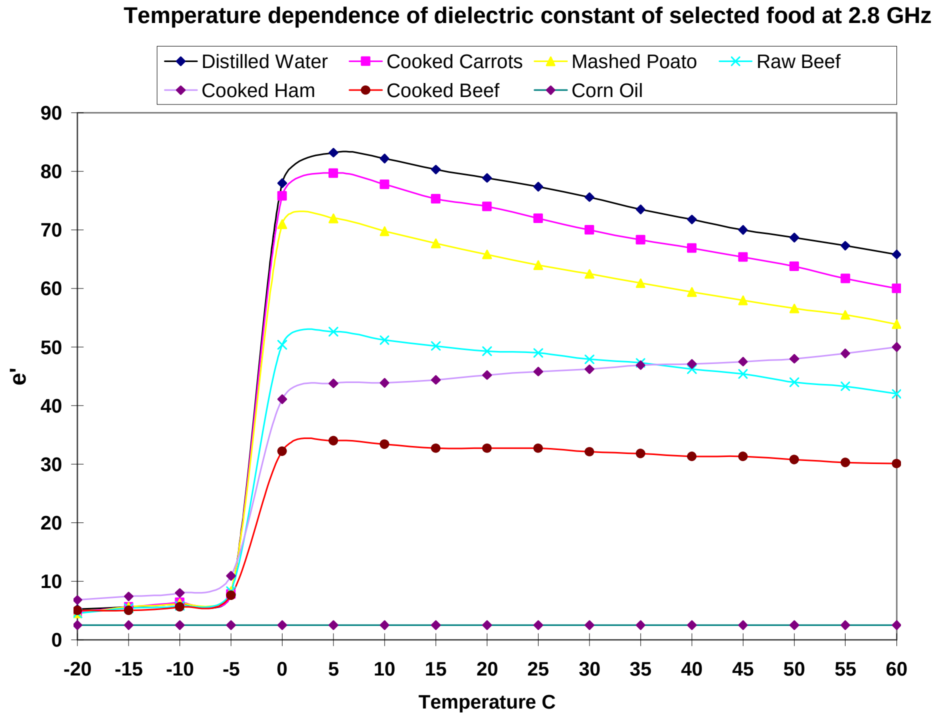


Figure 4.2 : Temperature dependence of dielectric constant of selected food From [59]

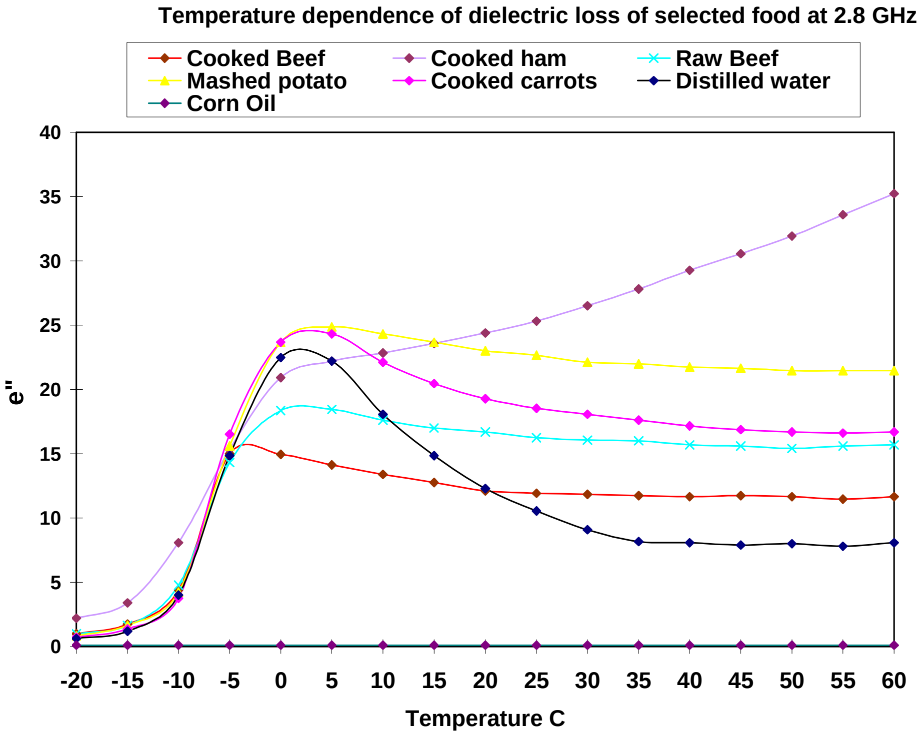


Figure 4.3. : Temperature dependence of dielectric loss of selected food. From [59].

Figure 4.2 and 4.3 show the dielectric constant and loss of various food products vary and how they vary differently with changing temperature. It shows that the dielectric properties of different food products above the temperature 0 ^{o} C decrease with increasing temperature except for the salted food such as cooked ham. The salt content in cooked ham makes its dielectric behaviour against temperature quite different from other food products. Dielectric properties of ham are dominated by the dielectric properties of salt, hence both of dielectric constant and loss of cooked ham increase with temperature. The variation of dielectric loss of salty material is different because its loss factor consists of dipolar and ionic loss. Further more the effect on the dielectric loss for the dipolar, ionic and mixed of dipolar and ionic material is illustrated in the figure 4.4

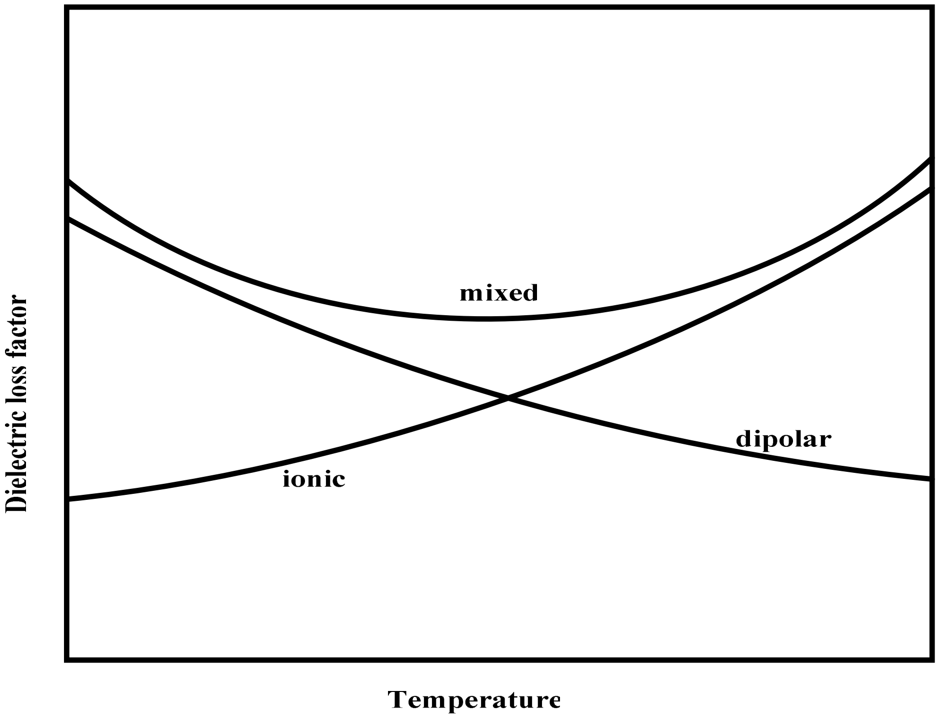


Figure 4.4: Variation of loss factor component with temperature. From [56].

The dependence of the Cole-Cole parameter of dielectric properties such as static permittivity with temperature is shown in the Hasted polynomial expression for free water[58]. The polynomial expression is shown in the equation below.

$$\varepsilon_s = 87.740 - 0.40008T + 9.398\times10^{-4}T^2 - 1.410\times10^{-6}T^3. \qquad \textbf{(4.5)}$$

where T is the temperature in ^{o}C and ε_s is the static permittivity.

Relaxation time is one of the parameters in the Cole-Cole equation that can be used to determine the value of dielectric properties. The dependence of relaxation time with temperature has been studied by Debye. He showed that if the molecule in the solution is spherical with radius a, viscosity η then single relaxation time dispersion is described by the following equation.

$$\tau = 4\pi a^3 \eta / kT \qquad \textbf{(4.6)}$$

where τ is relaxation time, T is a temperature in unit Kelvin and k is a Boltzmann constant.

The equation shows the relaxation is inversely dependent on the temperature. If the temperature changes, it will change the relaxation time. As a result with referring to the Cole-Cole equation the complex permittivity will change accordingly.

4.2.3 Composition dependence

Dielectric properties of food products depend on composition. Most food materials contain of carbohydrate, moisture, fat, protein and salt. There are other inorganic and organic substances which also occur in food. Water is one of the main components of food composition. It lies within cells and a part of water occurs in the extra cellular space. Also free water binds with the hydrophilic group of organic molecules and can be rotationally hindered by others molecules. So the interaction of water with other food components is very complex and every interaction will affect the dielectric properties of the food. In addition the presence of moisture in the form of free water and bound water and salt will affect the dielectric properties of food composition at the lower and high frequency. Free water and ionic materials have high dielectric activity in the microwave spectrum. Free water will affect the dielectric properties at higher frequencies. However the ionic material will affect the dielectric properties at the lower frequency of the microwave spectrum especially as a high increase of dielectric loss with the amount of ionic material. On the other hand, food components such as dehydrated protein, carbohydrate and fat have low dielectric activity in the microwave frequency spectrum. In addition hydrogen binding in water will bind with other food materials and this process will affect the dielectric properties of the food composition.

The complex interaction of every component in the food composition that affects the dielectric property can be modelled using the following dielectric modelling[60]. Some researchers have suggested the other modelling method such as multiple linear regressions, partial least square regression and artificial neural network to model the dielectric properties and the complex interaction between each component in the food composition. The Cole-Cole model for multiple relaxation times for free water, bound water and saline combined is given by

$$\varepsilon = \varepsilon_\infty - \frac{\left(\varepsilon_{\mathrm{s}_\gamma} - \varepsilon_\infty\right)}{1+\left(\mathrm{j}\omega\tau_\gamma\right)^{\left(1-\alpha_\gamma\right)}} + \frac{\left(\varepsilon_{\mathrm{s}_\delta} - \varepsilon_\infty\right)}{1+\left(\mathrm{j}\omega\tau_\delta\right)^{\left(1-\alpha_\delta\right)}} - \mathrm{j}\frac{\sigma}{\omega\varepsilon_0} \qquad \textbf{(4.7)}$$

$\varepsilon_{\mathrm{s}_\gamma}$	Static permittivity for the free water
τ_γ	Relaxation times for the free water
α_γ	A measure of the spread of the relaxation for the free water
$\varepsilon_{\mathrm{s}_\delta}$	Static permittivity for the bound water
τ_δ	Relaxation times for the bound water
α_δ	A measure of the spread of the relaxation for the bound water
ε_0	Permittivity for free space
σ	Static conductivity
ε_∞	Infinity permittivity

The Cole-Cole equation with multi relaxation times above describes the effect of free water, bound water and ionic conductivity in the food composition on their dielectric property. Free water and salt are two major components in the food composition that give the high effect on the dielectric property in the microwave spectrum. Bound water is a result from the hydrogen binding process of free water with other components in food. Normally the value of dielectric properties of bound water is very low and gives a low impact on the dielectric properties of food composition

Table 4.1: Effect on the dielectric constant and loss of salt, fat and free water with frequency and temperature. From [89].

Component (Food composition)	Effect on dielectric constant and loss	
	Frequency	Temperature
Salt (Polar)	ε” increases with decreasing frequency at low frequency. ε’ decreases with increasing frequency	ε” increases with increasing temperature. ε’ increases with increasing temperature
Fat (Non polar)	ε” and ε’ are constant at microwave frequency.	ε” and ε’ are constant with increasing temperature.
Free Water (Polar)	ε’ decreases with increasing frequency. ε” increases at relaxation frequency.	ε’ and ε” decrease with increasing temperature.

4.2.4 Density dependence

The dispersion and dissipation of electromagnetic energy interacting with materials depends on the shape, dimension and relative permittivity of material[60]. As a result density which is a mass per unit volume has an effect on the electromagnetic wave and dielectric properties.

The relationship of dielectric properties of granular material with density can be shown using the dielectric mixture equation for a two phase mixture[61].

$$\sqrt{\varepsilon} = v_1\sqrt{\varepsilon_1} + v_2\sqrt{\varepsilon_2} \tag{4.8}$$

Where ε complex permittivity of mixture, ε_1 and ε_2 are complex permittivity of granular material and host medium. v_1 and v_2 are the volume fraction of granular material and host medium and $v_1 + v_2$ =1.

If the host medium is air then ε_1=1-j0 and the complex permittivity of granular material as medium 2, $\varepsilon_2 = \varepsilon_2^{'} - j\varepsilon_2^{''}$.Stuart Nelson used the linear extrapolation technique to divide the real and imaginary parts of the linear relationship between the complex permittivity and density of the granular material as shown below [61].

$$\sqrt{\varepsilon^{'}} = \left(\frac{\sqrt{\varepsilon_2} - 1}{\rho_2} \right) \rho + 1 \text{and } \sqrt{\varepsilon^{''}} = \frac{\rho}{\rho_2} \left(\sqrt{\varepsilon_2} \right) \qquad \textbf{(4.9)}$$

where $v_2 = \frac{\rho}{\rho_2}$, ρ = density of air and granular material.

ρ_2 = density of granular material.

The above equation shows the dependence of dielectric properties of a mixture granular material and air on density.

4.3 Conclusion.

This chapter provides theoretical background on the dielectric properties of food when it is exposed to the microwave radiation. Factors affecting dielectric properties of food such as frequency, temperature, composition, density are elaborated. Further discussion on the higher effect of water and ionic conduction on dielectric properties of foodstuff is given. These will provide the better understanding of dielectric properties of food stuff which is useful to design the microwave sensor.

Chapter 5.

Extracting complex permittivity from microwave measurement techniques.

5.1 Introduction

Microwave measurement techniques depend on the physical state of sample (particulate, liquid or semi-solid) and measurement frequency. This chapter discusses detailed theory of measurement techniques adopted in this research study which covers open ended probe and waveguide cell techniques. Open ended probe can operate over broadband frequency and temperature. This technique was used to measure complex permittivity of sample between 500 MHz to 1 GHz frequency measurement. Waveguide cell can operate within limited frequency range and frequency measurement is restricted by the waveguide size. Waveguide cell (WKG 10) was used to measure complex permittivity of sample between frequency 2.3 GHz to 3.5 GHz.

5.2 Open ended probe.

The Agilent 85070E, ‘Performance’ probe was used to measure complex permittivity of sample. The probe measurement system (Agilent 85070E) controls the network analyser, S11 parameter to complex permittivity conversion and complex permittivity data presentation system. The software controls the network analyser to measure S11 parameter of sample and convert it to complex permittivity value. The result of complex permittivity reading is displayed in a variety of graphical and tabular formats. The probe is constructed from stainless steel and has an outer layer diameter of 1.6 mm and inner diameter of 0.3 mm. The end of probe is sealed with borosilicate glass dielectric.

5.2.1 Theory of open ended probe.

The Angilent software 85070E uses the reflected signal S_{11} and the point matching method to calculate the permittivity value[51,64]. The reflection coefficient of the coaxial line is obtained by matching the electromagnetic field at the interface z = 0 between the open-ended probe and measurement sample. The coaxial probe model for an aperture opening on an infinite ground plane can be derived using the matching technique for the magnetic field at the aperture of probe and sample.

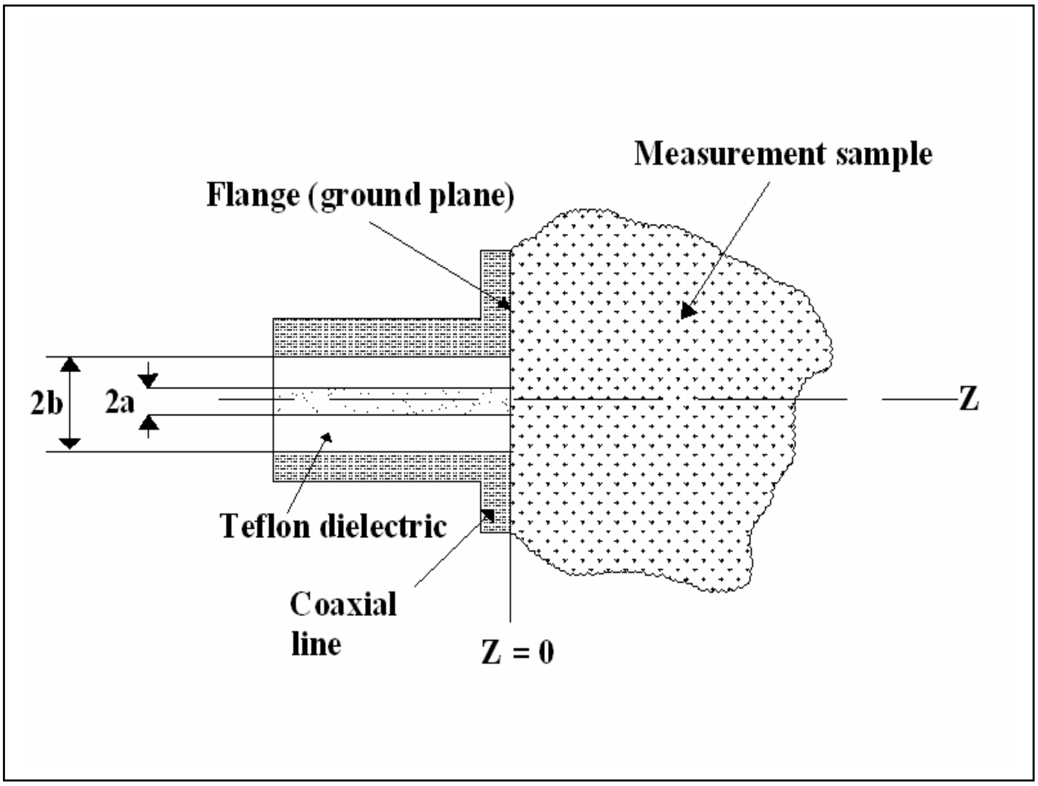


Figure 5.1: Open circuit coaxial line sample measurement configuration

The relationship between the reflection coefficient (Γ) and normalised admittance (Y) of the coaxial probe is expressed as below.

$$Y = \frac{(1-\Gamma)}{(1+\Gamma)} \tag{5.1}$$

Marcuvitz expressed the admittance of the probe as an integral over the aperture. Misra has discussed a quasi-static analysis of an open ended probe terminated by a semi-infinite medium on a ground plane[50]. The formulation for the admittance of the open-ended probe [63]:

$$Y = j\frac{k^2 Y_o}{\pi k_c \ln\left(\frac{b}{a}\right)} \int_a^b \int_a^b \int_0^\pi \cos\phi' \frac{\exp(-jkr)}{r} d\phi' d\rho' d\rho \quad \textbf{(5.2)}$$

Where

$r = \left\{\rho^2 + \rho'^2 - 2\rho\rho' \cos\phi'\right\}^{\left(\frac{1}{2}\right)}$ and $Y_0 = 0.02S, k_c = \omega\sqrt{\mu_0\varepsilon_0\varepsilon_c}$ and $k = \omega\sqrt{\mu_0\varepsilon_0\varepsilon^*}$,

$\omega = 2\pi f$ where f is operating frequency.

$\mu_0 = 4\times10^{-7} Hm^{-1} and\ \varepsilon_0 = 8.854\times10^{-12} Fm^{-1}$

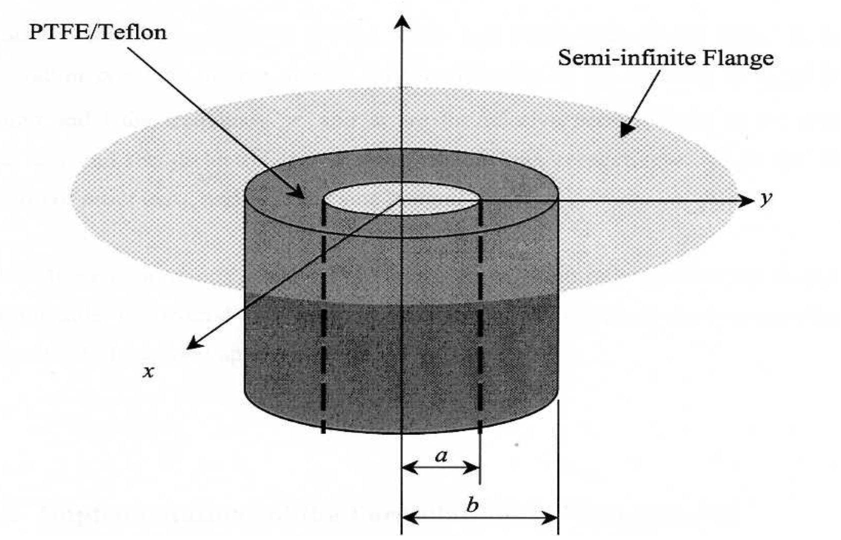


Figure 5.2: Geometry of an open ended probe with an infinite flange covering a semi infinite region of dielectric constant ε .

The other expression of probe admittance was derived by :

$$\begin{aligned}Y=&\frac{Y_0\sqrt{\varepsilon^*}}{\pi\ln\left(\frac{b}{a}\right)\sqrt{\varepsilon_c}}\int_0^{\frac{\pi}{2}}\frac{1}{\sin\theta}\left[J_0\left(k_0b\sqrt{\varepsilon}\sin\theta\right)-J_0\left(k_0a\sqrt{\varepsilon}\sin\theta\right)\right]^2d\theta\\&+j\frac{Y_0\sqrt{\varepsilon^*}}{\pi\ln\left(\frac{b}{a}\right)\sqrt{\varepsilon_c}}\int_0^{\pi}\left[\begin{array}{l}2\mathrm{S_i}\left(k_0\sqrt{\varepsilon^*\left(a^2+b^2-2ab\cos\theta\right)}\right)-S_i\left(2k_0a\sqrt{\varepsilon^*}\sin\left(\frac{\theta}{2}\right)\right)\\-\mathrm{S_i}\left(2k_0b\sqrt{\varepsilon^*}\sin\left(\frac{\theta}{2}\right)\right)\end{array}\right]d\theta\end{aligned}\qquad\textbf{(5.3)}$$

Where a and b are inner and outer radii of the probe, k_0 is the propagation constant in free space, $\varepsilon^* and\ \varepsilon_c$ are the permittivity of the sample and probe, J_0 is the Bessel function of order zero.

$$S_i\left(x\right)=\int_0^z\frac{\sin t}{t}dt$$

The expression above can be approximated in the terms of series expansion[51] :

$$\begin{aligned}Y=&\frac{Y_0\sqrt{\varepsilon^*}}{\pi\ln\left(\frac{b}{a}\right)\sqrt{\varepsilon_c}}\left[G_0\left(k_0\sqrt{\varepsilon a}\right)^4-G_1\left(k_0\sqrt{\varepsilon a}\right)^6+G_2\left(k_0\sqrt{\varepsilon a}\right)^8-.....\right]\\&+\ j\frac{Y_0\sqrt{\varepsilon^*}}{\pi\ln\left(\frac{b}{a}\right)\sqrt{\varepsilon_c}}\left[B_0\left(k_0\sqrt{\varepsilon b}\right)+B_1\left(k_0\sqrt{\varepsilon b}\right)^3-B_2\left(k_0\sqrt{\varepsilon b}\right)^5+....\right]\end{aligned}\qquad\textbf{(5.4)}$$

G_0, G_1, G_2, …. and B_0,B_1,B_2,….. are series coefficient of normalised conductance and susceptance.

To take the higher order mode of electrical field in the aperture probe, the expansion Gn and Bn will be :

$$\begin{aligned}G_n^{'}&=\frac{G_n}{10^{\left[\alpha+\beta(2n+3)+X(2n+3)^2\right]}}\\B_n^{'}&=\frac{B_n}{10^{\left[\alpha+\beta(2n)+X(2n)^2\right]}}\end{aligned}\qquad\textbf{(5.5)}$$

5.2.2 Calibration

Standard calibration was performed with deionised distilled water, air and a short at room temperature. The position of cable should remain similar between calibration and measurement, in order to obtain the measurement accuracy.

The Cole-Cole parameters for the reference material are used for the calibration process with the Network Analyzer. Liquids are the most preferable reference because they give better contact with the coaxial probe. Furthermore, liquids like water have established Cole-Cole properties data in the literature that have been evaluated several times by many researchers. Water is dipolar and has a high permittivity and loss in the microwave region. It is most suitable as a reference liquid for the determination of moisture content in materials using an open-ended probe. There are other reference liquids that are recommended as a reference material such as cyclohexane, methanol, dimethyl sulphide and silicone oil. A critical study of the reference liquid selection as calibration standards was reported by Nyshadham, Sibbald and Stuchly[63].

5.2.3 Complex permittivity measurement

The complete complex permittivity measurement system consists of vector network analyser under PC control, coaxial probe and Agilent 85070E software [64]. Coaxial probe transmits a signal to the sample under test. Signal field at the end of probe ‘fringe’ into the sample and a part of signal is absorbed by sample and other part is transmitted to the vector network analyser. The reflected signal has information about dielectric properties of sample under test. Vector network analyser is used to measure the reflected signal (S11 parameter) of sample. The measured reflection signal is converted to complex permittivity, (ε^*), using numerical models embedded in Agilent 85070E, ‘Performance’ probe software. All measurement procedures such as frequency setup, number of measurement point, calibration and complex permittivity measurement are performed by Agilent 85070E software. Prior to measurement, calibration is performed using distilled water, air and short. During the measurement, air bubbles or air gap between sample and end of the probe must be eliminated. Furthermore, it is important to make sure that measurement temperature is not changed throughout of the measurement process. The end surface of the probe also must be cleaned from residue that will affect the measurement accuracy.

5.3 Waveguide cell.

The waveguide cell uses transmission/reflection line technique, which involves placing a sample in a section of waveguide and measuring the two port complex S-parameter with a network analyser. The method is based on a concise closed form theoretical model relating the two-port S-parameters to the complex permittivity and permeability of the medium under test. For non self-supporting samples, a special waveguide cell with two identical Perspex windows is used to hold the sample in place. The conversion of S-parameters to complex dielectric parameters is computed by solving the equations using software written using Agilent VEE Pro running on a standard PC.

5.3.1 Theory of waveguide cell

The complex permittivity measurements are conducted over frequency bandwidth within the dominant mode (TE10) range of waveguide cell. The frequency selection for the measurement will depend on the dimensions of the waveguide transmission line used. A range of waveguide cells (WG10, WG12 and WG16) are constructed to cover a wide range of measurement frequencies.

5.3.1.1 Sample holder design

Waveguide cell uses the rectangular shape sample holder covered with 2 Perspex windows. The sample holder with Perspex window on both sides is used to contain the non self supporting sample such as liquid or semisolid.

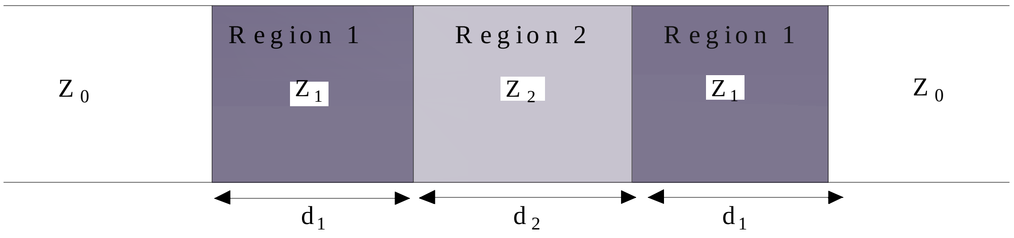


Figure 5.3: Four boundary of waveguide cell sample holder

Referring to Fig. 5.3, Regions 1 and 3 consist of Perspex dielectric windows with the length (d1) mounted in a copper waveguide and soldered into a brass flange which has been ground flat. Region 2, which contains the sample under test, consists of a short length of copper waveguide (d2) also fitted with ground brass flanges. The sample holder was designed to be placed midway between the waveguide transmission lines and perpendicular to the incident wave. The transverse and height dimension of the sample holder were selected to be exactly the same as waveguide to preserve the electrical continuity of the copper waveguide throughout the test assembly.

5.3.1.2 Haigh-Thompson-Gibson Equations.

Haigh, Thompson and Gibson made modifications on the equation for the transmission and reflection coefficient of 4 boundaries sample holder that was developed by Musel and Zacek. The modification was made on the arrangement of the 4 boundaries sample holder. The modified transmission coefficient τ_0 for the 4 boundaries of sample holder is described as [16]:-

$$\tau_0 = \left\{ \begin{aligned} & \cosh^2\left(\gamma_1 d_1\right)\left[\cosh^2\left(\gamma_1 d_1\right) + \sinh^2\left(\gamma_1 d_1\right)\right] \\ & + \frac{1}{2}\left(\frac{\gamma_1}{j\beta_0} + \frac{j\beta_0}{\gamma_1}\right)\frac{\gamma_1}{\gamma_2} \\ & \frac{1}{2}\sinh\left(2\gamma_2 d_2\right)\left[\begin{aligned} & \left(\frac{\gamma_1}{\gamma_2} + \frac{\gamma_2}{\gamma_1}\right)\sinh\left(2\gamma_1 d_1\right) \\ & + \left(\frac{j\beta_0}{\gamma_2} + \frac{\gamma_1}{j\beta_0}\right)\cosh^2\left(\gamma_1 d_1\right) \\ & + \left(\frac{j\beta_0 \gamma_2}{\gamma_1{}^2} + \frac{\gamma_1{}^2}{j\beta_0 \gamma_2}\right)\sinh^2\left(2\gamma_1 d_1\right) \end{aligned}\right] \end{aligned} \right\}^{-1} \tag{5.6}$$

Where γ_1 is the complex propagation constant for the region 1 and 2 (Perspex window), γ_2 is complex propagation of the sample and β_0 is the phase constant of the transmission line

Overall reflection coefficient for 4 boundaries sample is derived as [16]:

$$\rho_0 = \frac{a\left[\left(\frac{\frac{j\beta_0}{\gamma_1} - 1}{\frac{j\beta_0}{\gamma_1} + 1}\right)e^{2\gamma_1 d_1} + \left(\frac{\frac{\gamma_1}{\gamma_2} - 1}{\frac{\gamma_1}{\gamma_2} + 1}\right)\right]e^{2\gamma_2 d_2} + b\left[1 + \left(\frac{\frac{j\beta_0}{\gamma_1} - 1}{\frac{j\beta_0}{\gamma_1} + 1}\right)\left(\frac{\frac{\gamma_1}{\gamma_2} - 1}{\frac{\gamma_1}{\gamma_2} + 1}\right)e^{2\gamma_1 d_1}\right]}{a\left[e^{2\gamma_1 d_1}\left(\frac{\frac{j\beta_0}{\gamma_1} - 1}{\frac{j\beta_0}{\gamma_1} + 1}\right)\left(\frac{\frac{\gamma_1}{\gamma_2} - 1}{\frac{\gamma_1}{\gamma_2} + 1}\right)e^{2\gamma_2 d_2} + b\left(\frac{\frac{j\beta_0}{\gamma_1} - 1}{\frac{j\beta_0}{\gamma_1} + 1}\right)\left(\frac{\frac{\gamma_1}{\gamma_2} - 1}{\frac{\gamma_1}{\gamma_2} + 1}\right)e^{2\gamma_1 d_1}\right]} \tag{5.7}$$

where a and b are given by:

$$\text{a} = \left(1 + \frac{\text{j}\beta_0}{\gamma_2}\right)\cosh\left(\gamma_1 d_1\right) + \left(\frac{\text{j}\beta_0}{\beta_1} + \frac{\gamma_1}{\gamma_2}\right)\sinh\left(\gamma_1 d_1\right)$$

$$b = \left(1 - \frac{\text{j}\beta_0}{\gamma_2}\right)\cosh\left(\gamma_1 d_1\right) + \left(\frac{\text{j}\beta_0}{\beta_1} + \frac{\gamma_1}{\gamma_2}\right)\sinh\left(\gamma_1 d_1\right)$$

The complex permittivity of food sample using waveguide cell measurement technique is calculated by using the transmission coefficient that developed by Haigh, Thompshon and Gibson.

5.3.2 Complex permittivity calculation

5.3.2.1 Newton Ramphson approximation method

Newton Ramphson approximation is one of the optimisation methods that used to find the optimum value of the propagation constant in the transmission coefficient equations. Newton-Ramphson equation to solve the transmission equation is shown below[16].

$$\gamma_{(\mathrm{new})} = \gamma_{(\mathrm{old})} - \frac{\tau(\gamma)}{\tau^{'}(\gamma)} \qquad \textbf{(5.8)}$$

where γ is propagation constant and τ is transmission coefficient.

The optimum value of propagation constant is used in the equation below to calculate the value of complex permittivity.

$$\gamma = \frac{j2\pi\sqrt{\varepsilon - \left(\frac{\lambda_0}{\lambda_c}\right)^2}}{\lambda_0} \qquad \textbf{(5.9)}$$

where ε is complex permittivity, λ_0 is wavelength of free space and λ_c is cut off wavelength.

5.3.2.2 Nicholson–Ross-Weir method

There are various approaches for obtaining the permittivity and permeability from S-parameter measurements. Conversion of S-parameter to complex permittivity and permeability in this study was accomplished using the well known Nicholson-Ross-Weir (NRW) algorithm [65, 66]. The procedure proposed by the NRW method can be summarised by the block diagram in Fig.5.4. The operation of the VNA and calculation of the complex permittivity and permeability of the sample is performed by software written using Agilent VEE Pro running on a standard PC. A simplified flow chart for the software used for measurement and calculation of a sample holder with windows is shown in Fig.5.5. Data regarding the waveguide dimensions, sample length, holder length and window thickness and dielectric constant is entered first, after which the program determines the measurement start, stop and step frequencies by interrogation of the VNA via GPIB. The thickness of the windows is determined by measurement and the dielectric properties of the window material are derived from the measured S-parameters of the window. The program assumes that the windows at both ends of the sample holder are identical. The VNA is then instructed to make a single sweep of its calibrated frequency range and error corrected arrays of S11 and S21 versus frequency are transferred to the PC. Calculation of μ_r and ε_r is then performed at each frequency point as follows. Firstly, the S parameters of the windows are calculated using the thickness and dielectric constant data. Next, the windows S-parameters are used to de-embed the sample S-parameters from the measured S-parameters of the window-sample-window cascade. Finally, the complex μ_r and ε_r are calculated using the equations in Fig 5.4. This process is repeated at each frequency and the results plotted on the PC screen. The data can also be saved to a file in a common spreadsheet format for archiving and subsequent processing if required. A second version of the software is used for samples where the holder is not fitted with dielectric windows. This is usually used where the samples are a solid block of material rather than in the powder or granular form. In this case, the elements of the software involved with the calculation of window S parameters and the de-embedding routines are omitted and an additional stage in the calculation process is added before the $\frac{\mu_r}{\varepsilon_r}$ calculation to correct the measured phase of S21 for any air space in the sample holder. Such an air gap will occur if the sample length is less than the holder length. In all cases, it is assumed the sample completely fills the waveguide cross section.

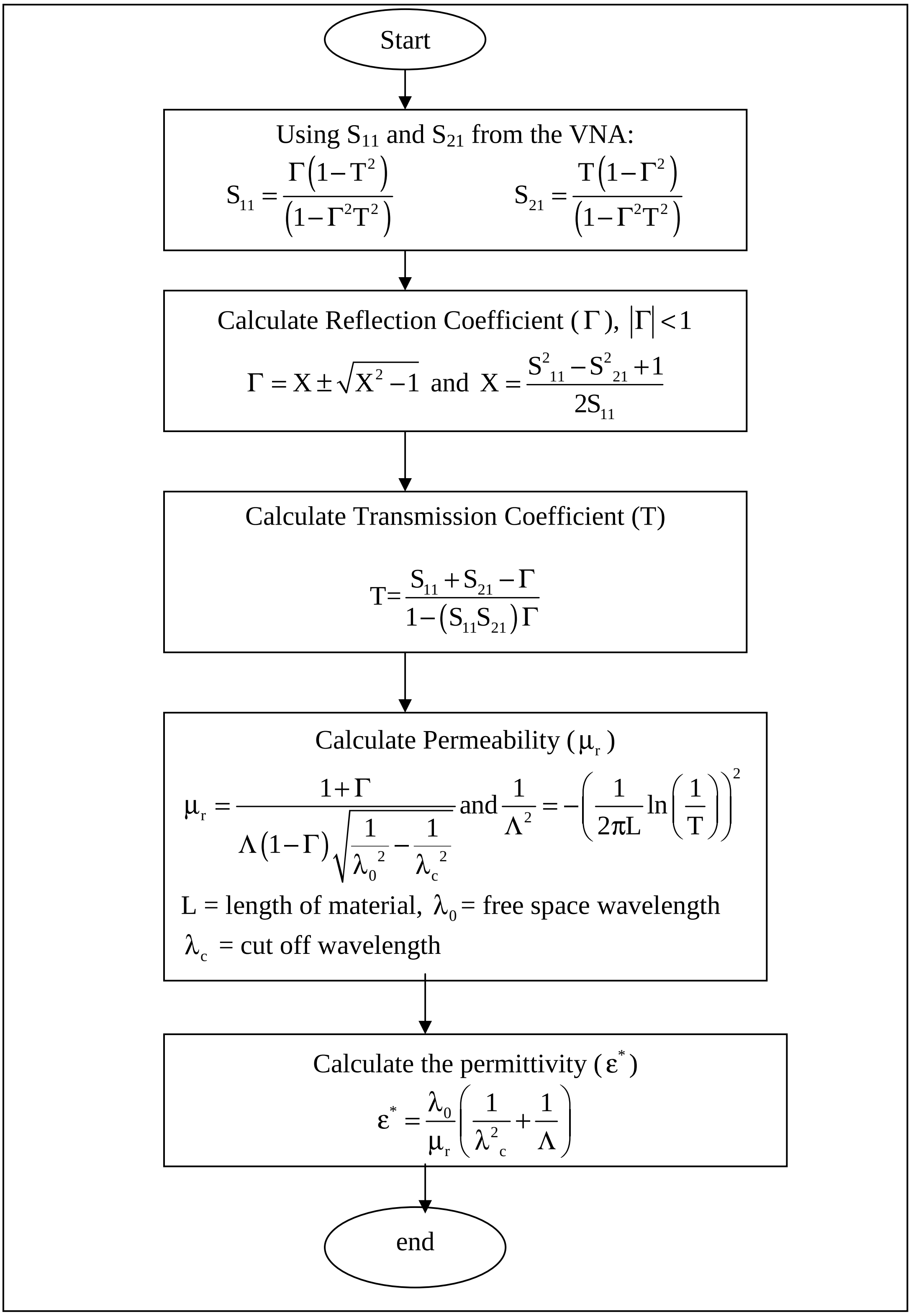


Figure 5.4: The process for NRW method.

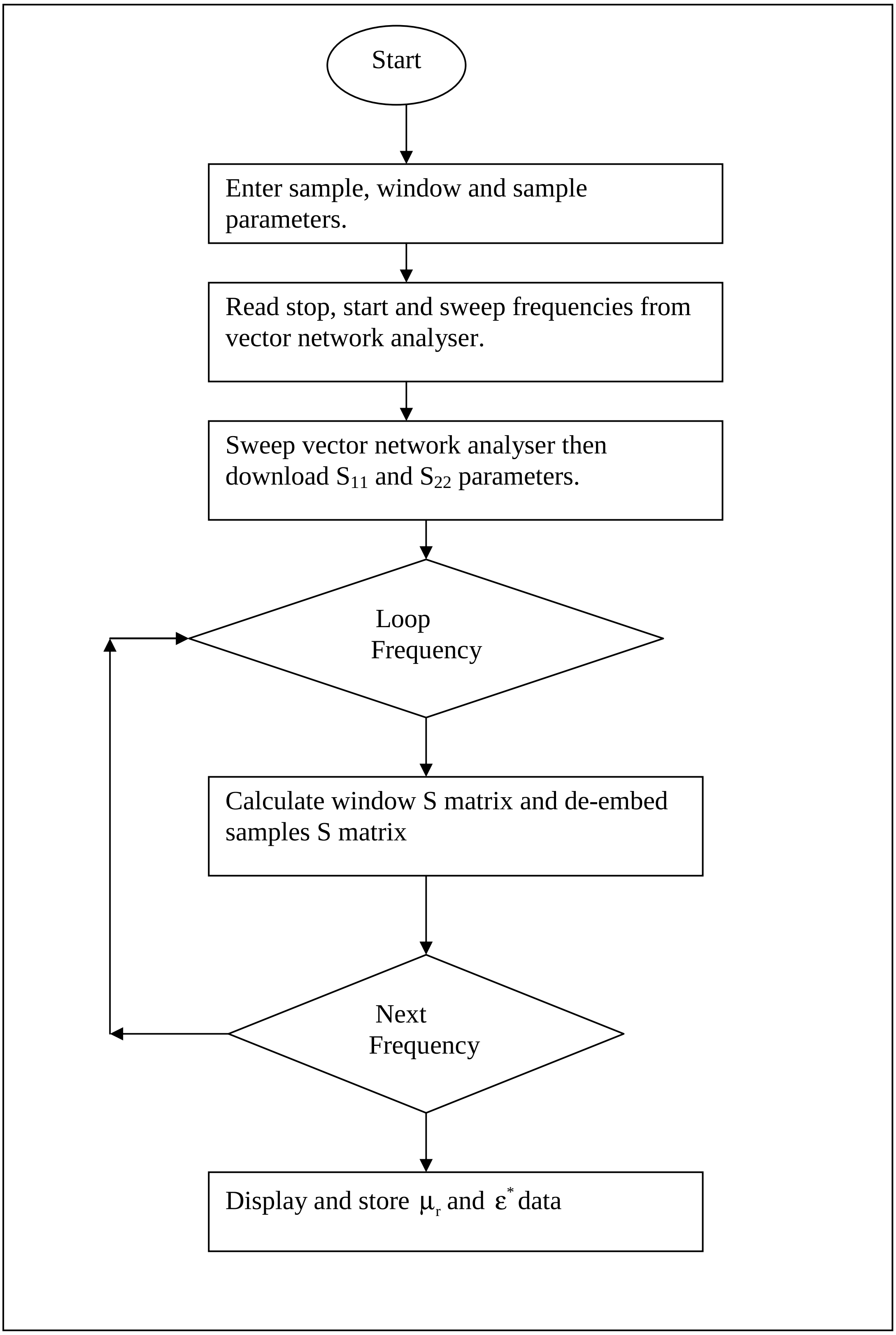


Figure 5.5 : Software flow chart

5.3.3 Calibration

Error calibration is very important to make sure accuracy of complex permittivity measurements. Calibration in the transmission line technique uses short circuited, open circuited and matched load termination. This calibration also set the reference measurement plane for placing the material under test between two waveguide straights and flange to flange adapter. Two ports TRL calibration technique with through, reflect and line standards is used to calibrate the waveguide cell measurement technique. Cal kit calibration software for TRL standards of waveguide cell is downloaded to VNA from PC. The arrangement of TRL calibration is shown in figure 5.6. Through standard (λg/8) and line standard (3λg/8) are placed in between waveguide straights and flange to flange adapter (Flann Model: 10441). Flush short is placed at both flange adapters (port 1 and port 2). Through, line and short calibration process are performed by using Hewlett Packard Vector Network Analyser 8510. Calibration accuracy was checked using two independent standards. For reflection a flush short was used, and over the waveband, attenuation was less than 0.1 dB and the phase shift was 180° ± 0.5°. For transmission an empty length of waveguide was inserted and from the attenuation and phase shift data the permittivity of air was calculated and found to be $1 \pm 0.0005 - j0 \pm 0.0005$.

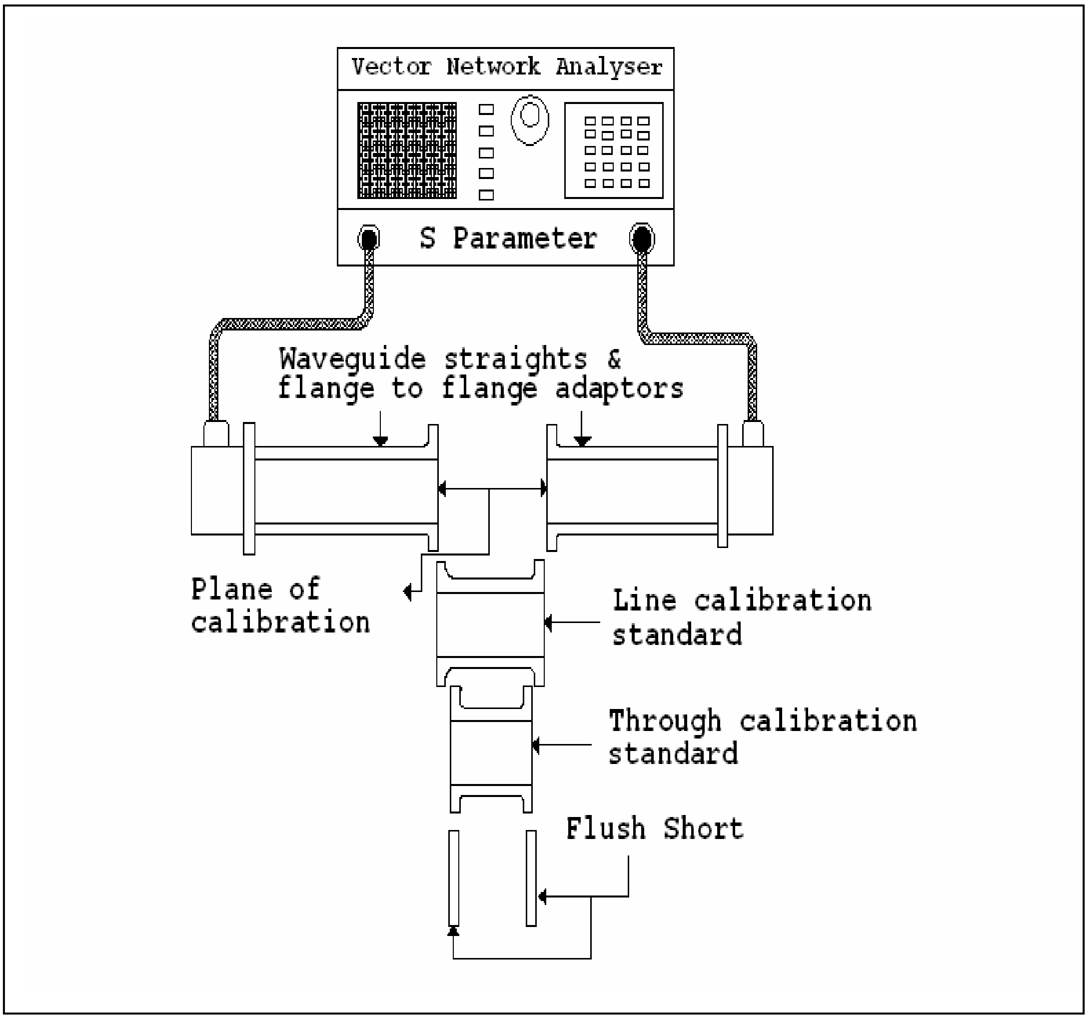


Figure 5.6 : TRL calibration standard arrangement.

5.4 Conclusion.

This chapter provides theory on the coaxial probe and waveguide cell complex permittivity measurement. Detailed discussion is outlined on measurement, calibration procedures, calculation of complex permittivity and sample holder design for waveguide cell measurements. In addition, explanation on measurement and calibration procedure for coaxial probe measurement is also provided in this chapter. Coaxial probe provides flexibility of selecting measurement frequency either broadband (0-40 GHz) or narrow band measurement, which is subjected to the setting of start and stop frequency measurement. On the other hand, waveguide cell only provides narrow band frequency measurement which its frequency measurement is restricted by the waveguide size.

Chapter 6

Complex Permittivity of Potato under Temperature Stress.

6.1 Introduction.

The objective of the present study was to examine the influence of temperature stress on the complex permittivity of potatoes during storage. The storage temperature is one of the most important post-harvest factors governing sugar content of potatoes. Potato under storage is not a static entity [67] and carbohydrates are converted from starch for respiration purposes. Sugar will start accumulating and this is very much affected by the storage temperature [68]. When potatoes are stored at low temperatures, they accumulate sugars, primarily glucose, fructose and sucrose in a process called ‘cold sweetening’ [69]. Intermediate storage temperatures (8-12°C) prevent this sugar accumulation. Normally, the reducing sugars concentrations do not change during the first three days of storage at low temperatures (4-6°C) [70,71], but later these increase rapidly compared with the concentrations in potato stored at higher temperatures [70,72].

The sugars content in potato is an important factor affecting the quality of potato products especially fried products such as crisps and fries. Commercial crisps or fries manufacturers require fresh potato with low sugar content to avoid browning of the finished products. Of the many chemical constituents affecting the colour of processed potato products, [73], sugar is generally considered to be the most important [74]. The presence of excessive sugar and free amino acids in potato during high temperature frying results in unacceptably brown coloured and bitter tasting products. The sugar content of potatoes depends on the genotype and several pre- and post-harvest factors. The pre-harvest factors include temperature, soil moisture, mineral and nutrition during growth, irrigation and maturity. Post-harvest includes mechanical stresses and storage conditions.

The dielectric properties of materials depend on many factors, including some that are related to chemical composition. The rise of sugar content in potato might have a significant impact on the permittivity. Once fundamental data on the relationship between dielectric properties and other factors have been established, the rapidity of which dielectric properties can be measured and the non-destructiveness of the methods, can lead to better methods of quality analysis. This study will investigate the feasibility of using microwave transmission line and open ended coaxial probe methods to measure the sugar content of potato due to temperature stress occurred during storage and the effect of sugar content on the dielectric properties at the microwave heating frequency (915 MHz and 2.45 GHz).

6.2 Methodology

6.2.1 Sample Preparation

Saturna potatoes were obtained from Mercian Potatoes (Chester, UK). Once obtained, the potatoes were divided into 3 batches and stored in the chill cabinet (Polar CB935 UK). The first batch was kept in non-stress condition (8^oC, 95 % relative humidity, leaky ventilation, darkness). The second batch of sample was temperature stressed by cooling the potato samples overnight at the temperature 4^oC (24 hours) and recovered to the temperature storage 8^oC for 6 days. The third batch of sample was kept in the stress condition 4^o C for 7 days. Other conditions such as the relative humidity, leaky ventilation and darkness were kept standard for both batches.

Saturna potatoes were peeled and slice by using a Mandolin Slicer (Bron Mandolin) into 6.5 mm of thickness. Then it was cut into a rectangular shape (34 mm x 72 mm) to fit the size of WG10 sample holder. This shape of sample was used for waveguide cell measurement.

Saturna potato was cut using a Mandolin Slicer (Bron Mandolin) into 2.5 cm of thickness and then cut into cylindrical shape with 1.5 cm diameter. This sample was put in the open ended probe sample holder.

The dielectric properties and moisture content of the samples for batch 1, 2 and 3 were measured on day 1, day 2 and until day 7.

Sucrose solution was prepared by dissolving of weight of granulated sucrose in the 300 ml beaker with weight quantities of distilled water. The sucrose solution was prepared in 4 concentration 2%, 4%, 8% and 10% w/w (weight/weight). The solution was stirred using magnetic stirrer for 15 min to aid homogeneity. The dielectric properties for every salt concentration were measured using open ended probe method.

6.2.2 Moisture content measurement.

Moisture content was determined with the AOAC 984.25 method that is based on the weight loss of sample after it has been dried for 48 hours at 100 C in a Carbolite AX 60 convection oven until a constant weight was attained.

6.2.3 Dielectric Measurement

Transmission line methods involve placing the material inside a portion of an enclosed transmission line. The line is usually a section of rectangular waveguide or coaxial line. There are a number of publications describing the transmission line technique as a sensor for measuring the dielectric properties of materials at microwave frequencies [75-78]. The transmission line measurement is restricted in the dominant mode and frequency band. The complex permittivity of a material is computed from the measurement of the reflected signal (S_{11}) and/or transmitted signal (S_{21}) [16]. Using this method, the sample must fully fill the sample holder and no air gaps are trapped between the fixture walls. A typical measurement system using a transmission line technique consists of a vector network analyzer, a coaxial airline or waveguide section, computer and software to perform the conversion of S-parameters to complex permittivity. Calibration standards are used to set the full 2-Port Calibration on the vector network analyser. Error calibration is very important to ensure the accuracy of any measurement. This calibration sets the plane of the incident and reflected waves at the end of the waveguides and by replacing the material under test between the ends, measurement start and end at the material. Open ended coaxial probe covers a broad range of frequency and needs minimal sample preparation. For the waveguide cells, the sample needs to be machined to fit to the shape of its sample holder and their frequency coverage is banded by their dimensions. For non self-supporting materials, it is necessary to include dielectric windows to contain the sample.

6.2.4 Waveguide cell design (2450 MHz)

The waveguide cell method has been implemented in WG-284 (2.5-4.0 GHz). In the case of non self-supporting samples, it is necessary to include dielectric windows to contain the sample. Referring to Fig. 5.3, regions 1 and 3 consist of Perspex dielectric windows mounted in a copper waveguide soldered into a brass flange which has been ground flat. Region 2, which contains the sample under test, consists of a short length of copper waveguide also fitted with ground brass flanges. This arrangement prevents sample leakage. The internal dimensions of the sample holder were 1.907x3.4x7.2 cm (WR-284). The sample holder was placed midway between the transmission lines and perpendicular to the incident wave. The transverse and height dimension of the sample holder were selected to be the same as the waveguide to preserve the electrical continuity of the copper waveguide throughout the test assembly. The transmission line measurements were conducted with the dominant mode (TE_{10}). Prior to measurements, the VNA and attached transmission line was an error corrected by a full 2-port calibration. During measurements, each sample was carefully filled into the waveguide cell guarded by two Perspex windows. It is necessary to have a flat and homogenous interface between the sample and Perspex windows to eliminate the error caused by air voids.

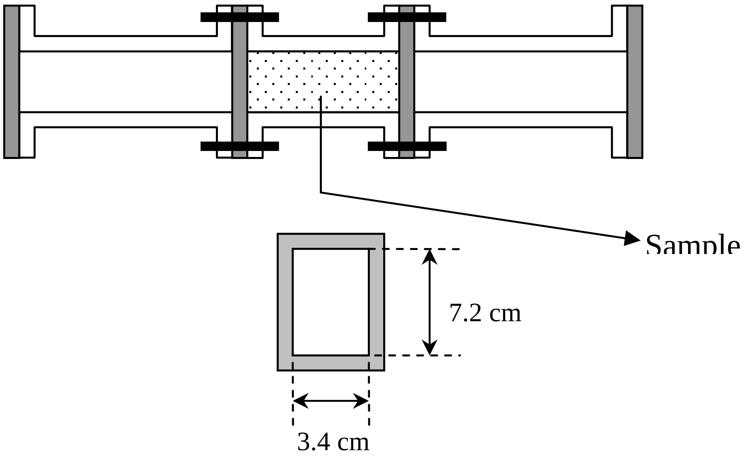


Figure 6.0: The sample holder setup of the waveguide 10 for the complex permittivity measurement at the frequency range 2.4 GHz to 3.5 Ghz.

6.2.5 Open ended coaxial probe (915 MHz)

Open ended coaxial probe can be used to measure the complex permittivity of a wide variety of samples such as semi solid, pliable solid and liquid materials. The Agilent 85070E performance probe was used to measure the complex permittivity of the potato sample between frequency ranges of 500 MHz to 1 GHz. The 85070E software controls the communication between the PC and Network Analyser and performs an online measurement of the S11 parameter and dielectric properties conversion from the measured S11 parameter. The dielectric properties reading is displayed as the dielectric constant, dielectric loss and loss tangent. The probe measurement system provides a convenient, repeatable method for the measuring complex permittivity of materials. The probe is immersed into the liquid or semisolid sample to make the dielectric properties measurement. The probe is made from stainless steel with its outer diameter of 1.6 mm and inner diameter of 0.3 mm and sealed with borosilicate glass dielectric at the open end.

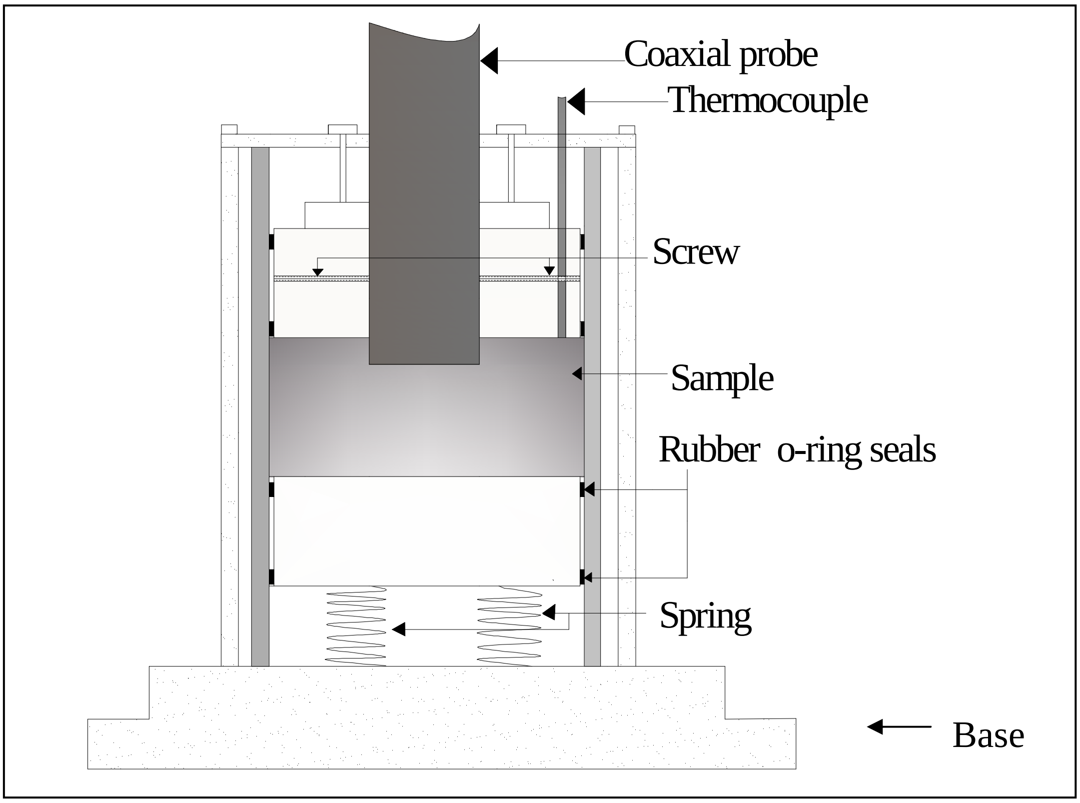
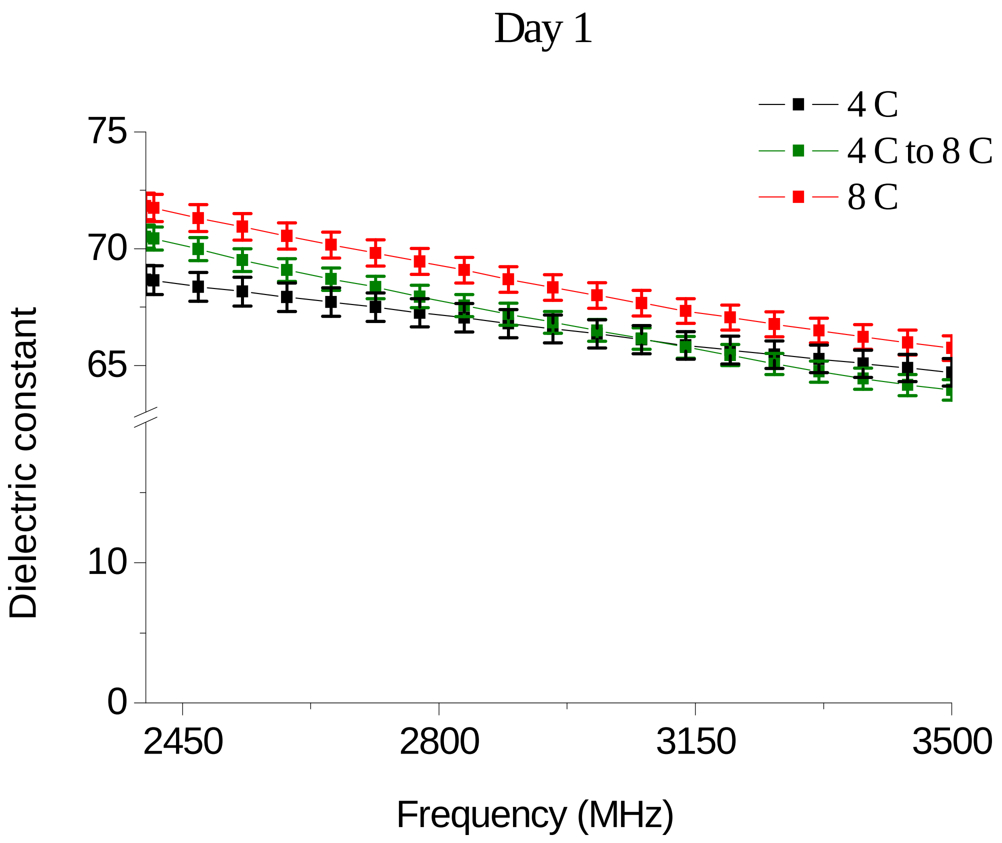


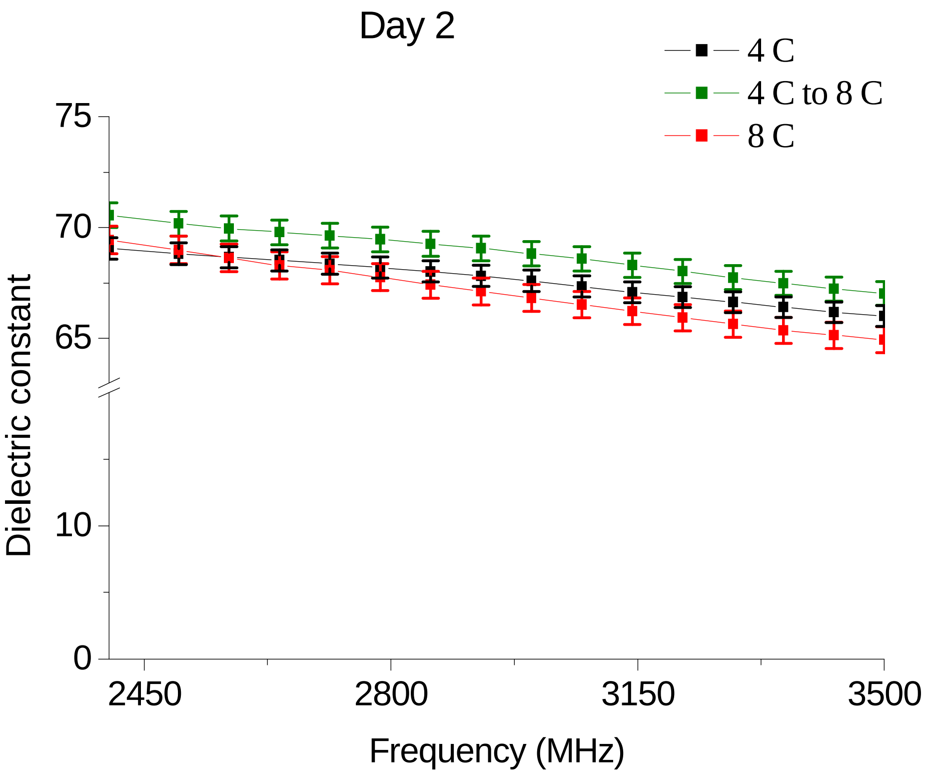
Figure 6.1: Sample holder setup of coaxial probe for measuring the complex permittivity of the shocked raw saturna potato.

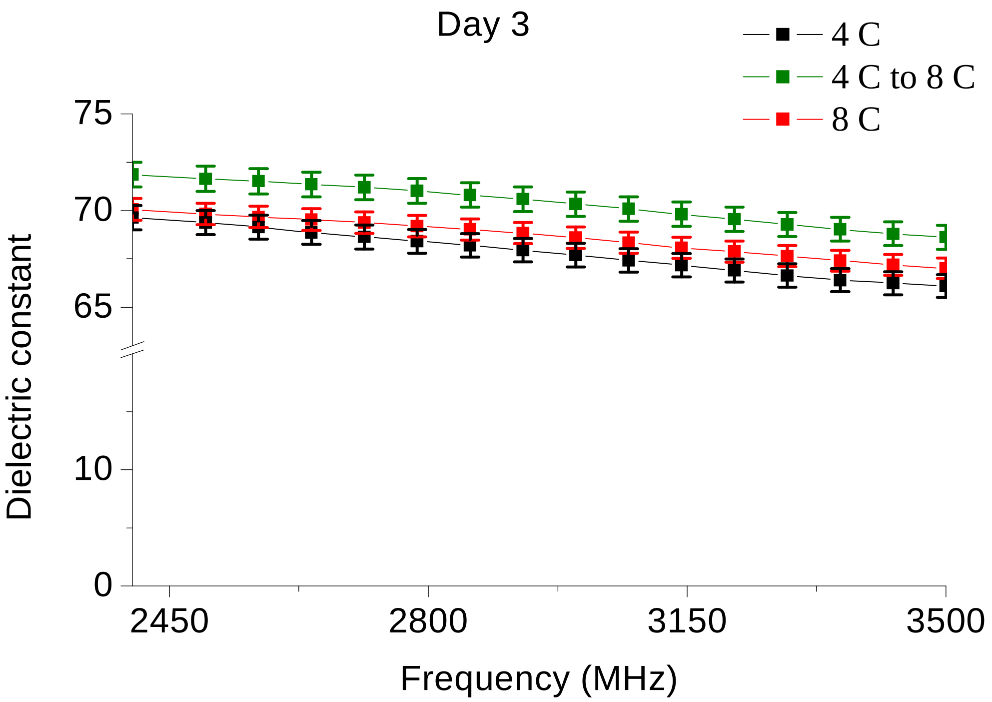
A special designed sample holder was constructed to ensure that raw Saturna potato could have a good contact with the coaxial probe and eliminate the air space gap between the sample and coaxial probe. The sample holder consisted of 0.25 cm thick and 10 cm high clear Perspex tube. The sample was placed between two polyethylene cylinders and compressed by two loaded springs at the bottom and two adjustable screws at the top to eliminate the air space gap between the raw saturna potato and the coaxial probe. The top polyethylene cylinder was attached to the coaxial probe by two screws. Rubber O ring seals were attached to the two polyethylene cylinders to prevent leakage if the samples were in the liquid or paste form.

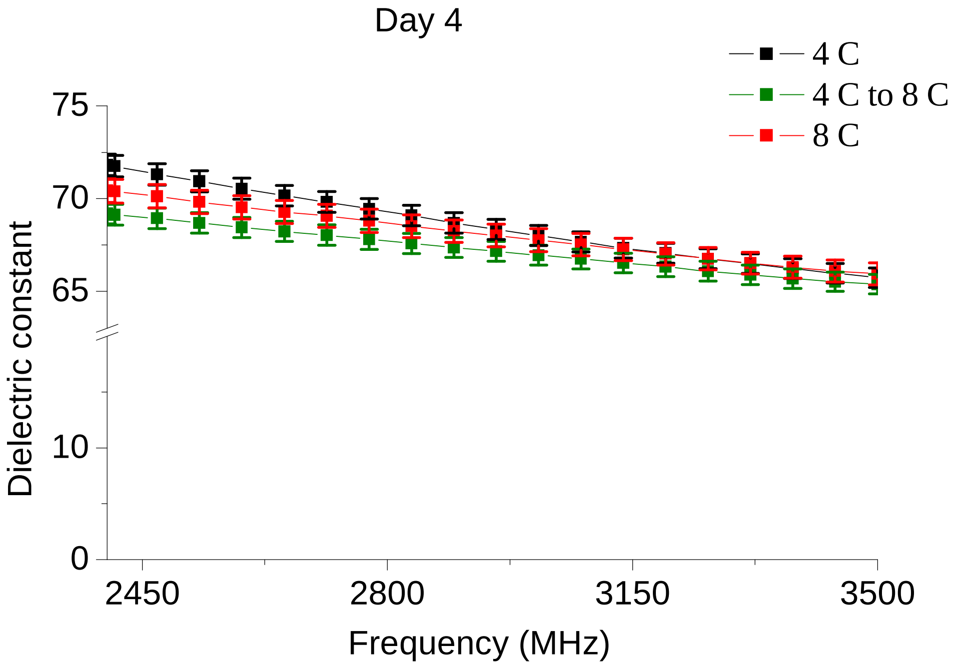
6.3 Results and Discussion

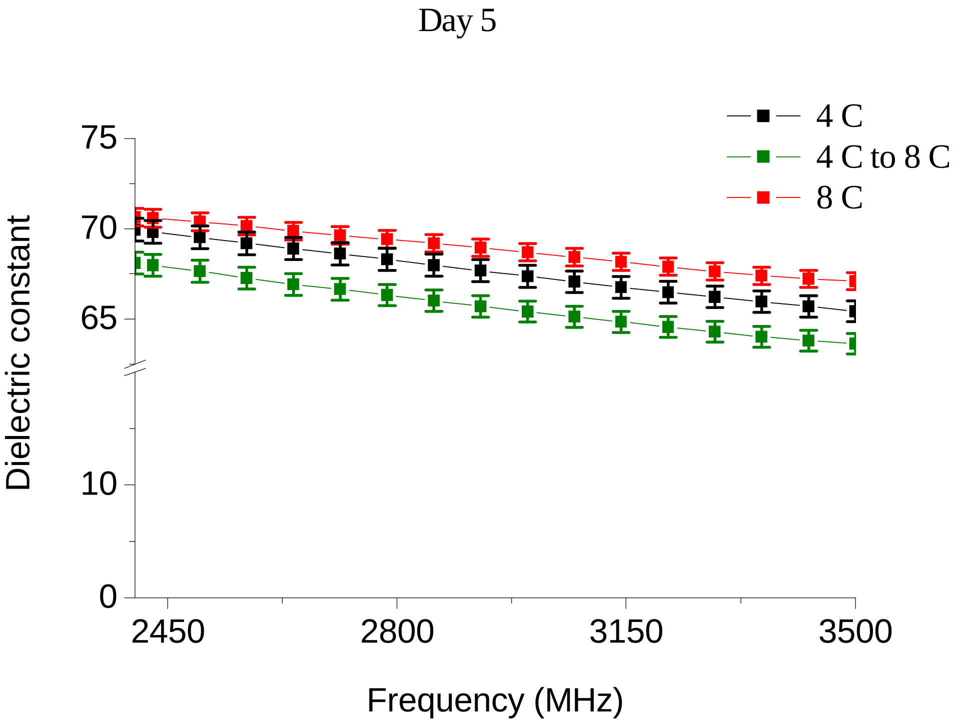
6.3.1 Waveguide cell

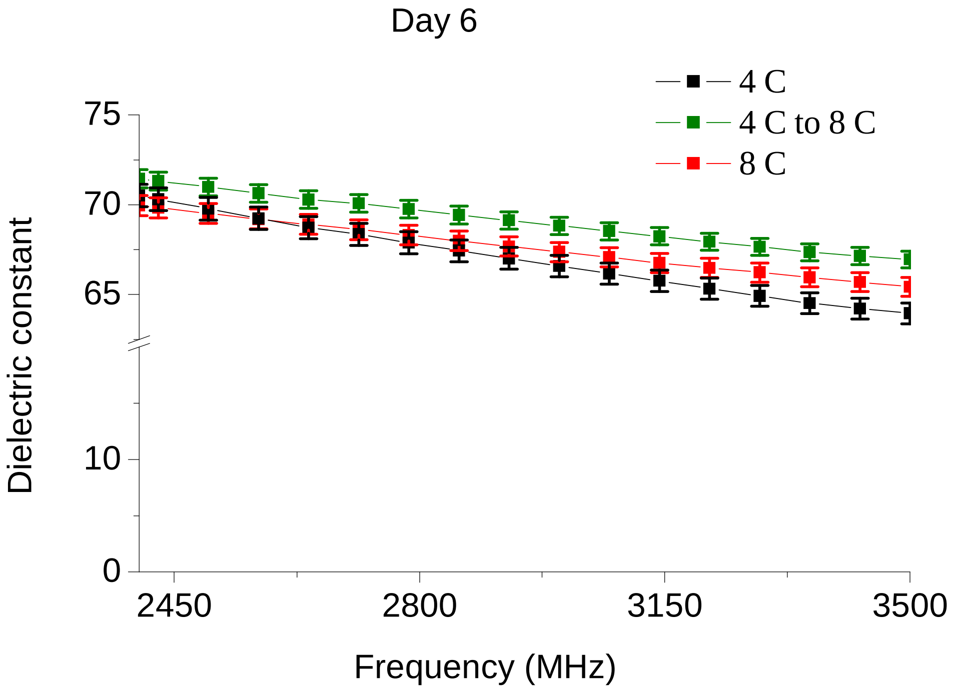



Day 2
4 C
4 C to 8 C
8 C
75
70
65
10
0
Dielectric constant
2450
2800
3150
3500
Frequency (MHz)


Day 3
4 C
4 C to 8 C
8 C
75
70
65
10
0
Dielectric constant
2450
2800
3150
3500
Frequency (MHz)


Day 4
4 C
4 C to 8 C
8 C
Dielectric constant
75
70
65
10
0
2450
2800
3150
3500
Frequency (MHz)


Day 5
4 C
4 C to 8 C
8 C
Dielectric constant
75
70
65
10
0
2450
2800
3150
3500
Frequency (MHz)



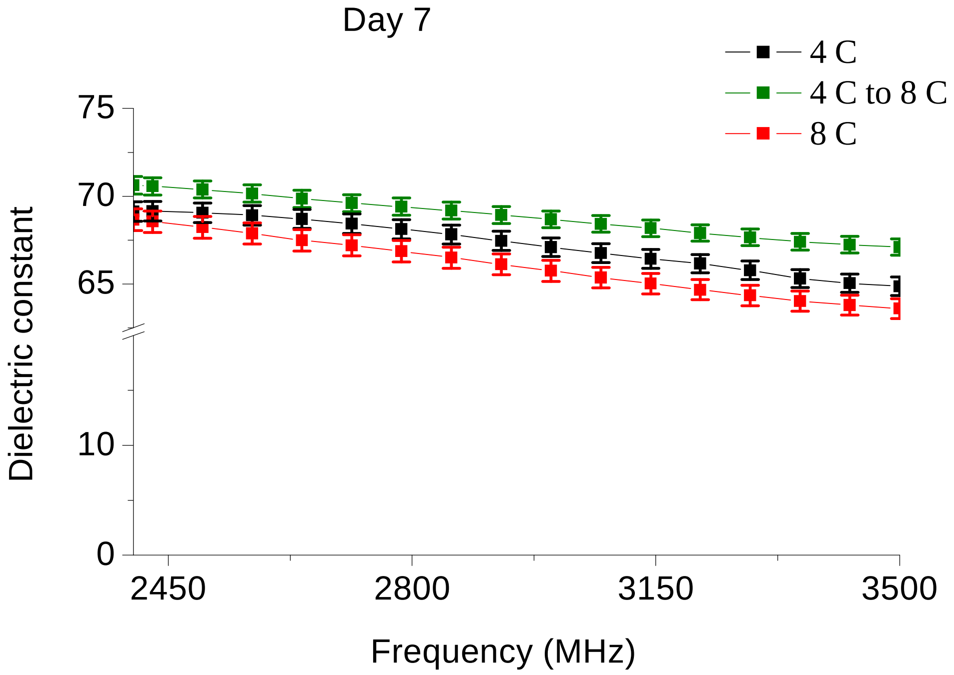
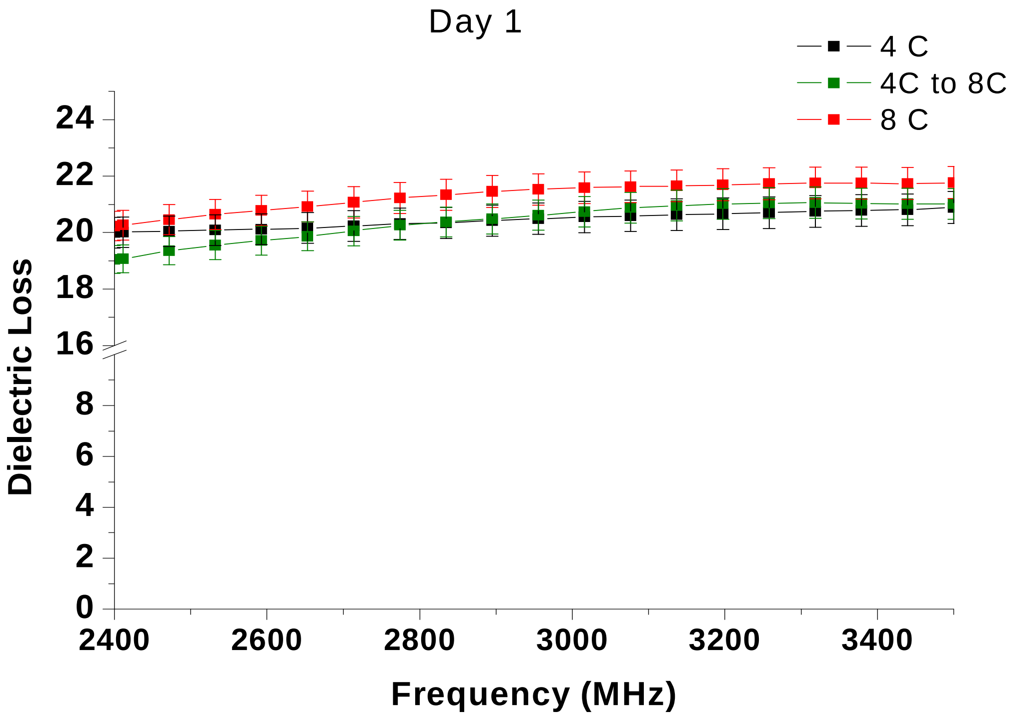
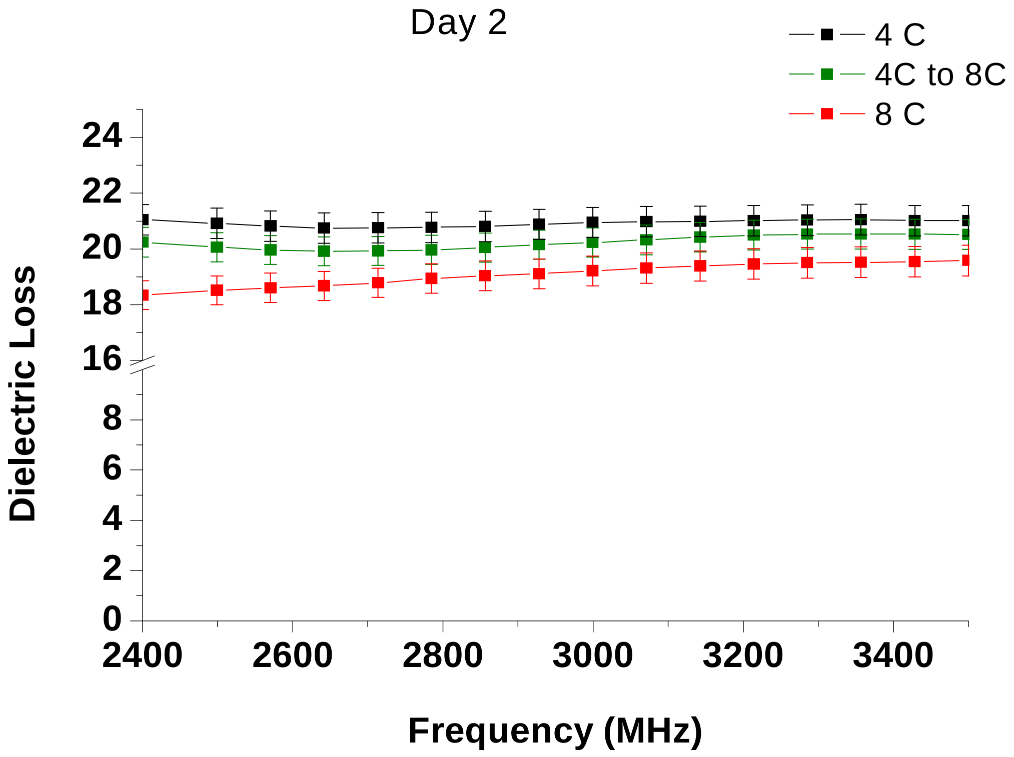


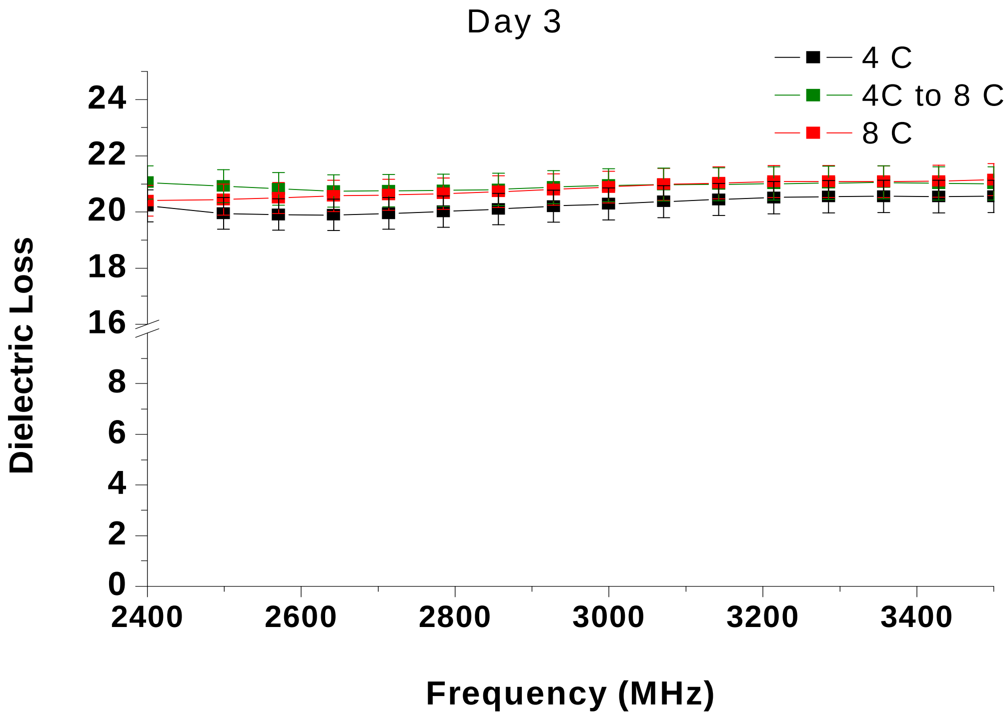
Figure 6.2: Dielectric constant of the raw saturna potato stored at the 3 different temperatures storage for 7 days with the frequency range 2.4 GHz to 3.5 GHz

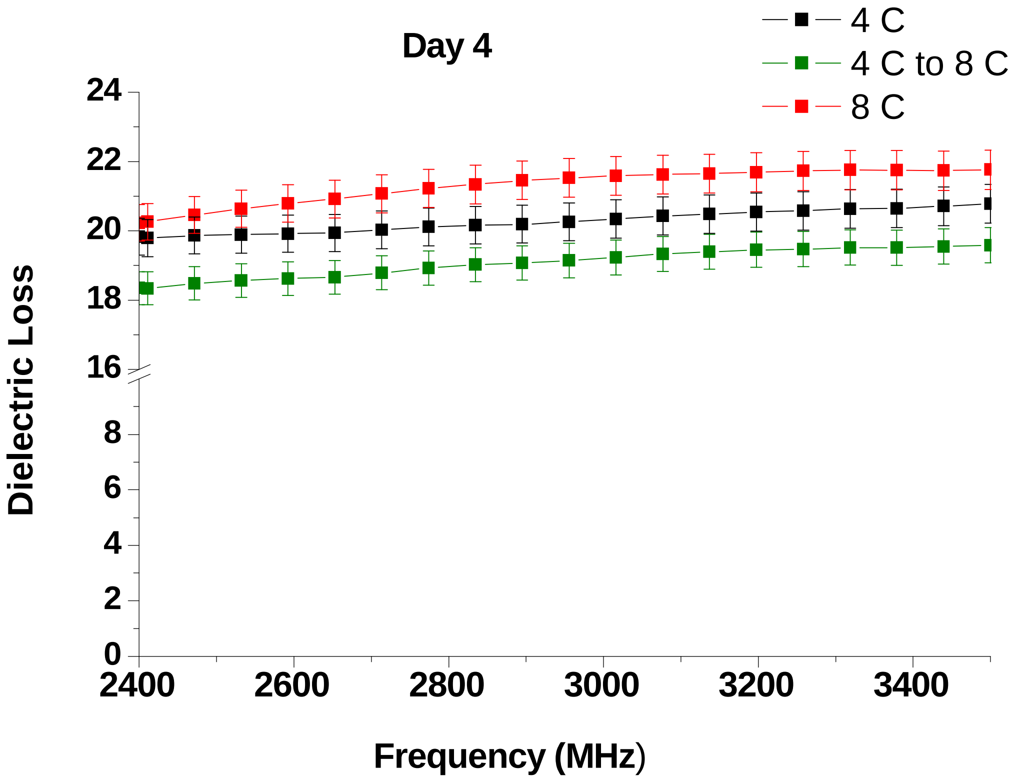
The dielectric constant measurement results for the raw saturna potato samples with 3 different storage temperatures are shown in the Figure 6.2. The measurement of the raw saturna potato samples shows that there is no significant relationship between the effect of the storage temperature and the dielectric constant of the samples. The change in the dielectric constant does not show any pattern of continuously increase or decrease with the change in the storage temperature. Thus the increase or decrease of the storage temperature does not have any significant impact on the dielectric constant of raw saturna potato. Figure 6.12 shows that the moisture content of the raw saturna potato does not change with the storage temperature from day 1 to day 7 and then its dielectric constant is not affected by the change in the storage temperature. Water is the polar food constituent and the change in the moisture content has a high impact on the dielectric properties. Dielectric constant depends on the food composition and the highest effect of the food composition on the dielectric constant comes from water. The major constituent of the saturna potato is water since its moisture content is 76 %. Then its dielectric constant is dominated by the dielectric constant of the free water. The addition of sugar should be able to change the dielectric properties of water, then it is possible to have the change in the dielectric properties of the saturna potato in the different storage temperature. If not then the change in the reducing sugar due to the storage temperature will not change the dielectric constant of the saturna potato.

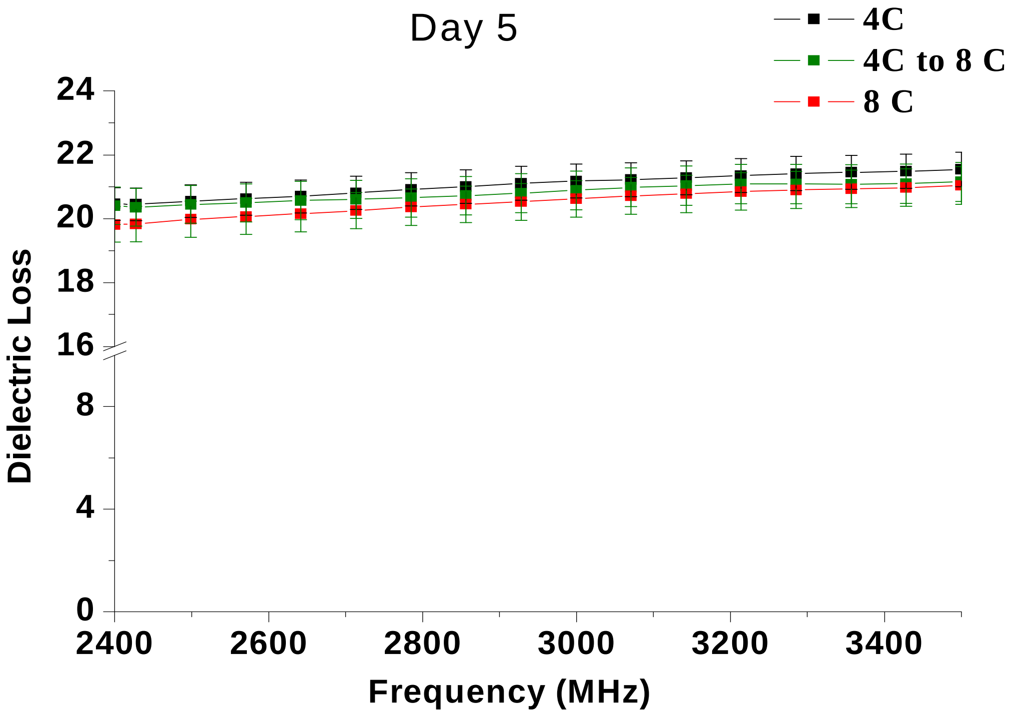
A separate study was conducted on the dielectric properties result for the 0 to 10 percent of sugar aqueous solution shows that its dielectric properties are not affected by the percentage of sugar. The measurement results are shown in the Figure 6.4. The dielectric constant of the different percentage of sugar aqueous solution is similar with the distilled water.

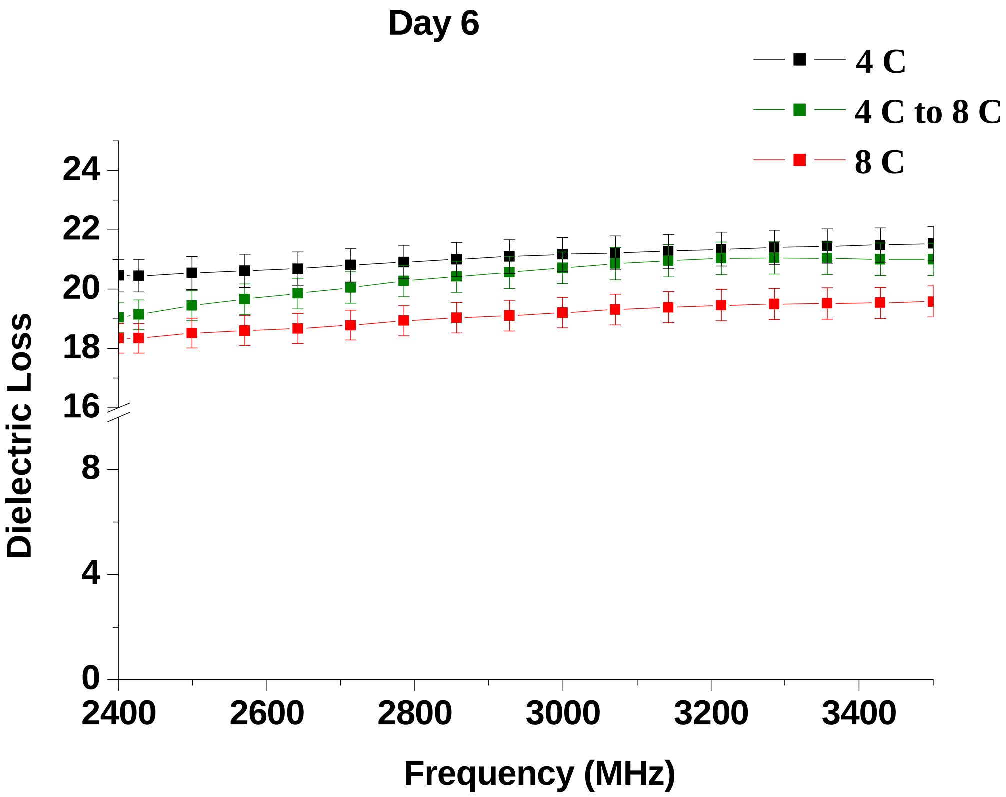

Day 1
4 C
4C to 8C
8 C
Dielectric Loss
24
22
20
18
16
8
6
4
2
0
2400
2600
2800
3000
3200
3400
Frequency (MHz)


Day 2
4 C
4C to 8C
8 C
Dielectric Loss
24
22
20
18
16
8
6
4
2
0
2400
2600
2800
3000
3200
3400
Frequency (MHz)


Day 3
4 C
4C to 8 C
8 C
Dielectric Loss
24
22
20
18
16
8
6
4
2
0
2400
2600
2800
3000
3200
3400
Frequency (MHz)


Day 4
4 C
4 C to 8 C
8 C
Dielectric Loss
24
22
20
18
16
8
6
4
2
0
2400
2600
2800
3000
3200
3400
Frequency (MHz)


Day 5
4C
4C to 8 C
8 C
Dielectric Loss
24
22
20
18
16
8
4
0
2400
2600
2800
3000
3200
3400
Frequency (MHz)


Day 6
4 C
4 C to 8 C
8 C
Dielectric Loss
24
22
20
18
16
8
4
0
2400
2600
2800
3000
3200
3400
Frequency (MHz)

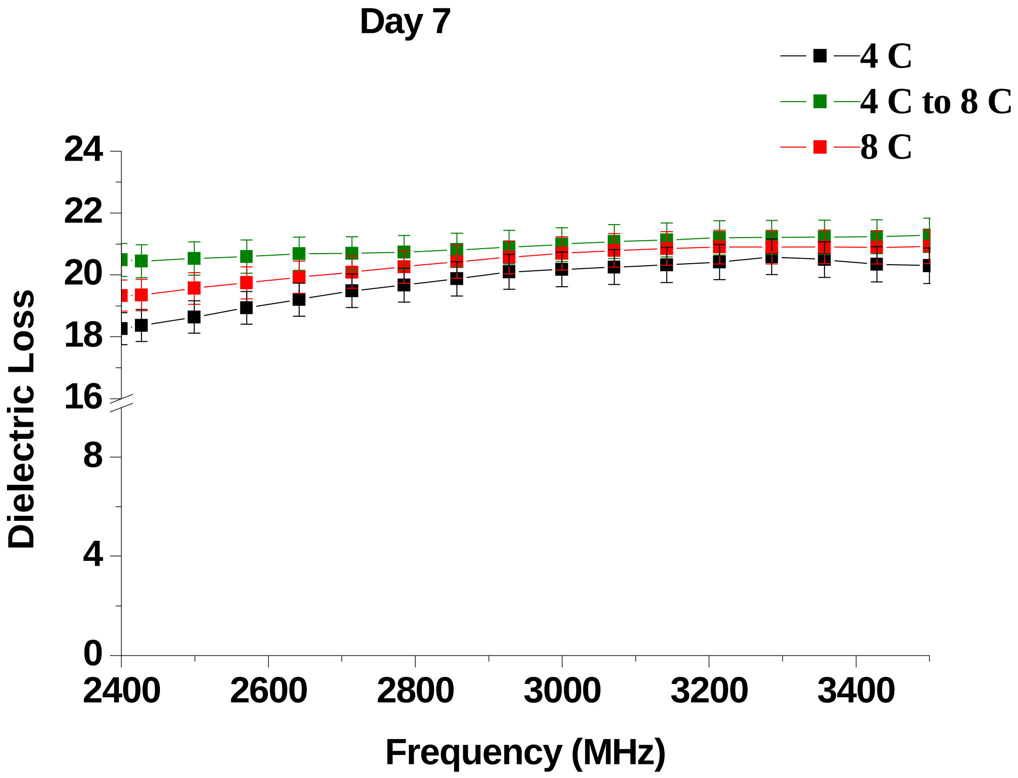


Figure 6.3: Dielectric loss of the raw saturna potato stored at the 3 different temperatures storage for 7 days with the frequency range 2.4 GHz to 3.5 GHz

The measurement results of the dielectric loss for the raw saturna potato samples are shown in the Figure 6.3. The change in the dielectric loss of the samples is minimal and small with the change of the storage temperature from day 1 to day 7. Furthermore, there is no pattern of increase or decrease of the dielectric loss between the temperature storage along the day of storage. The dielectric loss is not influenced by the changing of storage temperature. The other measurement result for the aqueous sugar solution result in the Figure 6.5 shows that the dielectric loss is not changed with the different percentage of sugar content. It also shows that the dielectric loss of 10% sugar aqueous solutions is quite similar with dielectric loss of the distilled water. Addition of sugar is not able to change the dielectric loss of water. The change in the reducing sugar content of saturna potato should be able to change the dielectric properties of water since water is a major constituent of raw saturna potato. Then it is possible to have the change in the dielectric properties that can be used to detect the accumulating of sugar in the saturna potato. The maximum content of the accumulating sugar in the raw potato stored in the 4 C for more than 10 days is 2.5g/(100g fresh weight of potato)[79]. The allowed limit of the reducing sugar content in the potato is below than 0.33 % of the potato tuber fresh weight [80]. It is not possible to detect the change in the dielectric loss for these low percentages of the sugar content in the saturna potato. It is supported by result in the figure 6.4 and 6.5 that there is no difference between the dielectric loss of the 10 % sugar aqueous solution and 100 % distilled water.

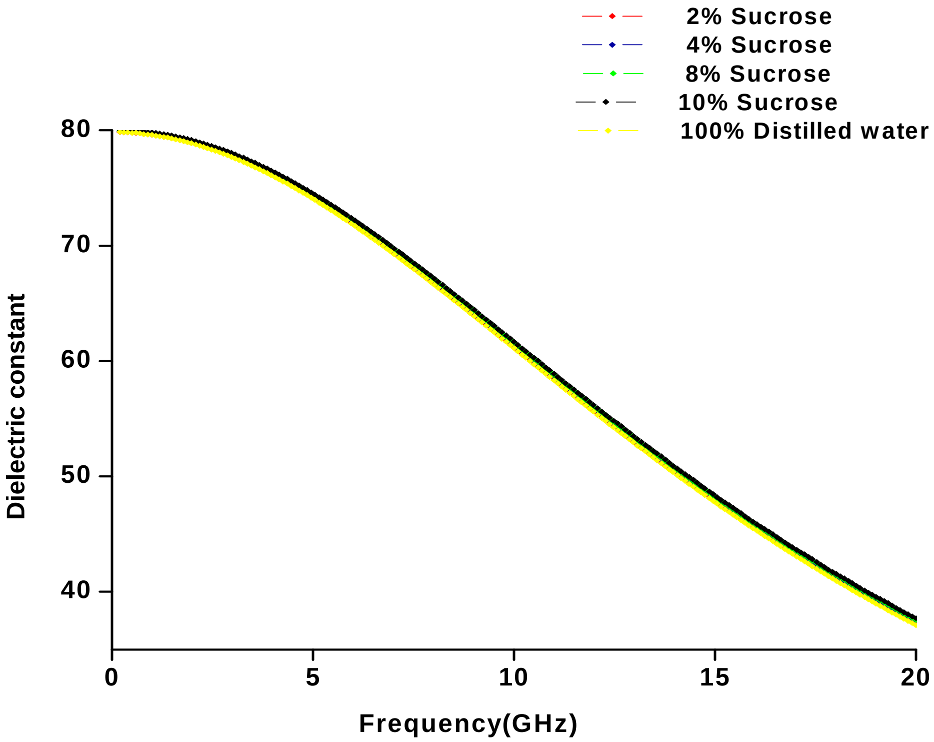


Figure 6.4: The dielectric constant of the different percentage of sucrose aqueous solution at the frequency range 200MHz to 20 GHz and temperature 20 C.

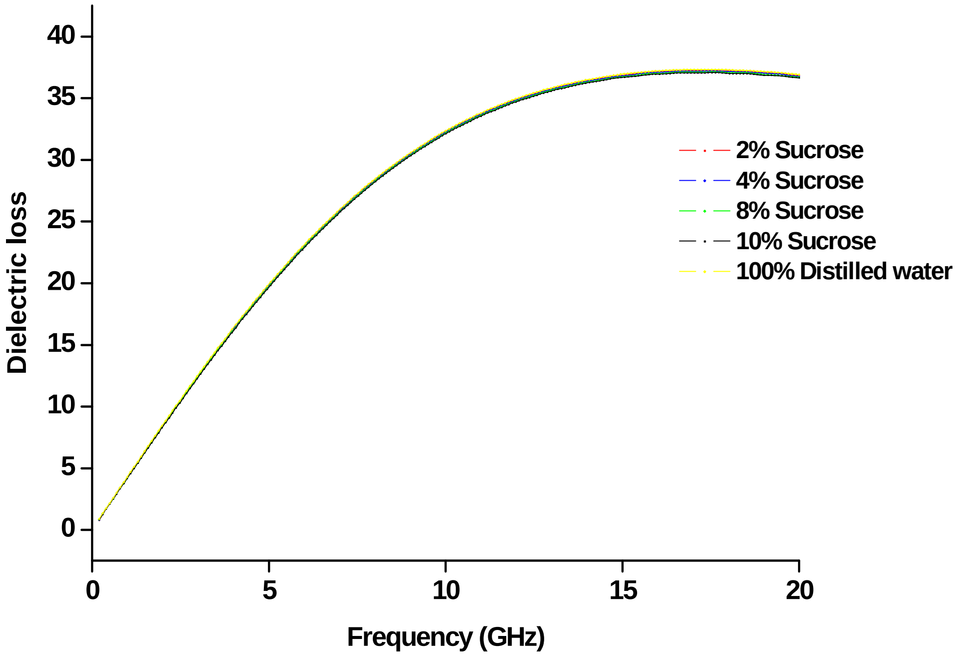


Figure 6.5: The dielectric loss of the different percentage of sucrose aqueous solution at the frequency range 200MHz to 20 GHz and temperature 20 C.

6.3.2 Complex permittivity of sample as a function of storage time at the frequency measurement 2.45 GHz

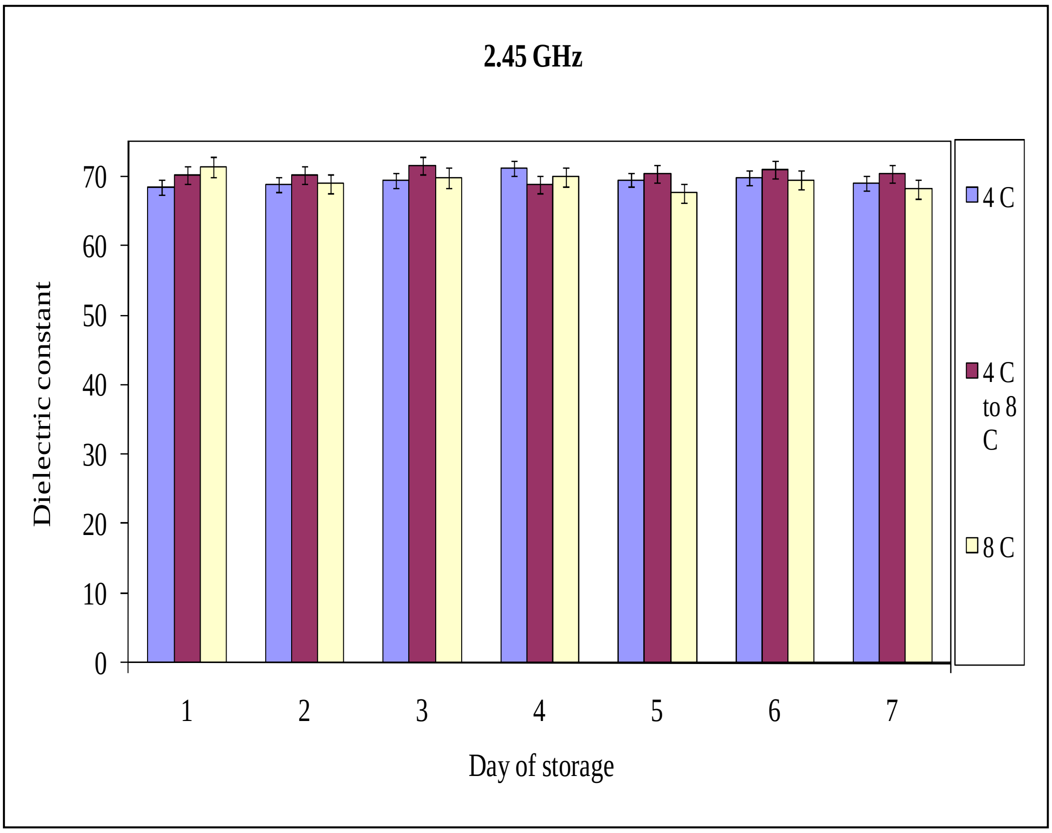


Figure 6.6: The dielectric constant of the different temperature storage of saturna potato between day 1 to day 7 at the frequency 2.45 GHz and temperature 20 C.

The measurement result of the saturna potato at the frequency 2.45 GHz is shown in the Figure 6.6. All the 3 dielectric constants of saturna potato are very similar, with differences of less than 2 % between sample kept in storage temperature 8 C, 4 C and also kept in 4 C for 24 hours then transferred to 8 C for another 6 days. The graph shows that dielectric constant is fluctuating with small value above and below 70 for every sample. The storage temperature has a negligible effect on the dielectric constant of saturna potato as shown in the Figure 6.2. This is most probably due to the not changing of the moisture content during the storage at the different temperature between day 1 to day 7. Raw saturna potato contains high moisture content, and it becomes an important factor to determine the changes in the dielectric constant.

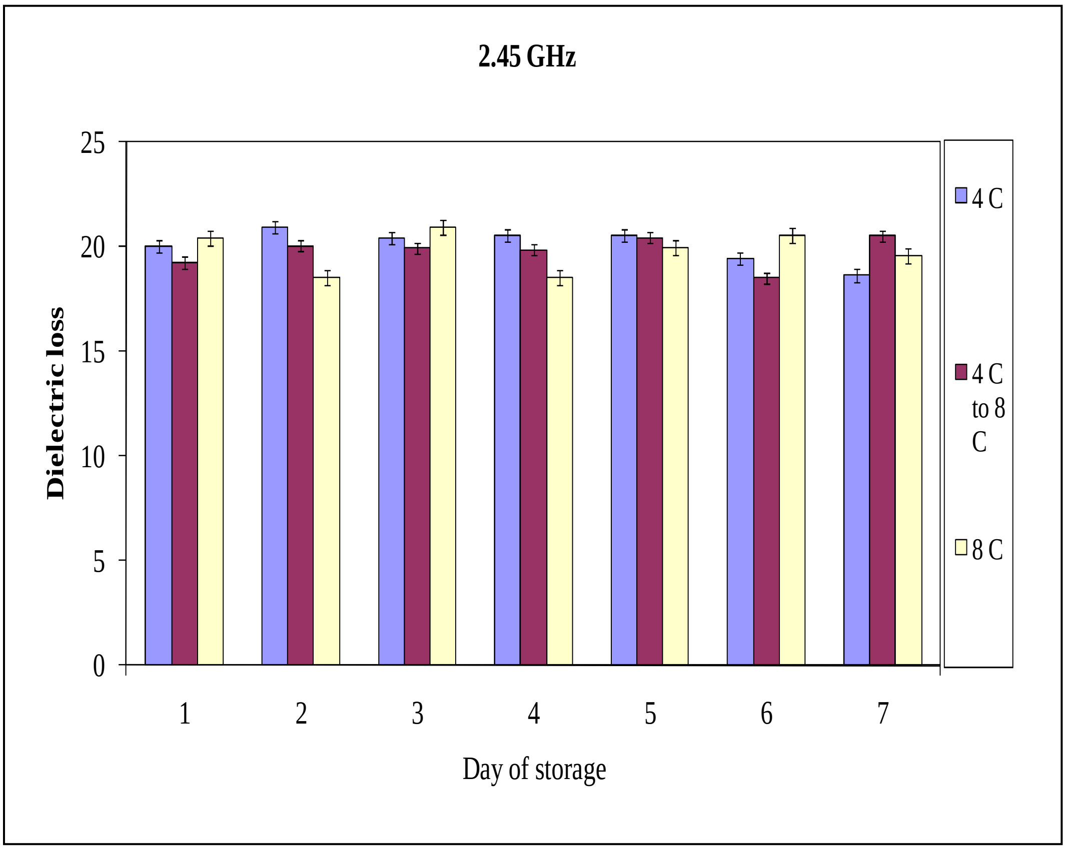
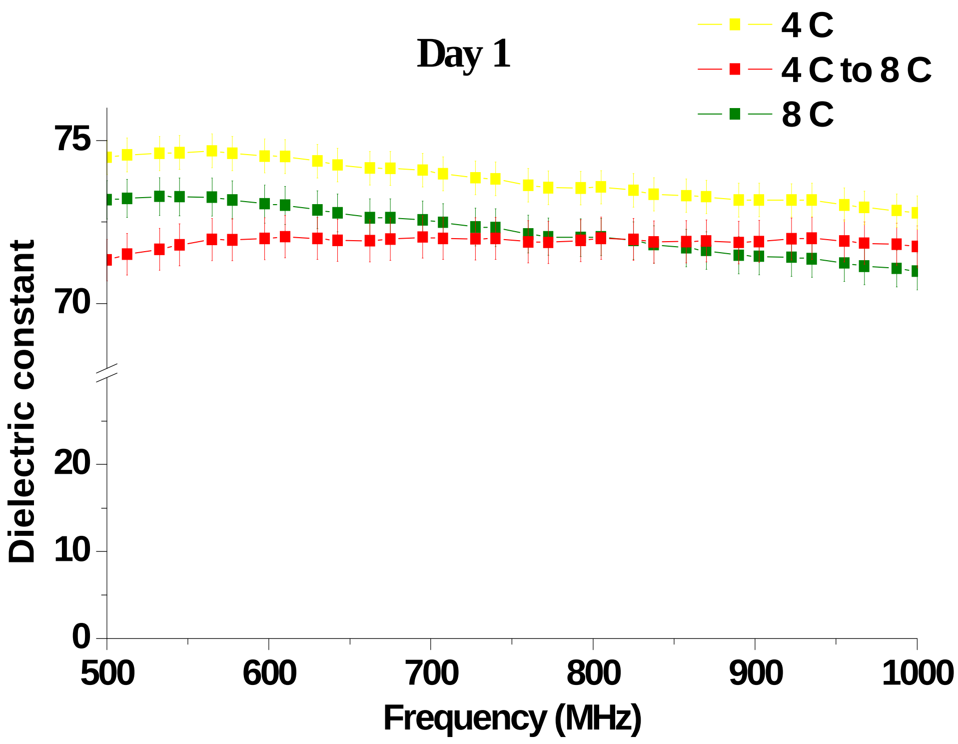
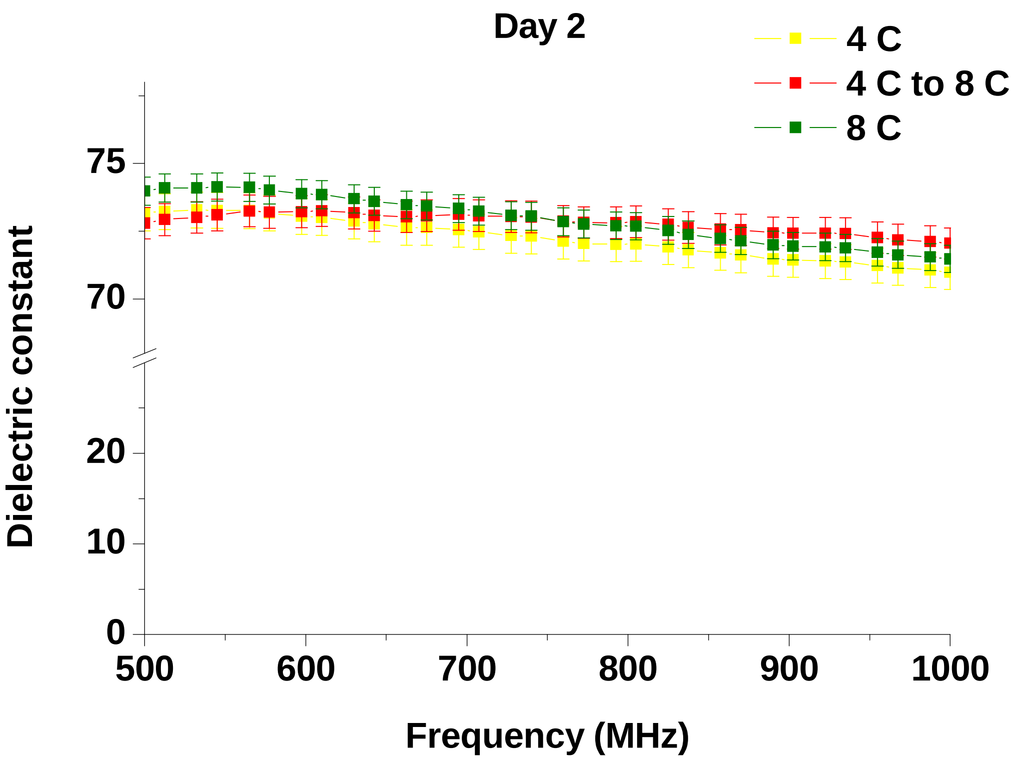


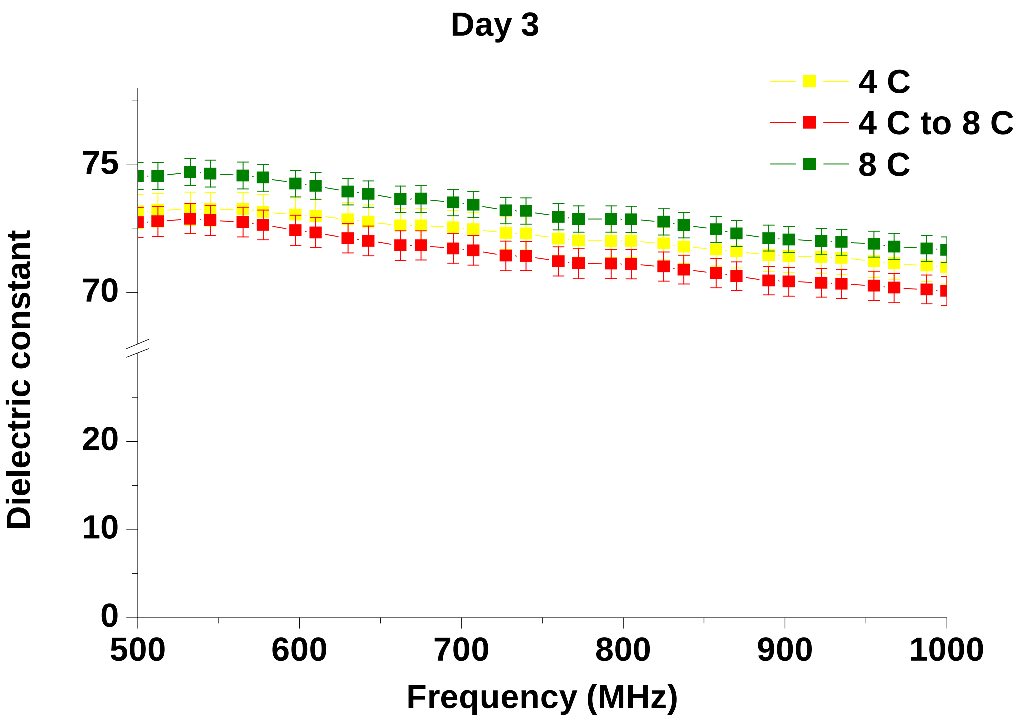
Figure 6.7: The dielectric loss of the different temperature storage of saturna potato between day 1 to day 7 at the frequency 2.45 GHz and temperature 20 C

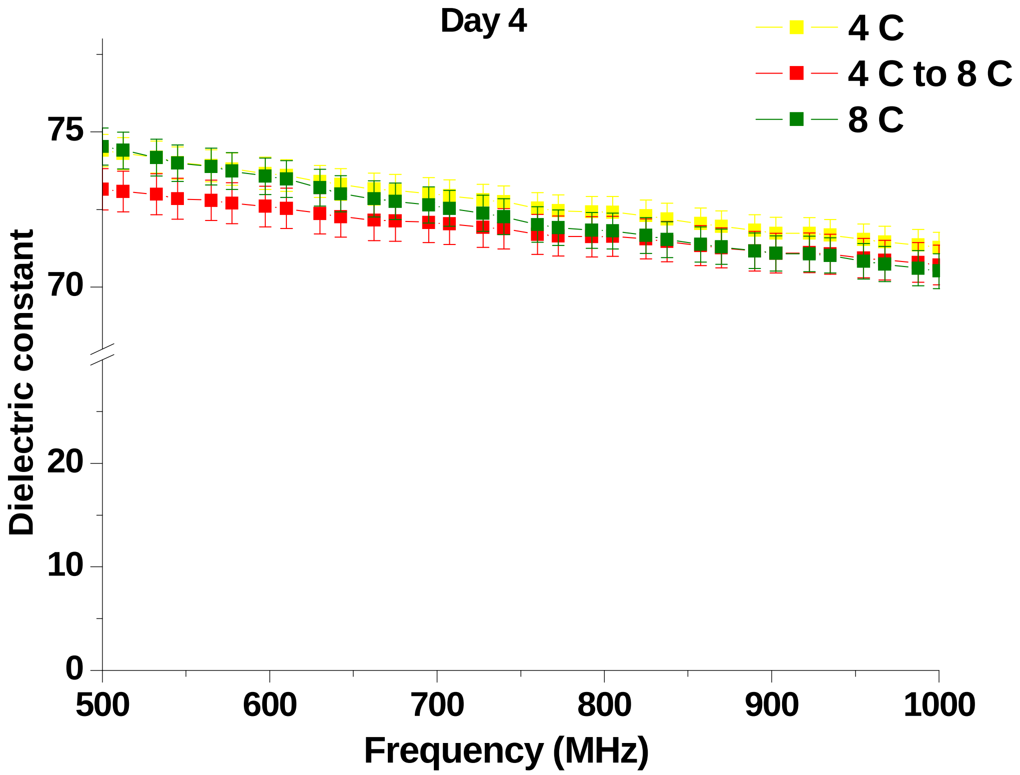
The result of measurement for the saturna potato stored at the different temperature is shown in the Figure 6.7. The dielectric loss of saturna potato is not much affected by the storage temperature. The dielectric loss for both samples with the 3 temperatures storage is fluctuating above and below 20 from day 1 to day 7. The result does not show the trend of continuously decrease or increase in the dielectric loss as the day of storage is increased. As discussed in the previous section, the change in the moisture content of saturna potato kept in the different storage temperature is minimal between days 1 to day 7. Raw saturna potato contains higher moisture content. The influence of the moisture content on the dielectric loss of the saturna potato is high. The higher change in the moisture content leads to the larger change in the dielectric loss of the saturna potato.

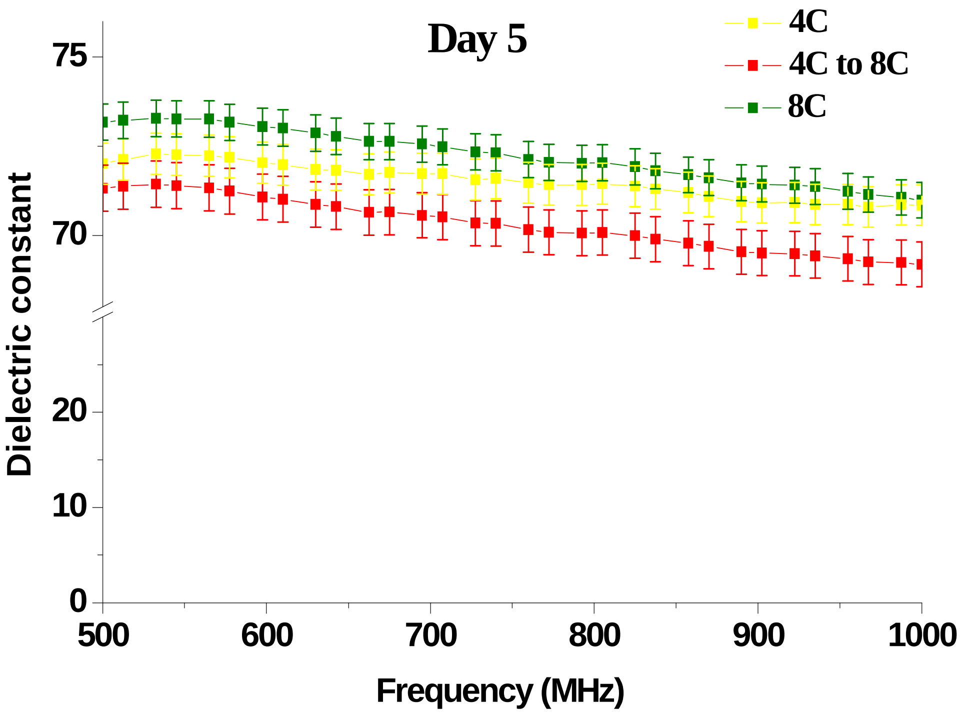
6.3.3 Open ended probe

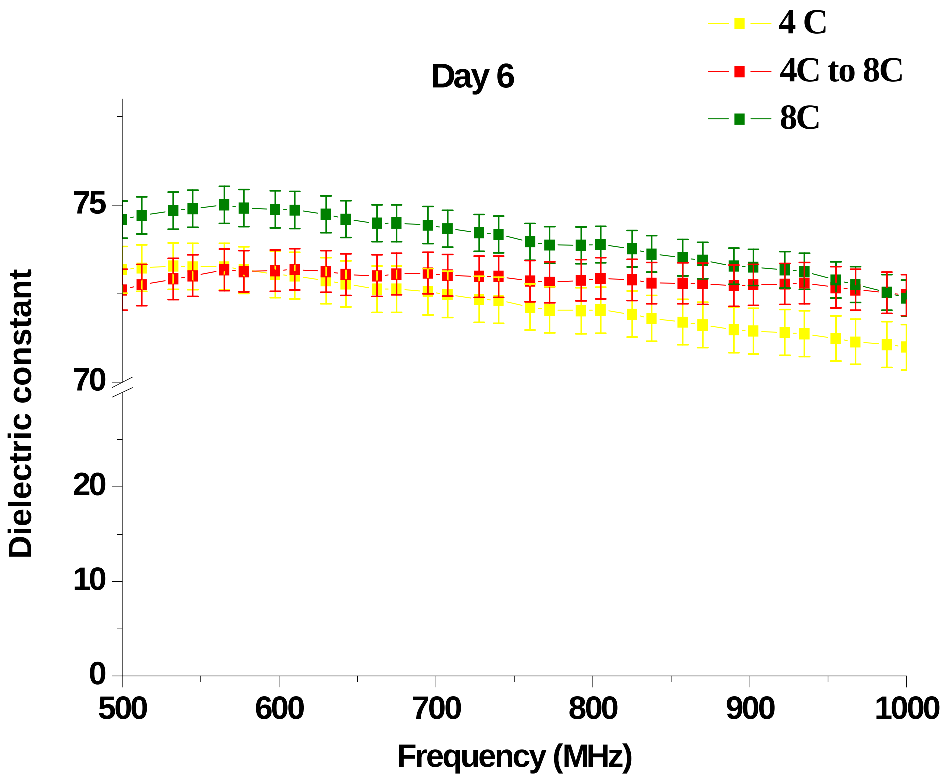





Day 3
4 C
4 C to 8 C
8 C
Dielectric constant
75
70
20
10
0
500
600
700
800
900
1000
Frequency (MHz)


Day 4
4 C
4 C to 8 C
8 C
Dielectric constant
75
70
20
10
0
500
600
700
800
900
1000
Frequency (MHz)


Day 5
4C
4C to 8C
8C
Dielectric constant
75
70
20
10
0
500
600
700
800
900
1000
Frequency (MHz)


Day 6
4 C
4C to 8C
8C
Dielectric constant
75
70
20
10
0
500
600
700
800
900
1000
Frequency (MHz)

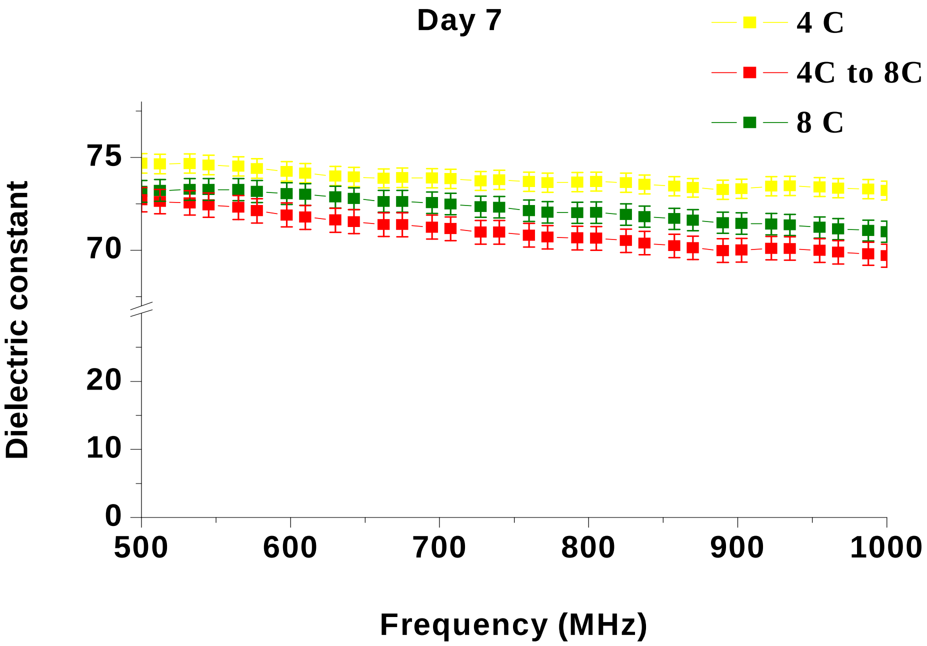
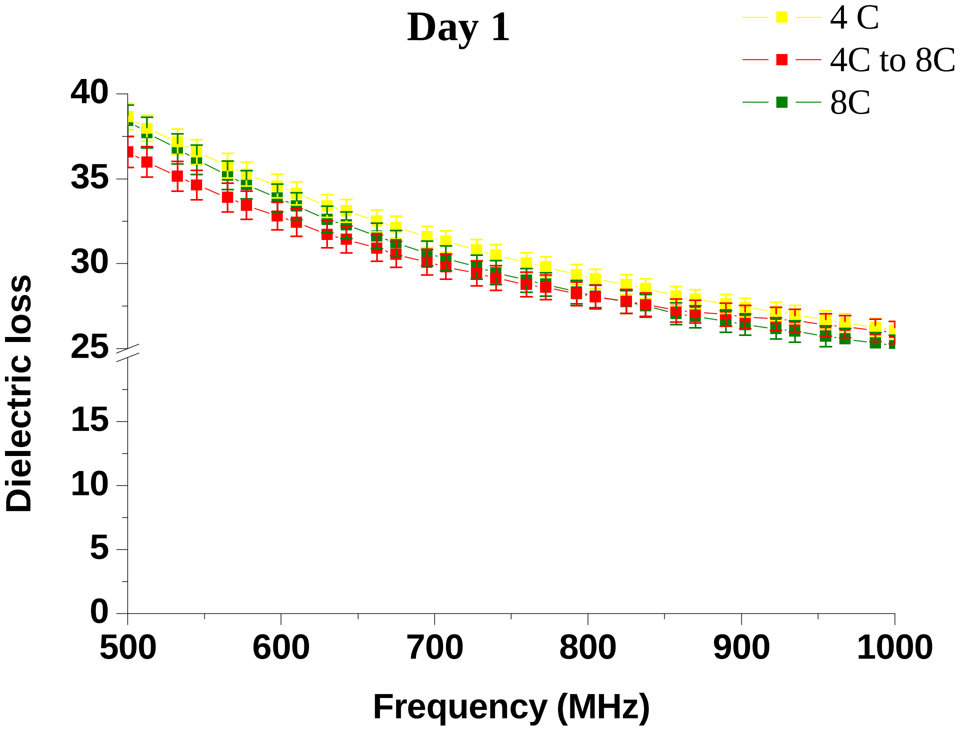
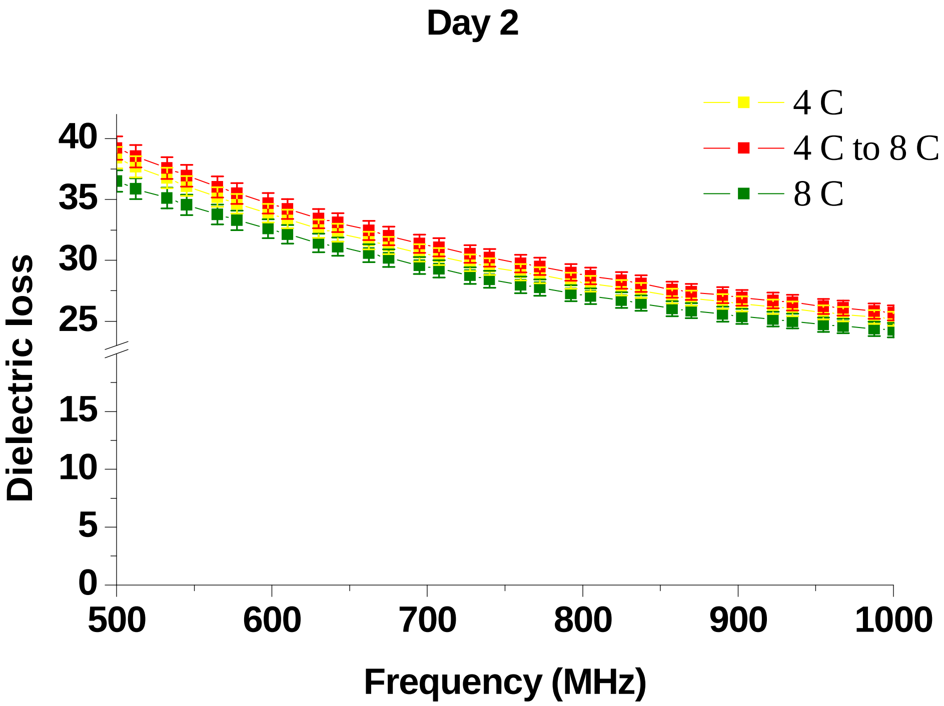


Figure 6.8: Dielectric constant of the raw saturna potato stored at the 3 different temperatures storage for 7 days with the frequency range 500 MHz to 1 GHz



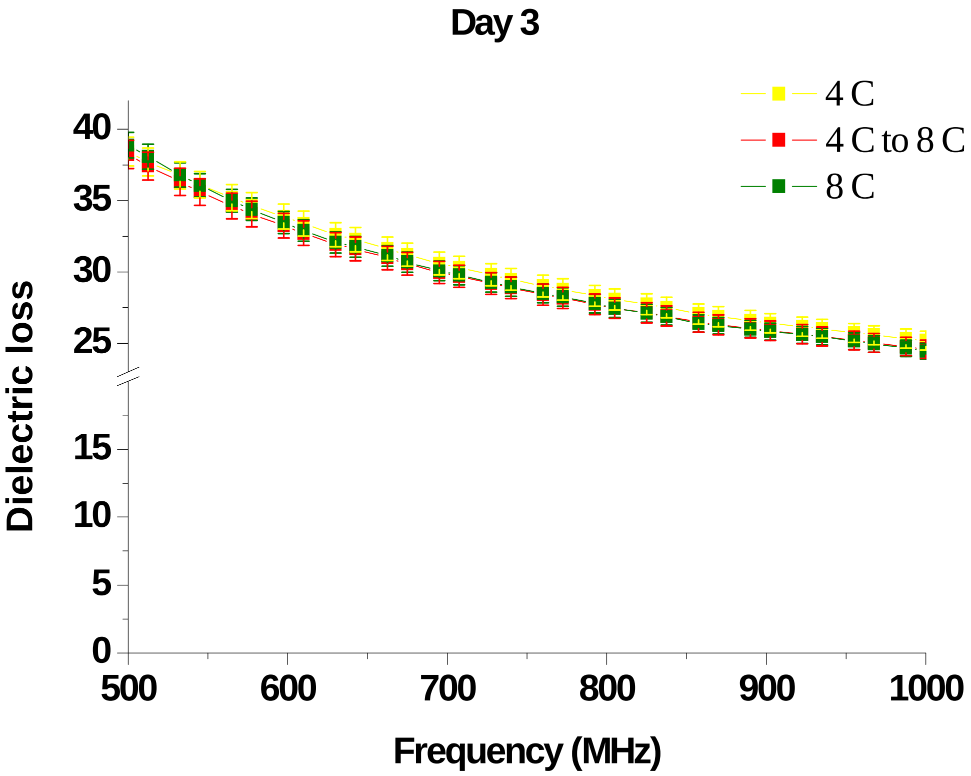
Day 1

4 C
4C to 8C
8C
Dielectric loss
40
35
30
25
15
10
5
0
500
600
700
800
900
1000
Frequency (MHz)

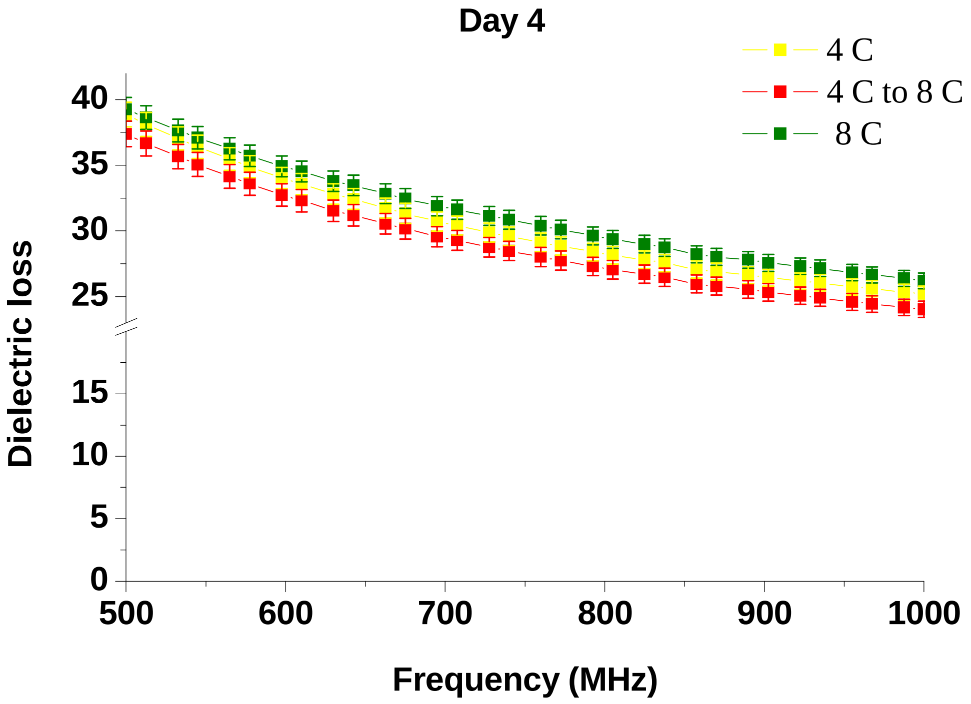


Day 2

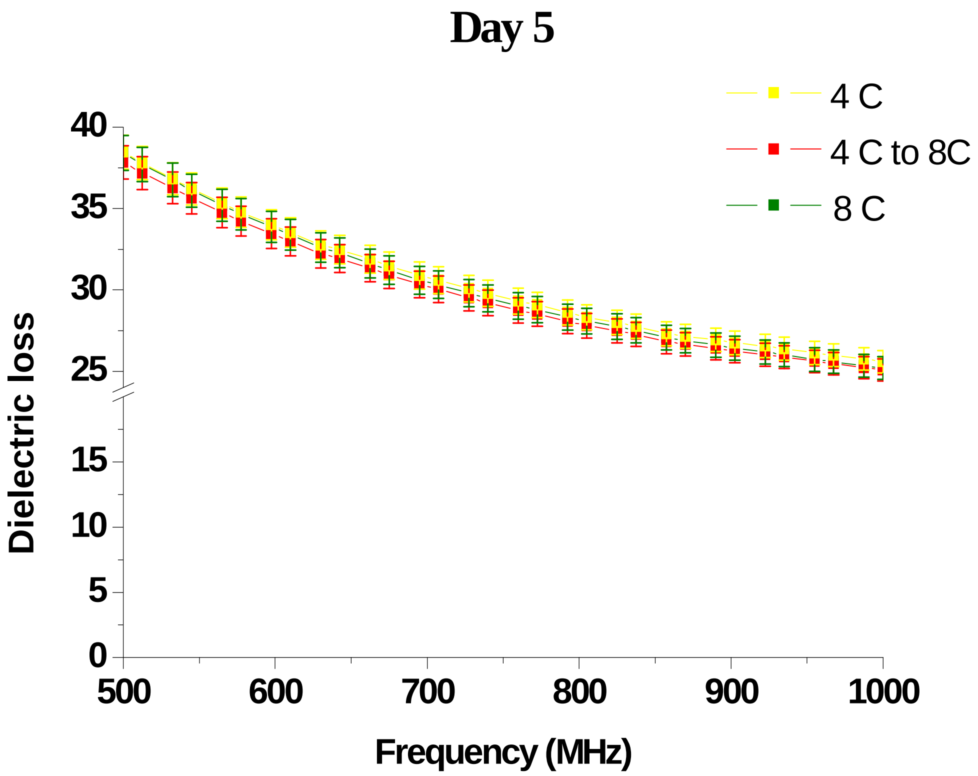
4 C
4 C to 8 C
8 C
Dielectric loss
40
35
30
25
15
10
5
0
500
600
700
800
900
1000
Frequency (MHz)

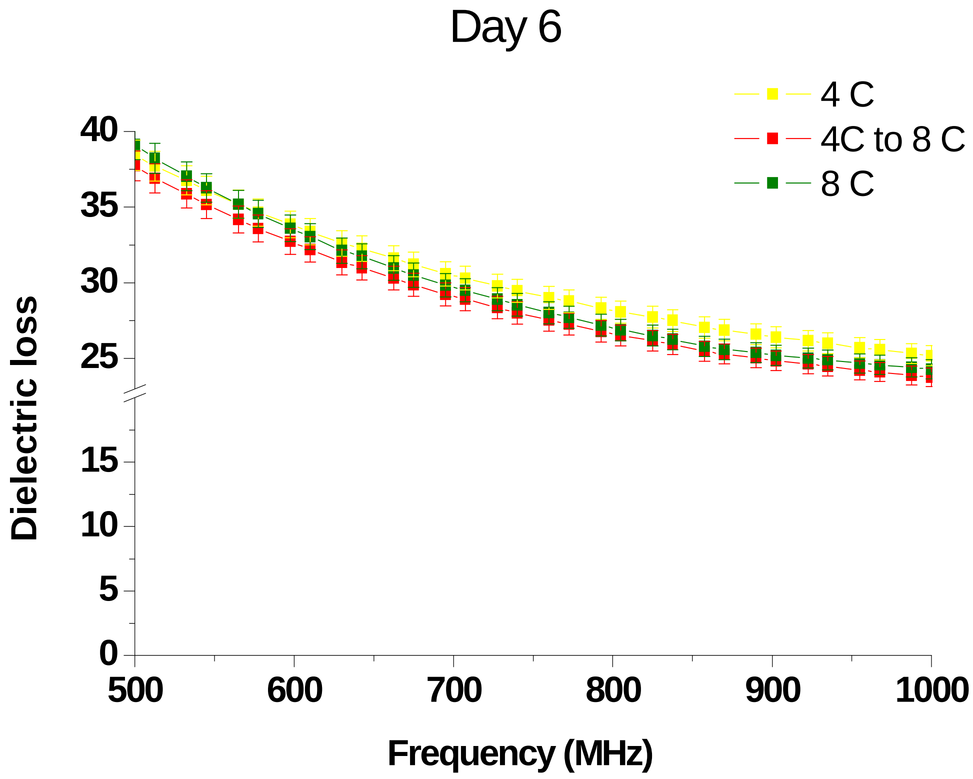


Day 3
4 C
4 C to 8 C
8 C
Dielectric loss
40
35
30
25
15
10
5
0
500
600
700
800
900
1000
Frequency (MHz)



Day 4
4 C
4 C to 8 C
8 C
Dielectric loss
40
35
30
25
15
10
5
0
500
600
700
800
900
1000
Frequency (MHz)


Day 5
4 C
4 C to 8C
8 C
Dielectric loss
40
35
30
25
15
10
5
0
500
600
700
800
900
1000
Frequency (MHz)


Day 6
4 C
4C to 8 C
8 C
Dielectric loss
40
35
30
25
15
10
5
0
500
600
700
800
900
1000
Frequency (MHz)

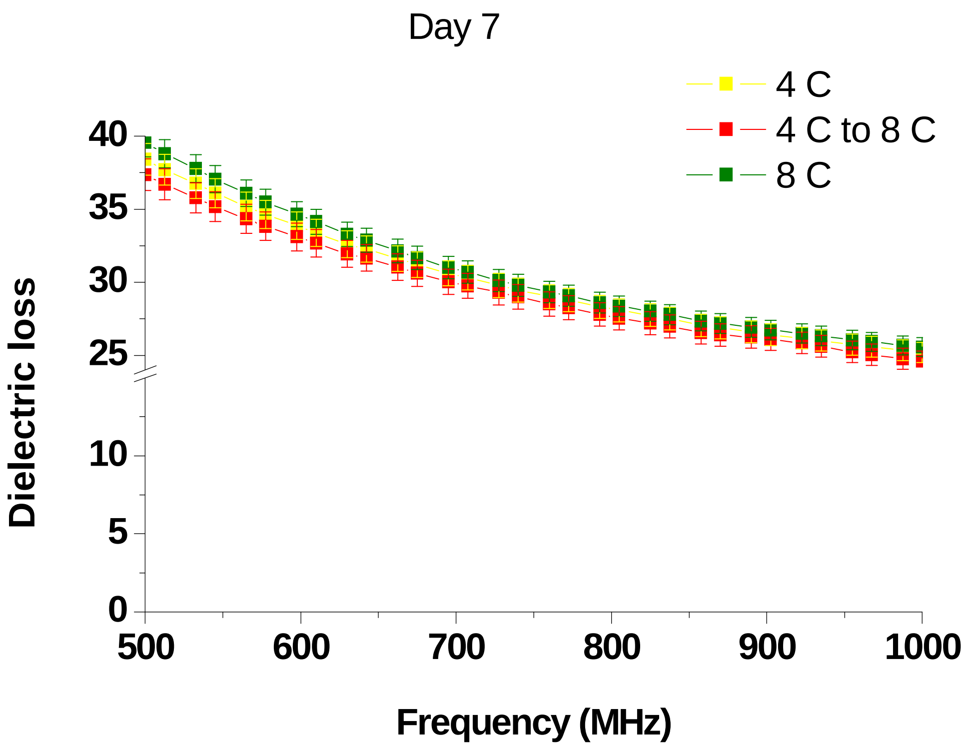


Figure 6.9: Dielectric loss of the raw saturna potato stored at the 3 different temperatures storage for 7 days with the frequency range 500 MHz to 1 GHz

The measurement results of dielectric constant and loss of the saturna potato at the frequency range 500 MHz to 1 GHz is shown in the Figure 6.8 and 6.9. The dielectric constant of saturna potato follows the similar trend of the frequency measurement range 2.4 GHz to 3.5 GHz. The dielectric constant and loss are not much affected by the storage temperature between day 1 to day 7. The details discussion on the effect of the storage temperature is discussed at the previous section 6.3.1. The dielectric loss of the saturna potato shows the effect of the ionic conduction where by the losses are elevated towards the lower frequency 500 MHz.

6.3.4 Complex permittivity of sample as a function of storage time at the frequency measurement 915 MHz

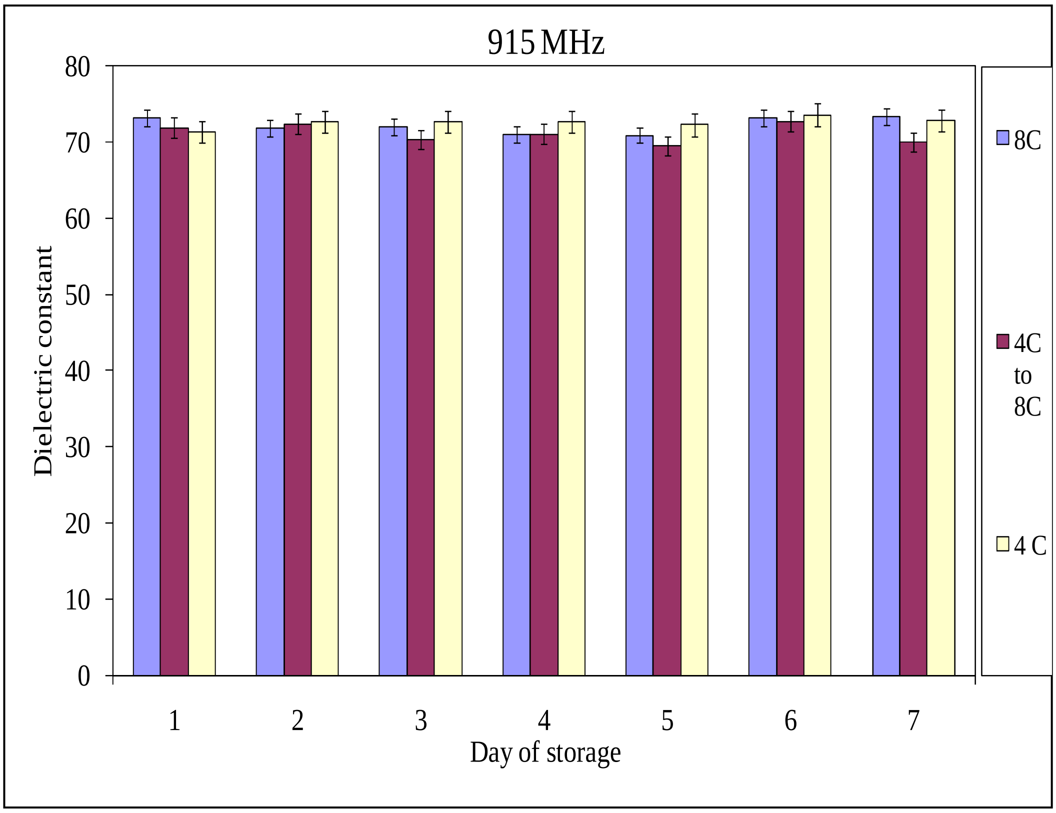


Figure 6.10: The dielectric constant of the different temperature storage of saturna potato between day 1 to day 7 at the frequency 915 MHz and temperature 20 C

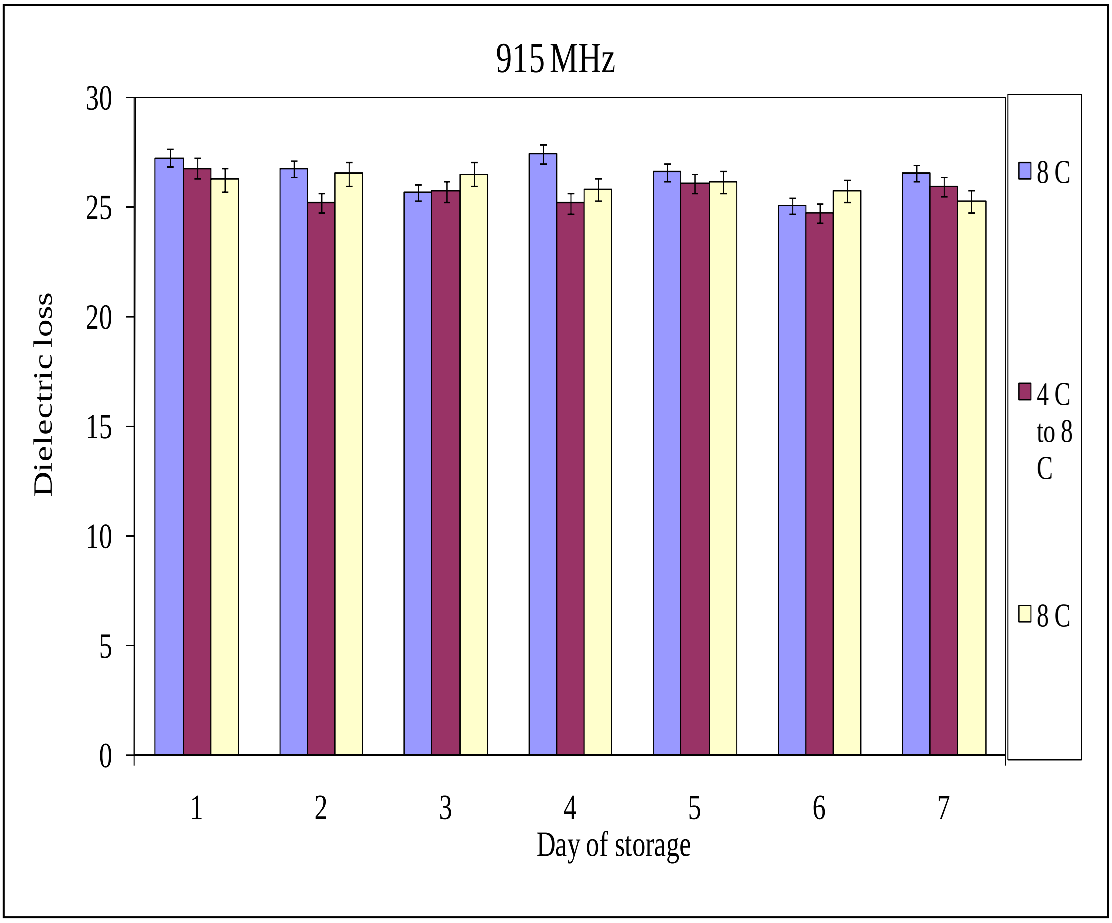


Figure 6.11: The dielectric loss of the different temperature storage of saturna potato between day 1 to day 7 at the frequency 915 MHz and temperature 20 C

The effect of the storage temperature on the dielectric constant and loss at the frequency 915 MHz is shown in the Figure 6.10 and 6.11. There is no pattern of continuously increase or decrease of the dielectric constant and loss as the day of storage is increased from day 1 to day 7. The dielectric constants of saturna potato for every storage temperature are fluctuating at the value of 74. The different of the dielectric constant and loss between the storage temperature is less than 4%. The storage temperature is not much affecting the dielectric constant and loss of the raw saturna potato at the microwave heating frequency 915 MHz.

6.3.5 Moisture content of sample as a function of time.

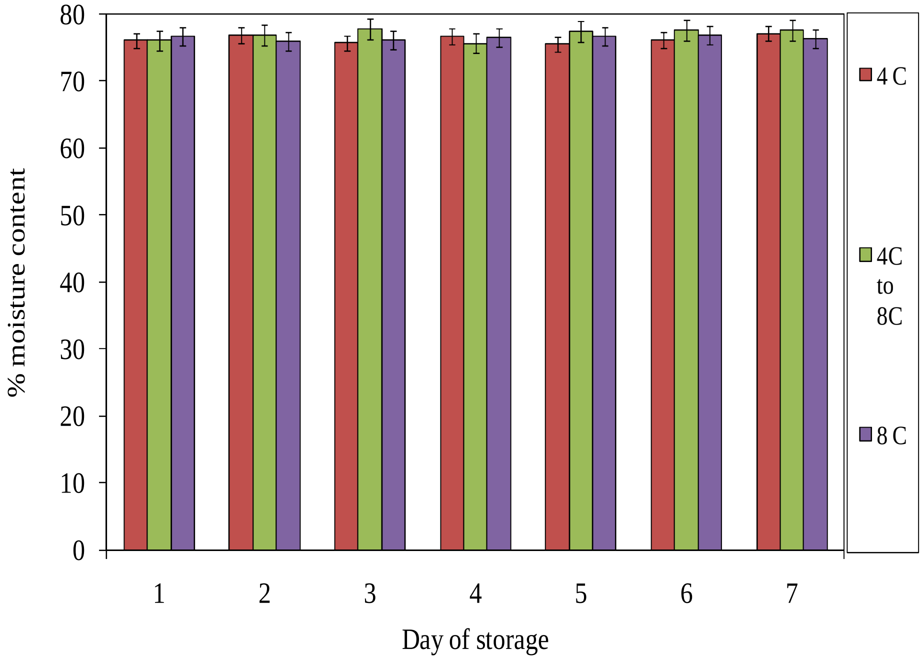


Figure 6.12: The moisture content of the different temperature storage of saturna potato solution between day 1 to day 7.

The measurement result of the moisture content for the raw saturna potato stored at the different temperature storage is shown in the Figure 6.12. The result does not show any significant difference in the moisture content. The highest difference between the moisture content of the saturna potato is around 4 %. The storage temperature does not affect the moisture content of the raw saturna potato during the 7 days of storage.

6.4 Conclusion

The suitability of using microwave measurements for sugar determination in the raw saturna potato has been investigated. The complex permittivity of the raw saturna potato stored at the 4 C for 7 days, 4 C for 24 hours then transferred to 8 C for another 6 days and 8 C for 7 days was evaluated at the 500 MHz to 1 GHz and 2.4 GHz to 3.5 GHz frequency ranges. The effect of the storage temperatures 4 C and 8 C was found to be less profound and marginal on the dielectric properties and moisture content of the raw saturna potato. The microwave measurement is an unsuitable method to measure the reducing sugar accumulation in the raw saturna potato. The influence of the storage temperature on the dielectric properties of the raw saturna potato at the 915 MHz and 2.45 GHz microwave heating frequencies has been established. This data provides a useful reference for the microwave heating design on the raw saturna potato stored in the 4 C and 8 C storage temperatures.

Chapter 7

Complex Permittivity Measurement of Fried Potato.

7.1 Introduction

Potato crisps are a high demand consumable snack product. The sales volume of potato crisps is 33% of total sales of snack in US [80]. The range of total oil content in the commercial potato crisps is in between 35.3 % to 44.5%, which adds to this product's taste and flavour so desirable to the consumer [81]. Nowadays, consumers are very concerned about the healthy food product that contains less fat.

Moisture evaporates from potato slice during frying in the high temperature of cooking oil. The amount of moisture loss is determined by the potato thickness, frying time, frying temperature and the texture of the potato [82]. Costa, Oliveira and Gekas [83] have studied the mechanism of water loss during the frying process. They found that the first stage of water loss during frying comes from its surface. During the second stage, there is an intense flow of water bubbles or boiling and there is an exponential of water loss occurs at this stage. The third stage of water loss occurs after the formation crust on the surface of fried potato.

The high frying temperature has caused the moisture of potato to boil explosively. Then the cell wall of the potato is damaged, and as a result it will create the capillary holes inside the fried potato. This will cause further cell wall bursting and damage, and consequently, the formation of capillary holes. Oil is absorbed into the slice through the voids left by moisture that had evaporated. For these reasons, regular potato crisps can have high of oil contents [84]. This mass transfer process is characterized by the movement of oil into the product and water loss in the form of vapour from the product [85] . The relationship of oil uptake and moisture loss of the thin crisps during immersion frying has been studied previously by Southern, Chen, Farid, Howard and Eyres[86]. A linear moisture-oil relationship reported for crisps was obtained in this study [87].

Based on the change of moisture and oil content of fried potato during the frying process, it is possible to relate it with the dielectric properties at microwave frequencies. The dielectric properties of food stuff depend on many factors and one of them is related with the food composition. Water and salt contribute to the high value of dielectric properties in the microwave frequency range. Water has a high dielectric constant at lower microwave frequencies and high dielectric loss at the higher frequencies. Raw potato contains high moisture content and the amount of moisture will reduce during the frying process. Dielectric properties of fried potato will change accordingly with the loss of moisture content of fried potato. Moisture content is an important parameter of the quality control of fried potato crisps. The good quality of the potato crisps usually requires the moisture content to be lower than 1.5± 0.1 wt % [88]. Moisture is detectable at the microwave frequency range using microwave techniques. It can be used to detect the moisture content of fried potato and monitor the quality of potato crisp.

The dielectric properties of fried potato have a significant effect on the microwave heating performance. Dielectric constant and loss describes the ability to absorb and transmit the electromagnetic energy. Dielectric properties are also used to determine the penetration depth (D_p) and power dissipation. Penetration depth is defined as the depth at which microwave power is reduced to 1/e or 37 % of its surface value, which is an important factor in characterising the heat distribution in the microwave heated material [89].

This study will investigate: 1) the use of the microwave transmission line method and coaxial probe to measure the complex permittivity of fried potato at the 0 min, 1min, 2 min, 2.5 min, 3 min and 4 min of frying time and 2) the influence of temperature on the complex permittivity of fried potato. The data of dielectric properties of fried potato can be used to detect the moisture content of fried potato and also to determine the depth penetration and power dissipation for the microwave heating or microwave frying mechanism at the two microwave heating frequencies. The industrial microwave heating frequencies are 915 MHz and 2.45 GHz [90]

7.2 Material and method

7.2.1 Sample preparation

Estima, King Edward and Maris Piper are the best known and popular varieties on sale in UK. They are widely grown across the country, so the stocks are always available for the commercial production of crisp. So these varieties of potato, Estima, King Edward and Maris Piper were used in the experiment. Potatoes were bought from the local ASDA supermarket at Manchester. Potatoes were peeled, washed and cut by using a Mandolin Slicer (Bron Mandolin) into 2mm of thickness. The potato slices were washed with cool water to remove free starch and surface was blotted with towel paper before frying.

Potato frying was conducted in a deep fryer (Buffalo deep fryer) and filled with 3.5 L vegetable oil at 180 C frying temperature. Potato slices were put in the hot oil and frying was performed for 1 min, 2 min, 2.5 min, 3 min and 4 min respectively. Fried potatoes were blotted with towel paper to remove excessive oil on its surface. Fried potatoes were placed in a desiccator to cool their temperature to room temperature. Then the fried potatoes were transferred to a sealed plastic bag and kept in the fridge (Polar refrigeration) at 8 C for 12 hours. Then the fried potatoes were mashed at the cool temperature with a blender (Philip blender) for 5 seconds to produce the homogeneous sample for complex permittivity measurement.

7.2.2 Moisture content measurement

Moisture content of fried potatoes was determined by measuring the weight loss of triplicate sample through 48 hours drying in the air oven (Carbolite AX60 air convection oven).

7.2.3 Coaxial probe measurement

The coaxial probe measurement technique was used to measure the complex permittivity of the blended fried potato in the frequency range of 500 MHz to 1 GHz. This method was also used to determine the complex permittivity of blended fried potato at the microwave heating frequency 915 MHz. The detailed procedure of coaxial probe measurement is discussed in chapter 5.

7.2.3.1 Sample holder setup for coaxial probe measurement.

A special designed sample holder was constructed to ensure that blended fried potato could have a good contact with coaxial probe and eliminate the air space gap between the sample and coaxial probe. The sample holder consisted of 0.25 cm thick and 10 cm high clear Perspex tube. The sample was placed between two polyethylene cylinders and compressed by two loaded springs at the bottom and two adjustable screws at the top to eliminate any air space gap between the fried blended potato and the coaxial probe. The top polyethylene cylinder was attached to the coaxial probe by two screws. Rubber O ring was attached to the two polyethylene cylinders to prevent leakage of blended fried potato. The setup is illustrated in Figure 7.1.

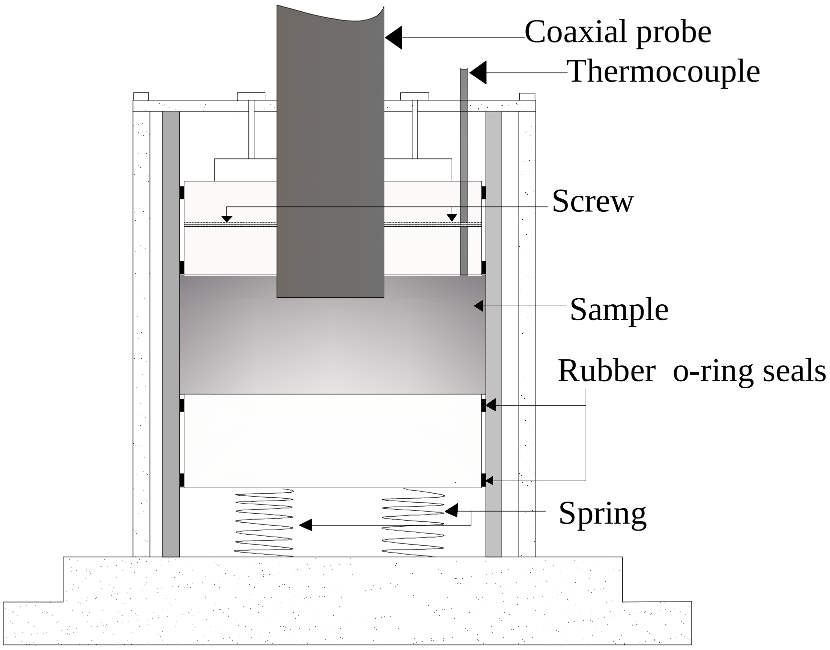


Figure 7.1: Sample holder setup of coaxial probe for measuring the complex permittivity of blended fried potato.

7.2.4 Waveguide cell measurement

The waveguide cell method has been implemented in WG-284 (2.5-4.0 GHz). In the case of non self-supporting samples, it is necessary to include dielectric windows to contain the sample. Referring to Fig. 7.2, sample holder consist of Perspex dielectric windows mounted in a copper waveguide soldered into a brass flange which has been ground flat. Sample holder also contains the sample under test, consists of a short length of copper waveguide also fitted with ground brass flanges. This arrangement prevents sample leakage. The internal dimensions of the sample holder were 1.907x3.4x7.2 cm (WR-284). The sample holder was placed midway between the transmission lines and perpendicular to the incident wave. The transverse and height dimension of the sample holder were selected to be the same as the waveguide to preserve the electrical continuity of the copper waveguide throughout the test assembly. The transmission line measurements were conducted with the dominant mode (TE_{10}). Prior to measurements, the VNA and attached transmission line was an error corrected by a full 2-port calibration. During measurements, each sample was carefully filled into the waveguide cell guarded by two Perspex windows. It is necessary to have a flat and homogenous interface between the sample and Perspex windows to eliminate an error caused by air voids.

7.2.5 Temperature control chamber setup

A temperature control chamber was designed to control the temperature of the blended potato sample at specified measurement temperatures (20 C – 60 C) while complex permittivity measurements were made. The chamber was constructed from 0.5 cm thick Perspex sheet with 28 cm height, 19 cm width and 26.5 cm long. A Peltier thermoelectric air cooler (Model no.: AC-162, TE Technology Inc, Michigan USA) was mounted at the bottom of the chamber. The Peltier thermoelectric air cooler controls the temperature of the chamber and its operation was controlled by Thermoelectric Cooler Temperature controller (Model no. : TC-36-25 RS 232, TE Technology Inc, Michigan USA). A thermocouple was attached on the top side of the sample holder and temperature was monitored by a Thermocouple data logger (Model no. : USB TC-08 Picotech UK). An illustration of the temperature chamber is included in Figure 7.2 and Figure 7.3. In order to ensure the targeted temperatures were reached in the sample material, each sample was allowed to equilibrate at the desired temperature for 30 minutes before measurements were taken.

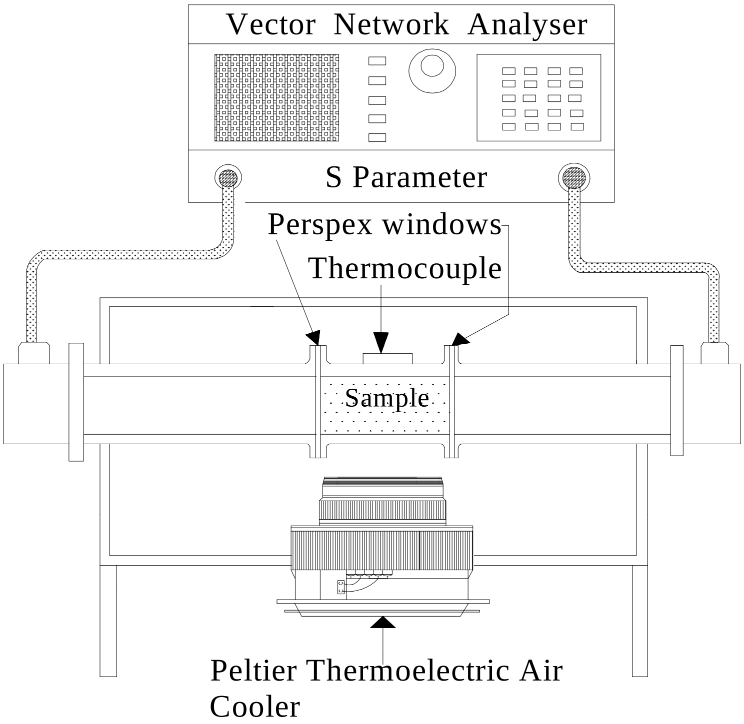


Figure 7.2: Transmission line (waveguide 10) setup for complex permittivity measurements of blended fried potato under temperature control

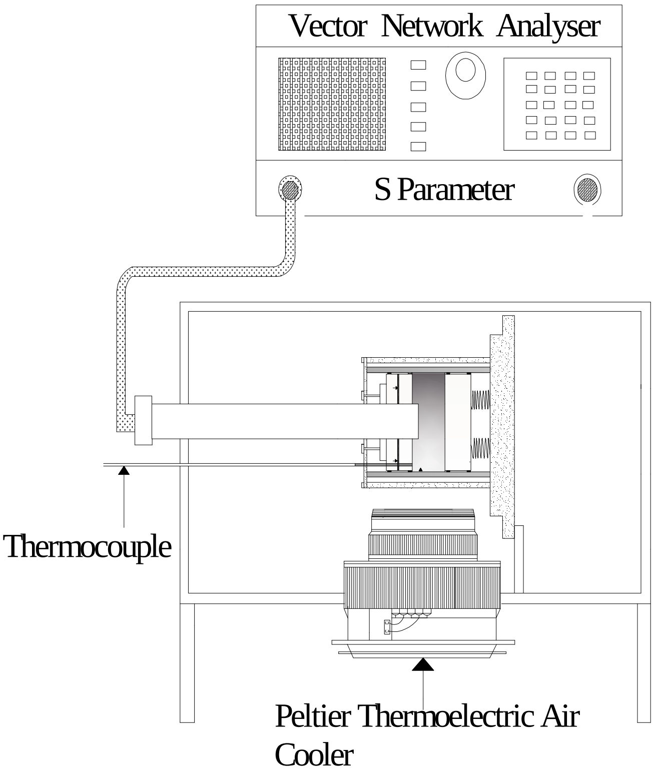


Figure 7.3: Coaxial probe setup for complex permittivity measurements of blended fried potato under temperature control.

7.3 Results and discussions

7.3.1 Waveguide cell

7.3.1.1 Blended Fried Estima

Dielectric constant measurement results for 0 min, 1 min, 2 min, 2.5 min, 3 min and 4 min frying time are shown in Figure 7.4. The measurement of dielectric constant of fried estima potato with different frying times at a frequency range of 2.3 GHz to 3.5 GHz at 20 C shows that there is a relationship between the frying time and the dielectric constant. Results indicated that dielectric constant decreased over the frying time. These results can be explained by correlating the loss of moisture content of Estima fried potato with the frying time and dielectric properties. More moisture evaporated from the Estima potato as the frying time is increased and this will decrease the value of dielectric constant.

Over the frequency band, there is a slight reduction in the dielectric constant for 0 min to 2.5 min frying time. The dielectric constant of 3 min and 4 min frying time remains constant over the frequency band. This effect has a similarity with dielectric properties of polar and non-polar material. Polar material is frequency dependence but non polar material is not frequency dependence. In this case, water is polar material and has a dominant effect on the dielectric constant at 0 min to 2.5 min of frying time, where as cooking oil is a non polar material and has a dominant effect on the dielectric constant of fried potato at 3min to 4 min of frying time. The frequency dependence of the dielectric properties of material is explained by the Debye equation in chapter 2.

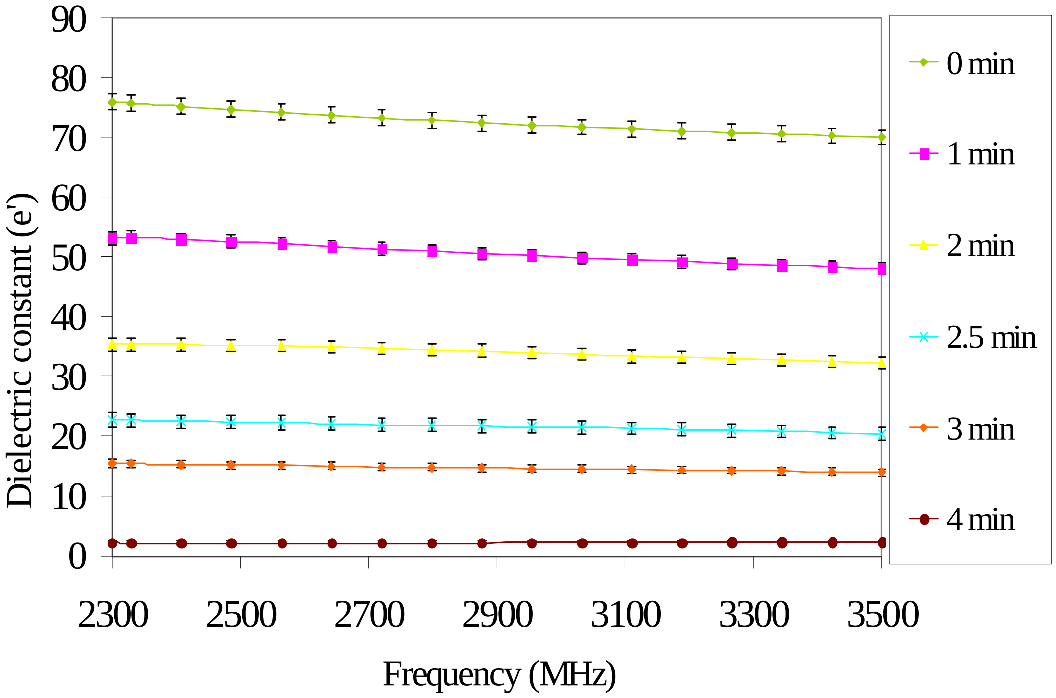


Figure 7.4 : Dielectric constant as function of frying time for fried estima potato at frequency range 2.3 GHz to 3.5 GHz at 20 C.

Table 7.1 : Moisture content of Estima potato as a function of frying time

Frying time	Moisture content (Based on wet basis)
0 min	78.5 %
1 min	37.6 %
2 min	21.8 %
2.5 min	14.0 %
3 min	11.5 %
4 min	2.4 %

The dielectric constant of blended fried Estima potato decreases consistently as the frying time is increased. This is due to the loss of moisture from the potato during the frying process. This result is in agreement with a previous study on the effect of moisture on the dielectric constant of food [89]. Moisture has a significant effect on the dielectric properties. The lower moisture content leads to a lower value of dielectric constant and loss. Krokida measured the moisture content of fried potato and found that the moisture content of potato decreases significantly during frying [82]. As frying time is increased more moisture will evaporate and the cooking oil is absorbed. This phenomenon has a relationship with the changing of dielectric constant of fried potato from 0 min to 4 min frying time. At the early stage of frying time, the potato contains high moisture content and this contributes to the high value of dielectric constant. At the last stage of frying process, more moisture has evaporated from fried potato and then the dielectric properties values of fried potato are small and less affected by water. At this stage dielectric constant of fried potato is dominated by the dielectric properties of cooking oil. The dielectric constant of fried potato at 4 min frying time is 2.2 and the dielectric constant of cooking oil is 2.5 at temperature 25 C and frequency range 2.3 GHz to 3.5 GHz.

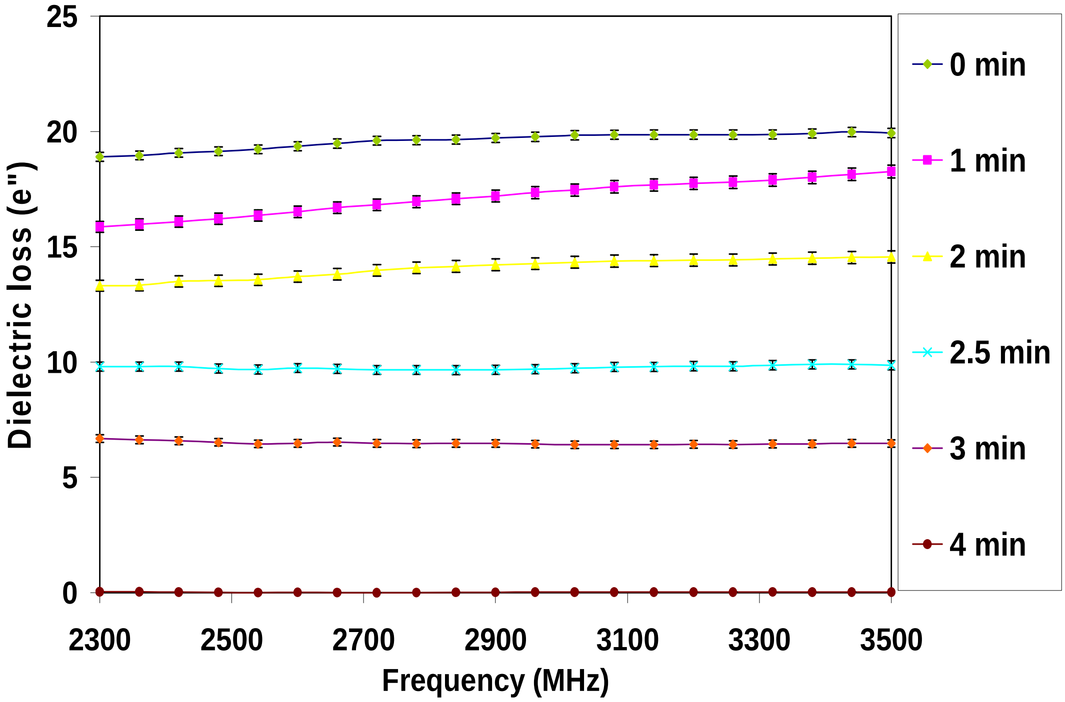


Figure 7.5: Dielectric loss as function of frying time for fried estima potato at frequency range 2.3 GHz to 3.5 GHz at 20 C.

Figure 7.5 shows the result of dielectric loss of fried Estima potato as a function of frying time over the frequency range 2.3 GHz to 3.5 Ghz. Dielectric loss decreases as frying time is increased. It follows the similar trend of dielectric constant of fried Estima potato with different frying time. There is slightly increased of dielectric loss over the frequency band for frying time 0 min to 2.5 min. On the other hand, dielectric loss for 3min and 4 min frying time remains unchanged and not frequency dependence over the frequency range 2.3 GHz to 3.5 GHz. Moisture content in fried potato is higher at the 0 min and gradually decreased as the frying time is increased. Hence dielectric loss of fried Estima is higher at 0 min frying and decreased as frying time increased.

7.3.1.2 Blended Fried King Edward.

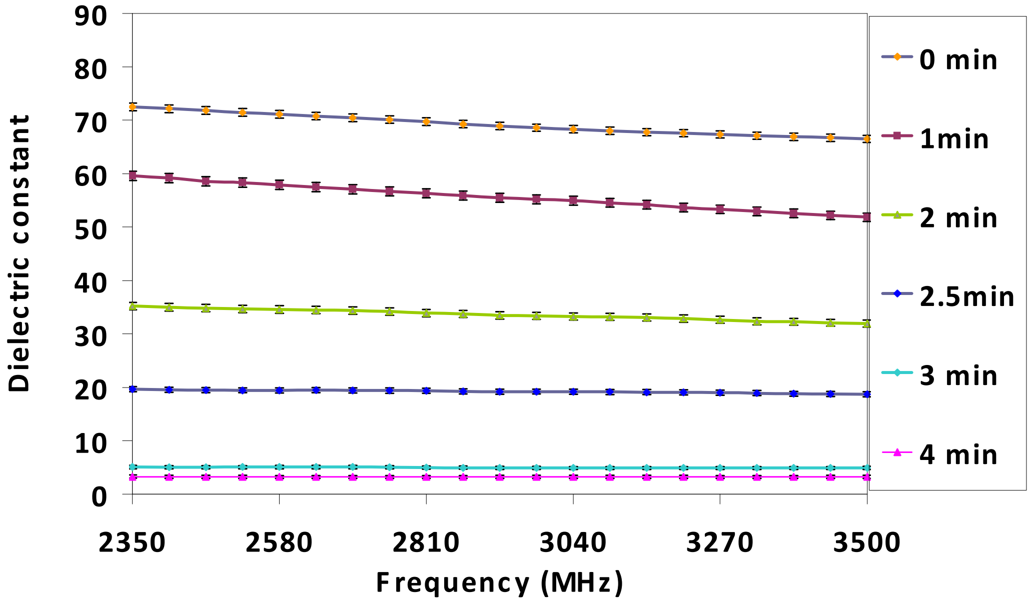


Figure 7.6: Dielectric constant as function of frying time for fried King Edward potato at frequency range 2.3 GHz to 3.5 GHz at 20 C.

Figure 7.6 shows the effect of frying time towards the values of the dielectric constant of fried King Edward potato. The experimental results in Figure 7.6 show that dielectric constant of fried King Edward potato follows the similar trend with the dielectric constant of fried Estima potato. Dielectric constant of fried King Edward potato is decreased with increasing the frying time. It can be seen from Figure 7.6 and table 7.2, when the frying time is increased, more moisture has evaporated and then the dielectric constant was influenced by frequency, especially at the higher moisture content and then becomes less dependence with the frequency at the lower moisture content. For example, the dielectric constant of 0 min and 1 min frying time decreases consistently with an increase in frequency. On the other hand, dielectric constant of 3 min and 4 min frying time remains unchanged with an increase of frequency. Table 7.2 shows the moisture content decreases as frying time is increased. The longer the frying time leads to the lower the value of dielectric constant and moisture content. The dielectric constant of raw King Edward potato is lower than raw Estima potato and this would indicate that the raw King Edward potato had a lower moisture content compared to raw Estima potato.

Table 7.2 : Moisture content of King Edward potato as a function of frying time

Frying time	Moisture content (Based on wet basis)
0 min	76.9%
1 min	35.8%
2 min	22.7 %
2.5 min	16.3 %
3 min	5.9 %
4 min	3.3%

Figure 7.7 shows the effect of frying time on the dielectric loss of fried King Edward potato. The effect of frying time and moisture on the dielectric loss of fried King Edward potato follows the similar trend of dielectric constant of fried King Edward potato against frying time and moisture content.

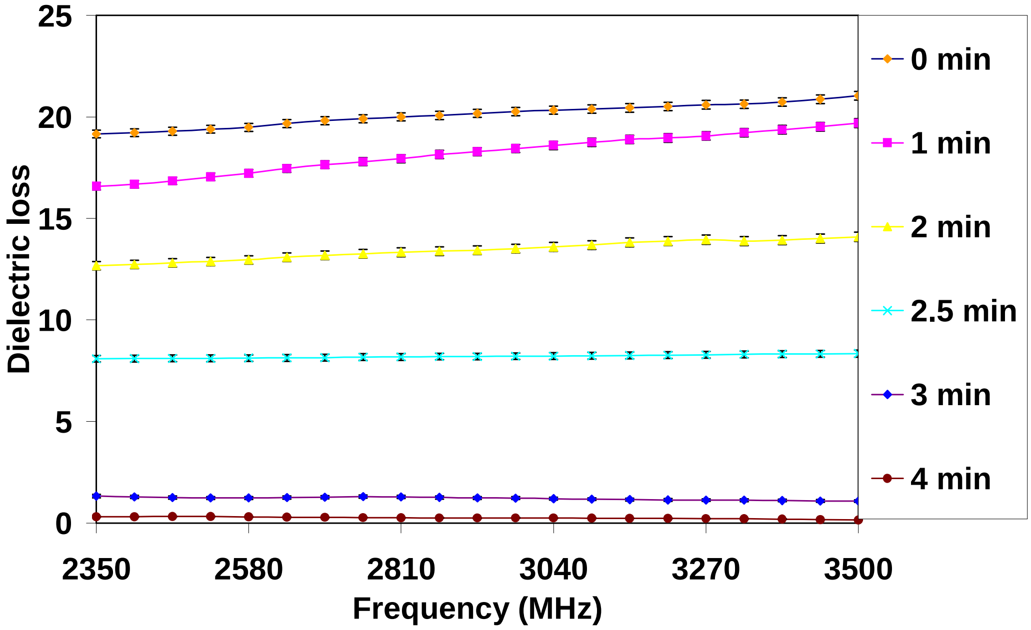


Figure 7.7: Dielectric loss as function of frying time for fried King Edward potato at frequency range 2.3 GHz to 3.5 GHz at 20 C.

7.3.1.3 Blended Fried Maris Piper

Figure 7.8 shows the effect of frying time on the dielectric constant of blended fried Maris piper potato over the frequency range 2.3 GHz to 3.5 GHz at a temperature of 20 C. Raw Maris piper potatoes contains a moisture content of 66.2 % with lower dielectric constant compared to raw Estima and King Edward potato. The dielectric constant was decreased with increasing frying time and hence decreases of moisture content. The moisture content and frying time have a significant effect on the dielectric constant of fried Maris Piper potato. The decrease in moisture decreases the polarisation, which decreases the dielectric constant of fried Maris piper potato during the frying process. This follows the similar trend of the dielectric constant of fried Estima and King Edward potatoes.

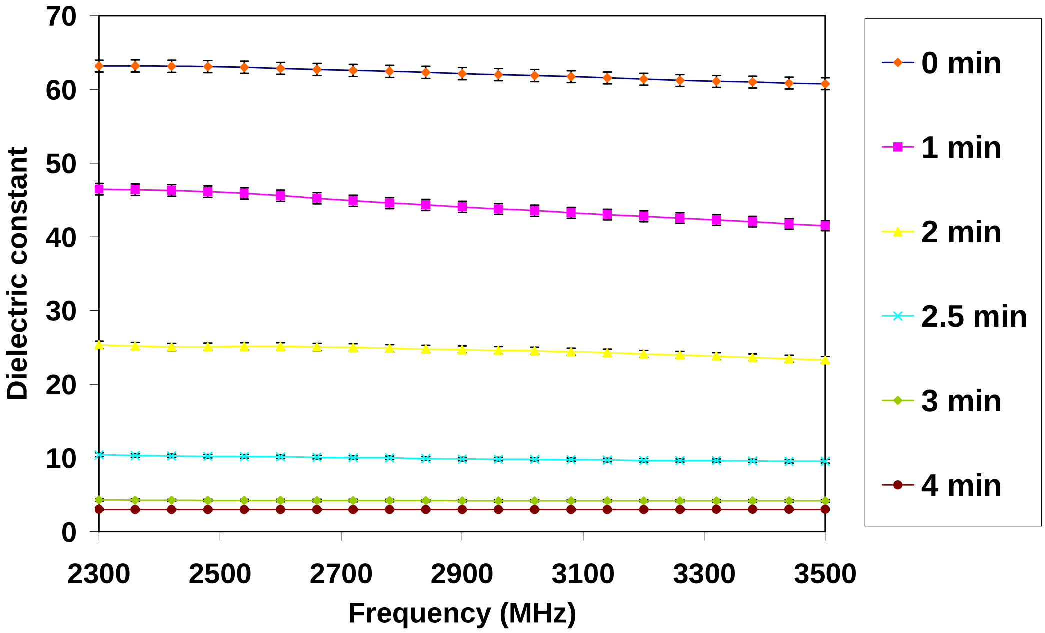


Figure 7.8: Dielectric constant as function of frying time for fried Maris piper potato at frequency range 2.3 GHz to 3.5 GHz at 20 C.

Table 7.3 shows the relationship between the frying time and moisture content of fried Maris Piper potato. This table shows a high amount of moisture loss between 66.2 % and 4.2 % during 0 min to 3 min of frying time. This data agreed with the study conducted by Costa, Oliveira and Gekas [83] on the moisture loss during the frying process of potato. The high amount of water loss has resulted in a higher decreased rate of dielectric constant between 0 min to 3 min of frying time.

Table 7.3 : Moisture content of Maris Piper potato as a function of frying time

Frying time	Moisture content (Based on wet basis)
0 min	66.2 %
1 min	30.7 %
2 min	17 %
2.5 min	9.8 %
3 min	4.2 %
4 min	1.6%

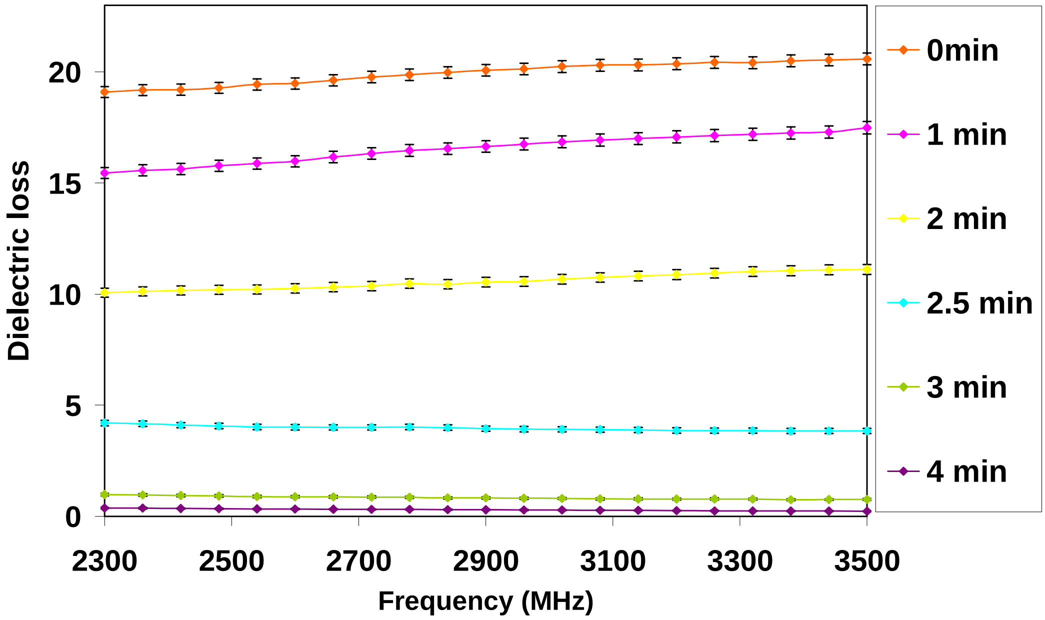


Figure 7.9: Dielectric loss as function of frying time for fried Maris Piper potato at frequency range 2.3 GHz to 3.5 GHz at 20 C.

Figure 7.9 shows the dependence of dielectric loss of fried Maris piper potato on the frying time. The dielectric loss of fried Maris Piper potato decreased with an increase of frying time. When the frying time is increased, more moisture evaporated from fried Maris piper potato and then this will decrease the dielectric loss of fried Maris piper potato. Cooking oil is absorbed into the crisps through the pore or voids that are left by moisture in the evaporation process. As a result, at 4 minutes of frying time, the dielectric loss of cooking oil has dominated the dielectric loss of fried Maris piper potato. This follows the similar trend of the dielectric loss of fried Estima potato and King Edward potato against frying time. At the earlier stage of frying time, the dielectric loss of Maris piper potato was dominated by the existence of free water then cooking oil will take an effect on the dielectric loss of Maris piper potato at the last stage of frying time.

7.3.1.4 The effect of different blending time on the complex permittivity of blended fried potato chips

Fried potato was blended to achieve more homogeneous sample to solve the problem of additional brown layer on the surface of fried potato. The fried estima potato was mashed at a temperature of 8 C to prevent moisture loss during the blending process. Figure 7.10 shows the effect of blending time on the value of dielectric constant. The blending times of 5 sec, 10 sec and 15 sec do not give significantly different values of dielectric constant. The value of dielectric constant is around 53 at the frequency 2450 MHz. The value of dielectric constant decreased as the blending time was increased to 20 sec. Dielectric loss of fried potato is not changed between the blending time 5 sec, 10 sec and 15 sec as shown in Figure 7.11. However, the dielectric loss decreased as the blending time was increased to 20 sec. The blending time of 5 seconds was selected to blend the fried potato to achieve a more homogeneous sample.

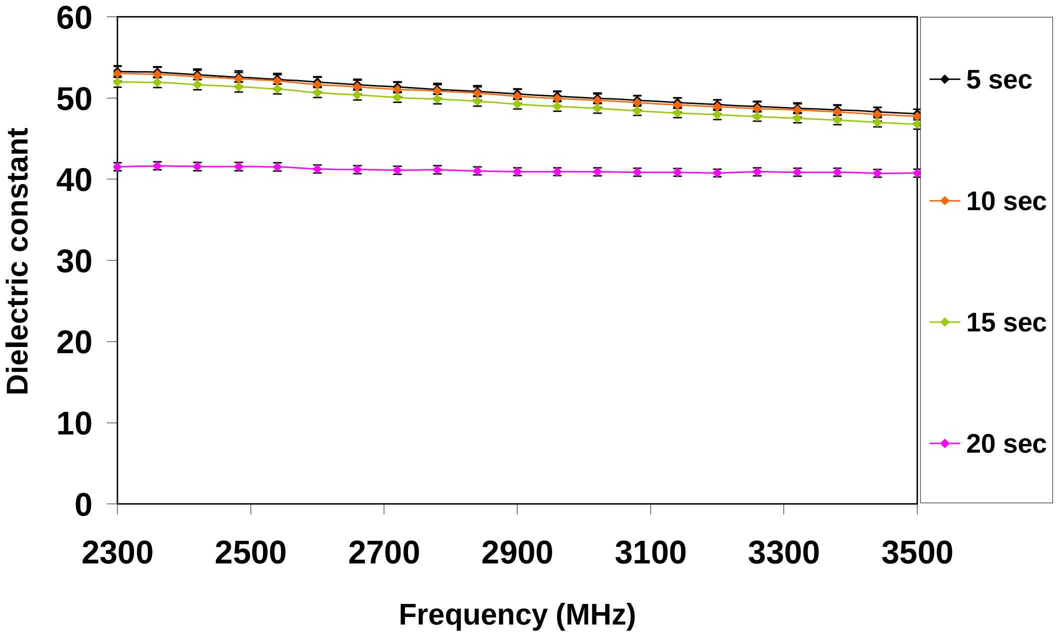


Figure 7.10: Dielectric constant of blended fried estima for 1 min frying time with different blending time at temperature 20 C.

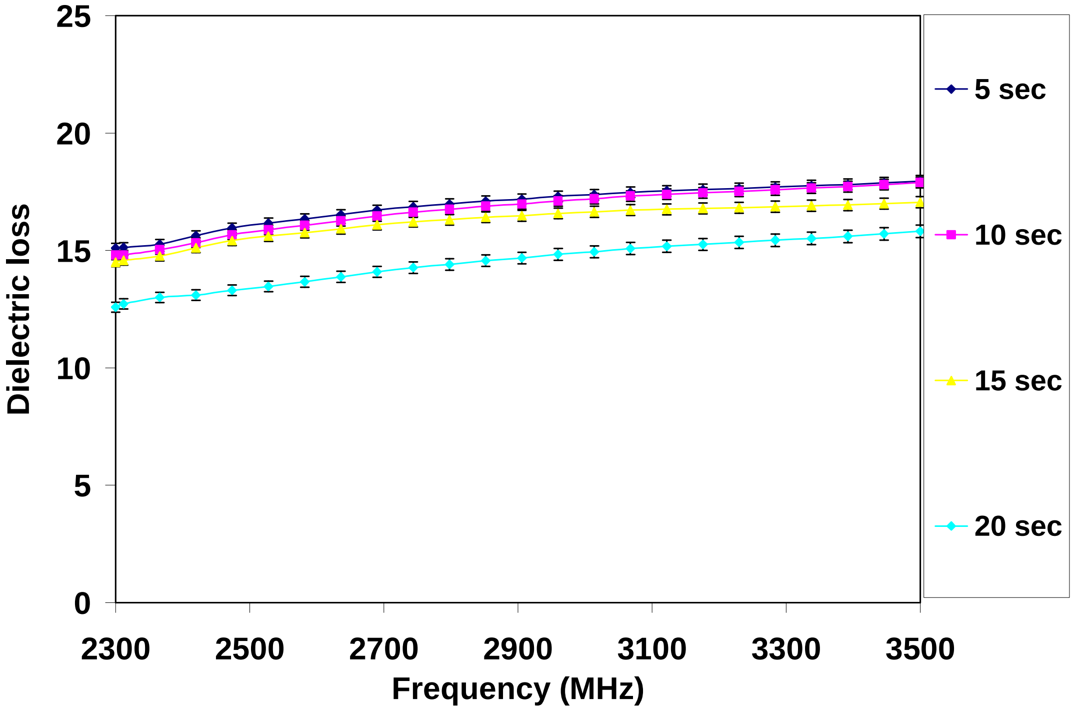


Figure 7.11: Dielectric loss of blended fried estima for 1 min frying time with different blending time at temperature 20 C.

7.3.2 Open ended probe

7.3.2.1 Blended fried Estima potato

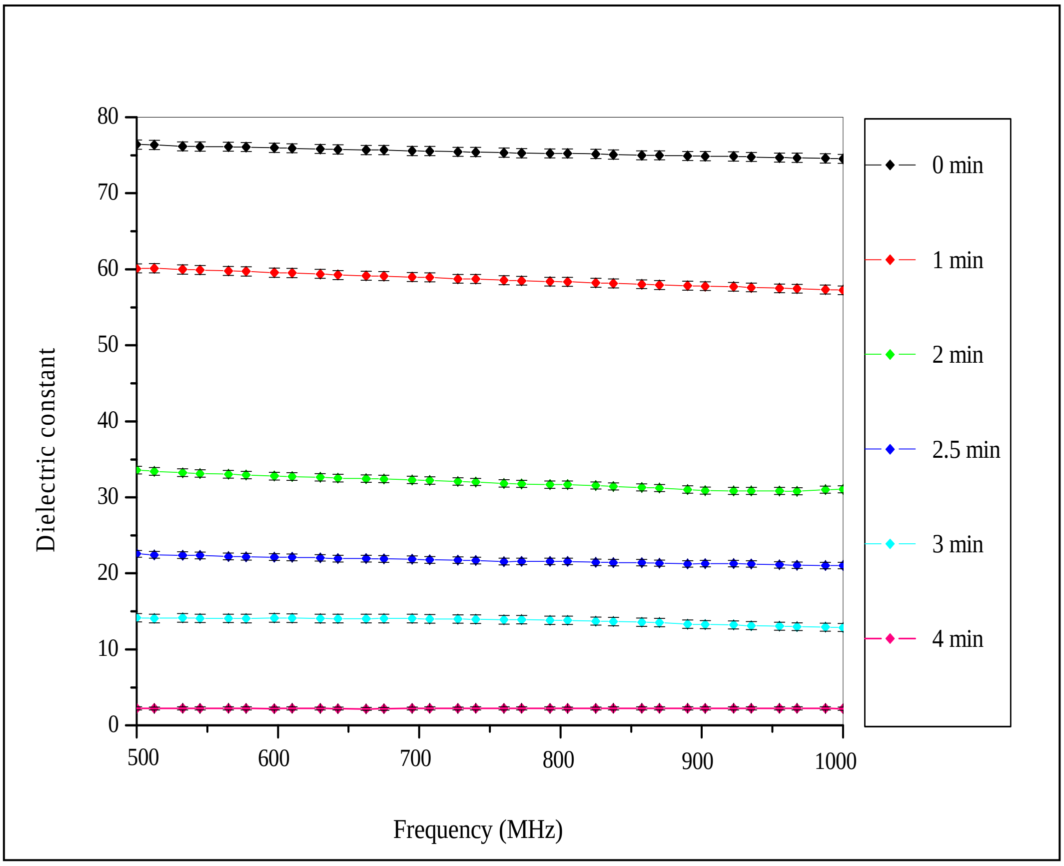


Figure 7.12: Dielectric constant as function of frying time for fried Estima potato at frequency range 500 MHz to 1 GHz at 20 C.

Figure 7.12 shows the result of the effect of frying time on the dielectric constant of blended fried estima potato. Previous study conducted on the moisture loss of fried potato shows that the rate of moisture loss is determined by frying time [82]. Furthermore, moisture has a relationship with the dielectric properties of fried potato, whereby the high content of moisture will lead to the high value of dielectric constant and loss. As the frying time is increased, more moisture is evaporated from the fried potato and then the dielectric constant is decreased.

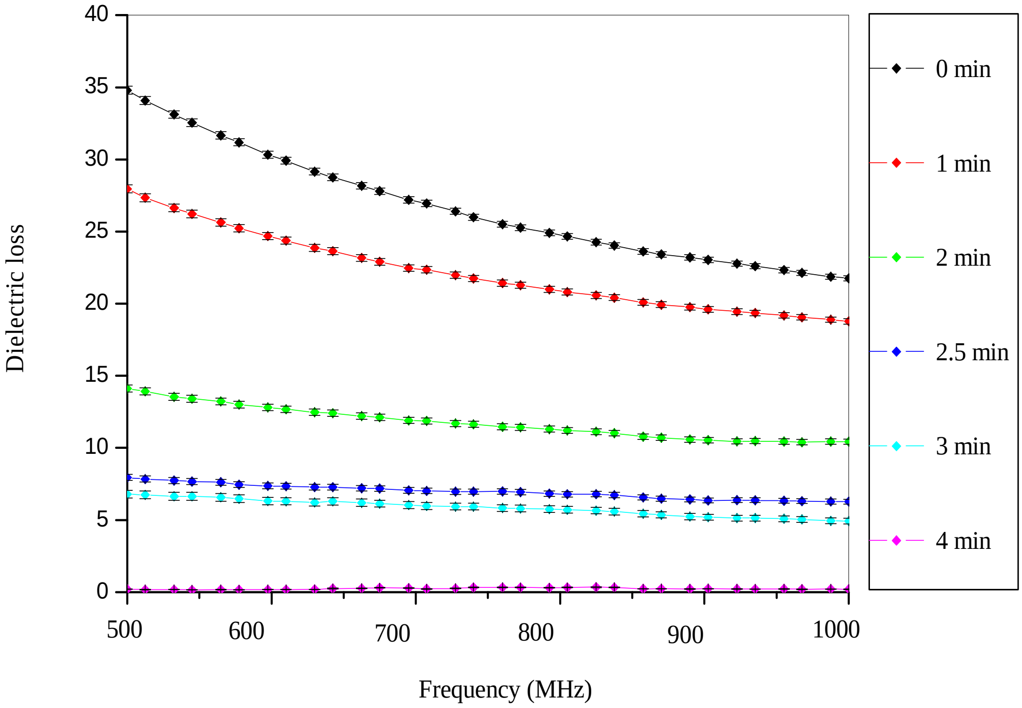


Figure 7.13: Dielectric loss as function of frying time for fried Estima potato at frequency range 500 MHz to 1 GHz at 20 C.

Figure 7.13 shows the effect of frying time on the dielectric loss of the blended fried Estima potato. The dielectric loss is elevated towards lower frequency and this is caused by the presence of the ionic conductivity of dissolved ions in raw potato. Dielectric loss behaviour of raw potato is associated with the conductivity of dissolved ion [91]. The effect of ionic conductivity on the dielectric loss at the lower frequency is discussed in chapter 2 for the topic of the Cole-Cole equation with the ionic conductivity. The effect of ionic conductivity on dielectric loss becomes lesser as the frying time is increased from 0 min to 4 min. This is due to the loss of moisture from fried Estima potato and then dissolved ion becomes less active and little effect on dielectric loss of fried Estima. Table 7.1 shows that the moisture loss is increased as the frying time is increased and this will lead to the decrease of dielectric loss of blended Estima potato as shown in the Figure 7.13. Free water or moisture has a significant effect on the dielectric loss of material whereby the higher moisture content, the larger dielectric loss of the material.

7.3.2.2 Blended fried King Edward potato.

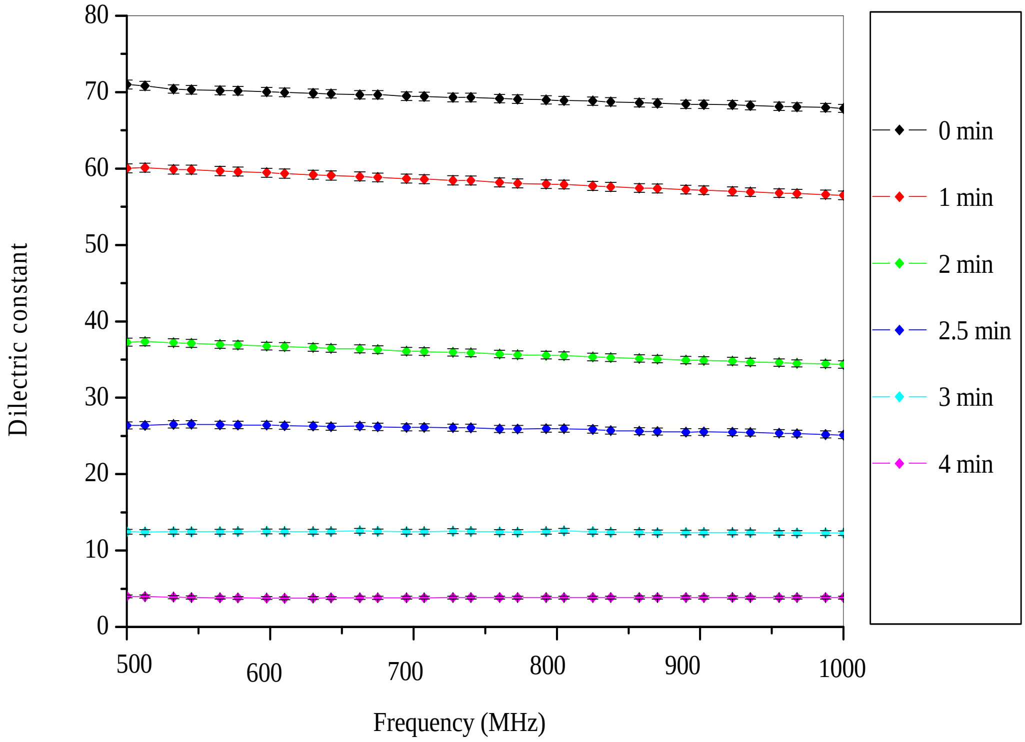


Figure 7.14: Dielectric constant as function of frying time for fried King Edward potato at frequency range 500 MHz to 1 GHz at 20 C

The result of the effect of frying time on the dielectric constant of blended fried King Edward potato is shown in Figure 7.14. The value of dielectric constant of raw King Edward potato is lower than the dielectric constant of raw Estima potato because the moisture content of raw King Edward is lower than the moisture content of raw Estima potato. The dielectric properties of blended fried King Edward potato follow the similar trend of the dielectric constant of blended Estima with the frying time. As the frying time is increased, the moisture is evaporated from the King Edward potato then the dielectric constant is decreased accordingly. The value of dielectric constant

is dominated by the amount of free water that remains in the fried potato. During the frying process, there is a big decrease of dielectric constant between 0 min to 4 min frying time as there is huge amount of water loss. Table 7.2 shows that the amount of water loss during this frying time is around 73%. This is agreed with the study conducted on the moisture loss during frying process of potato by Costa, Oliveira and Gekas [83].

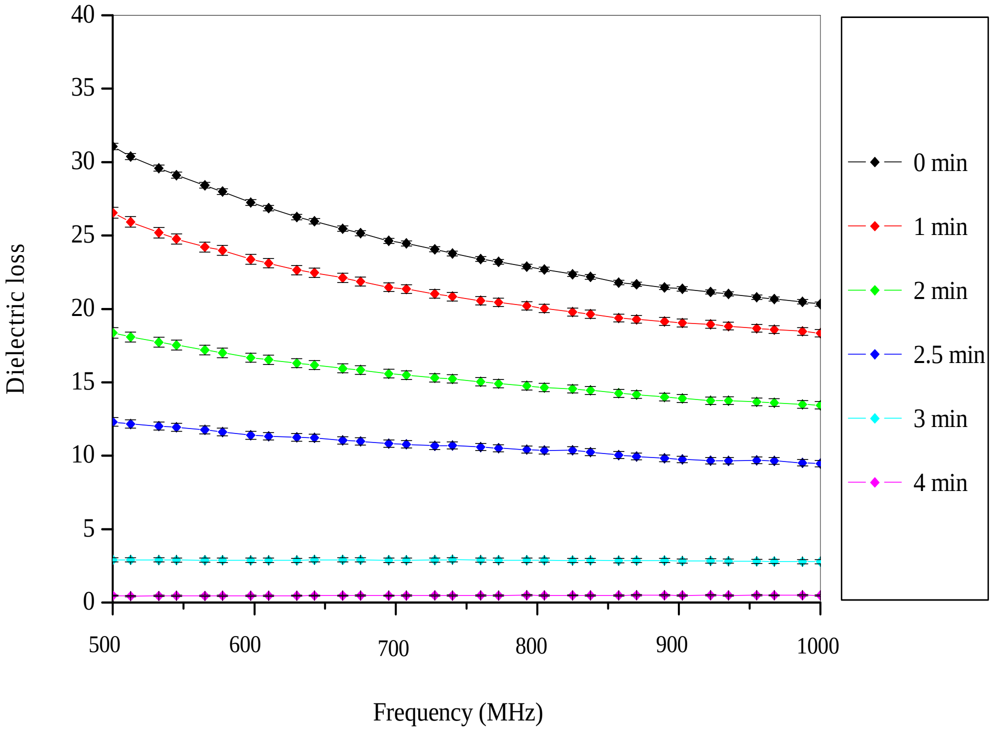


Figure 7.15: Dielectric loss as function of frying time for fried King Edward potato at frequency range 500 MHz to 1 GHz at 20 C

Figure 7.15 shows the effect of frying time on the dielectric loss of blended King Edward potato over the frequency range 500 MHz to 1 GHz. The effect of the ionic conductivity of the dissolved ions on the dielectric loss is shown in the Figure 7.15. It follows the similar trend with the dielectric loss of fried blended Estima potato. The dielectric loss is elevated as the frequency is decreased from 1 GHz to 500 MHz. The effect is quite severe on the lower frequency range. This trend follows the Cole-Cole equation with the ionic conduction parameters, where the dielectric loss is affected by

the dipolar effect of free water and the ionic conduction of the dissolved ion. According to the Cole-Cole equation, the effect of the ionic conduction on the dielectric loss is lower at the higher frequency and becomes higher at the lower frequency. Water plays an important role on the effect of ionic conduction on the dielectric loss. As the frying time is increased, more moisture is evaporated then the moisture content of the blended friend King Edward is lower. Figure

7.15 show the effect of ionic conductivity of the dissolved ion on the dielectric loss is lower at the 3 min and 4 min frying time.

Table 7.2 shows that the moisture content of blended fried King Edward potato is decreased as the frying time is increased. The amount of free water which affects the dielectric loss is also decreased. Then dielectric loss of blended fried King Edward potato is deceased when the frying time is increased.

7.3.2.3 Blended fried Maris Piper potato

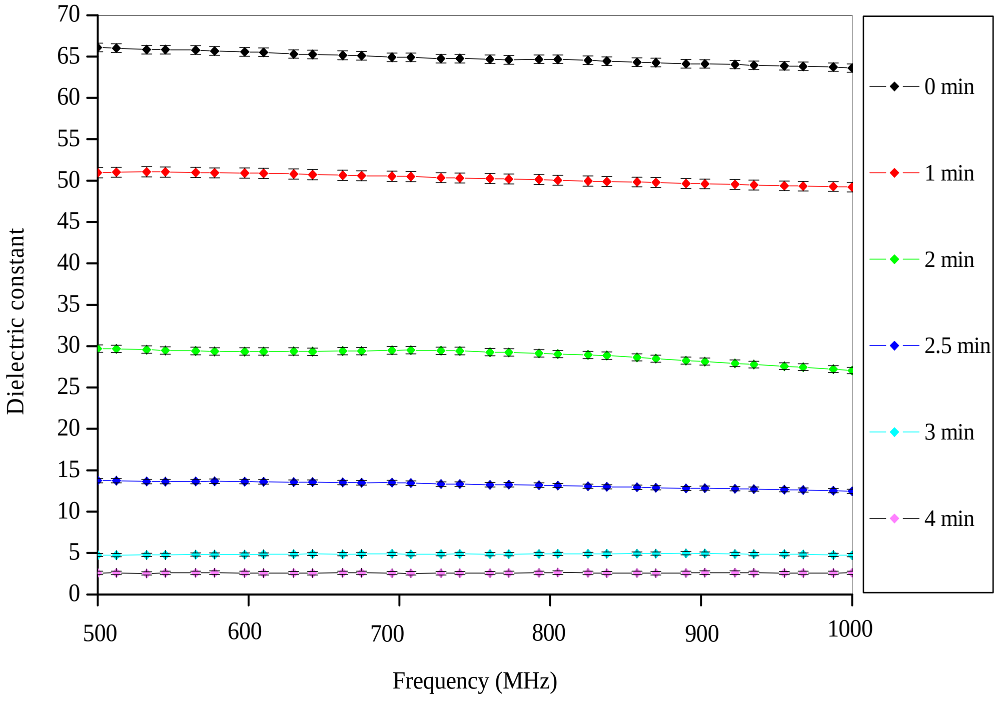


Figure 7.16: Dielectric constant as function of frying time for blended fried Maris Piper potato at the frequency range 500 MHz to 1 GHz at 20 C.

Figure 7.16 illustrates the experimental result carried out on the effect of the frying time on the dielectric constant of the blended fried Maris Piper. The results show similar characteristic to those of the blended fried Estima and King Edward potato. The dielectric constant of the sample decreases consistently as the frying time is increased. Table 7.3 shows that the percentage of moisture content is decreased as the frying time is increased. The effect of frying time on the sample is related with the evaporation of the moisture from the fried potato during the frying process. Water as a polar constituent significantly affects the dielectric properties of materials. The decrease in moisture content decreases the polarisation, decreasing the dielectric constant of the blended fried Maris Piper potato.

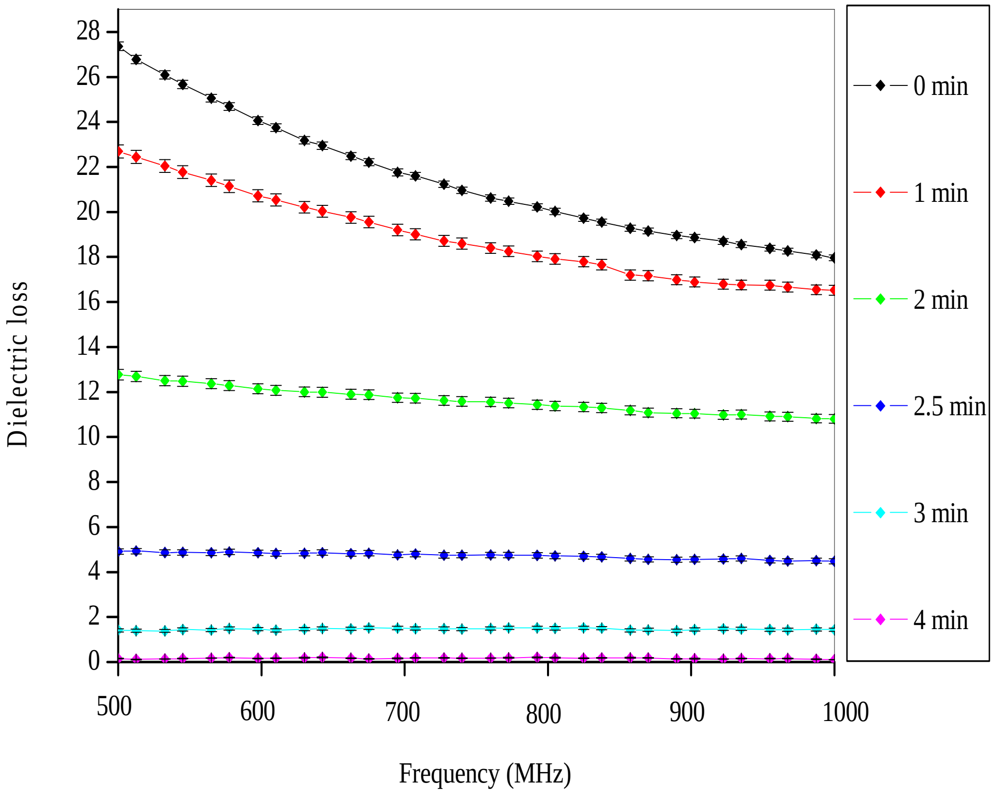


Figure 7.17: Dielectric loss as function of frying time for fried Maris Piper potato at frequency range 500 MHz to 1 GHz at 20 C.

The dielectric loss measurement results for blended fried Maris Piper potato sample of 0, 1, 2, 2.5, 3 and 4 minutes frying time are shown in Figure 7.17. The measurement of blended fried Maris potato samples at the frequency range 500 MHz to 1 GHz at temperature 20 C shows that there is a relationship between the frying time and dielectric loss. The dielectric loss of sample decreases as the frying time is increased.

The dielectric loss of sample shows the similar characteristic with the dielectric loss of Estima and King Edward potato. The dielectric losses of 0 to 2 minutes frying time are elevated towards lower frequency as shown in Figure 7.17. The ionic conductivity of the dissolved ion affects the dielectric loss at the lower frequency. The dielectric loss of fried blended Maris Piper potato at the early frying is affected by the polar effect of free water and ionic conductivity of the dissolved ion. As the frying time is increased, more moisture is evaporated and the volume of dissolved ions is decreased, then the effect of ionic conductivity also decreased. As a result the dielectric loss of blended Maris Piper potato for 3 and 4 minutes frying time is not elevated towards the lower frequency.

The experimental results show that the frying time has an effect on the moisture content and the ionic conductivity of fried blended Maris Piper potato. As the frying time is increased, the moisture content and ionic conductivity effect are decreased.

7.3.3 The effect of temperature on the dielectric properties of fried potatoes.

The dielectric properties of food materials also depend on temperature. The nature of that dependence is illustrated as a function of the dielectric relaxation time.

The relationship between the relaxation time and temperature is [103]:

$$\tau = \mathrm{V}\,\frac{3\upsilon}{\kappa \mathrm{T}} \qquad \textbf{(7.1)}$$

where V = volume of molecules, ν = viscosity, k = constant, T = temperature in unit kelvin.

The relation of viscosity and temperature is [104]:

$$\nu = e^{\frac{E_a}{RT}} \qquad \textbf{(7.2)}$$

where ν = viscosity, E_a = activation energy, R = universal gas constant, T = temperature in unit Kelvin.

$$f_c = \frac{1}{2\pi\tau} \qquad \textbf{(7.3)}$$

where f_c = relaxation frequency, τ = relaxation time

The dielectric loss is:

$$e^{''} = e^{''}{}_{(d)} + e_{(i)}{}^{''} \qquad \textbf{(7.4)}$$

where $e_d{}^{''}$ = dipolar loss of the free water, $e_i{}^{''}$ = ionic loss of the ionic conductivity.

The ionic loss of the ionic conductivity is given by:

$$e_i{}^{''} = \frac{\sigma}{\varepsilon_0 \omega} \qquad \textbf{(7.5)}$$

where σ = electrical conductivity, ω = radian frequency, ε_0 = permittivity of the free space.

As the temperature of food material increases, relaxation time as shown in equation (1) decreases, then the relaxation frequency in equation (3) increases and peak of dielectric loss will shift to the higher frequency. Thus above the dispersion region dielectric constant will increase with increasing temperature, while below the dispersion region, the dielectric constant decreases with increasing temperature. Dielectric loss either will increase or decrease, depending on the frequency measurement is higher or lower than relaxation frequency.

Ionic conductivity (σ) increases with temperature [98]. The dielectric loss for ionic conductivity as shown in the equation (5) will increase accordingly.
The effect of the temperature on the dielectric properties not only depends on the temperature but also depends on the frequency and moisture content. The detail of the contribution of the frequency and moisture content on the temperature dependence of dielectric properties is discussed in the following results and discussion.

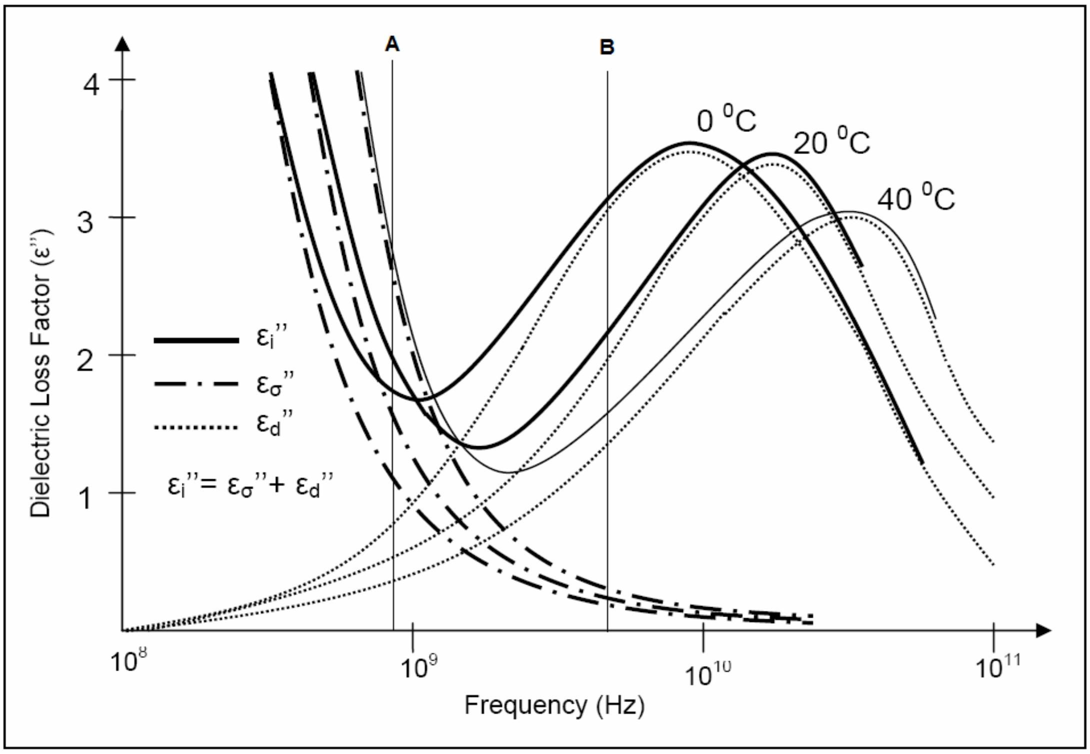


Figure 7.18: The frequency dependence of dipole loss e”$_d$, the ionic conductivity loss e”$_\sigma$, and total dielectric loss e”$_1$ for 0.5 N aqueous sodium chloride at three temperatures [97].

The effect of the temperature on the dielectric loss of the saline solution is shown in the Figure 7.18. The increase or decrease of the dielectric loss with the increase in temperature depends on the measurement frequency. At the frequency slightly below 1 GHz (A), the dielectric loss of the saline solution is increased with the increase in the temperature, while at the higher frequency near to the peak of the dipolar loss (B), the dielectric loss is decreased with the increase in the temperature. This is the situation where the effect of the temperature on the dielectric loss is related with the frequency measurement.

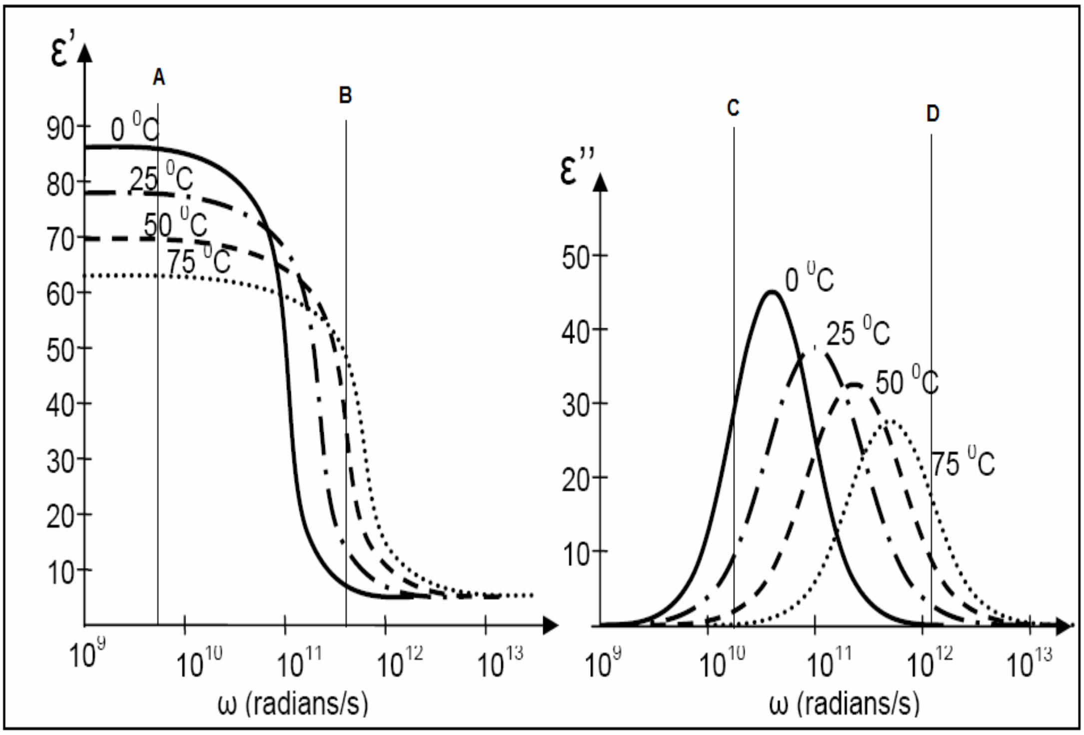


Figure 7.19 The effect of temperature on dielectric constant and loss of water (based on Mudget,1988[101]).

The effect of temperature on the dielectric properties of the water is shown in the Figure 7.19. The impact of temperature on the dielectric can be categorised into the two measurement frequencies, firstly the measurement frequency (A and C) lower than the dispersion peak loss of water and secondly frequency measurement (B and D) above the dispersion peak loss of water. The dielectric constant and loss decrease with the increase in the temperature at the frequency measurement A and C, but increase as the temperature is increased at the frequency measurement B and D. This is an example where the increase or decrease of the dielectric properties is not only affected by the temperature but also depends on the frequency. Equation 7.1 shows that the increase in the temperature will decrease the relaxation time and then the relaxation frequency is increased. This will shift the relaxation frequency loss or dispersion peak loss to the higher frequency as shown in the Figure 7.19. Temperature dependence behaviour in most cases is complex and the effect of the temperature on the dielectric properties can be determined at the specific frequency and under the condition of interest [105].

7.3.3.1 The effect of temperature on the dielectric properties of fried potatoes at the microwave heating frequency 2.45 GHz.

7.3.3.1.1 Blended fried Estima potato

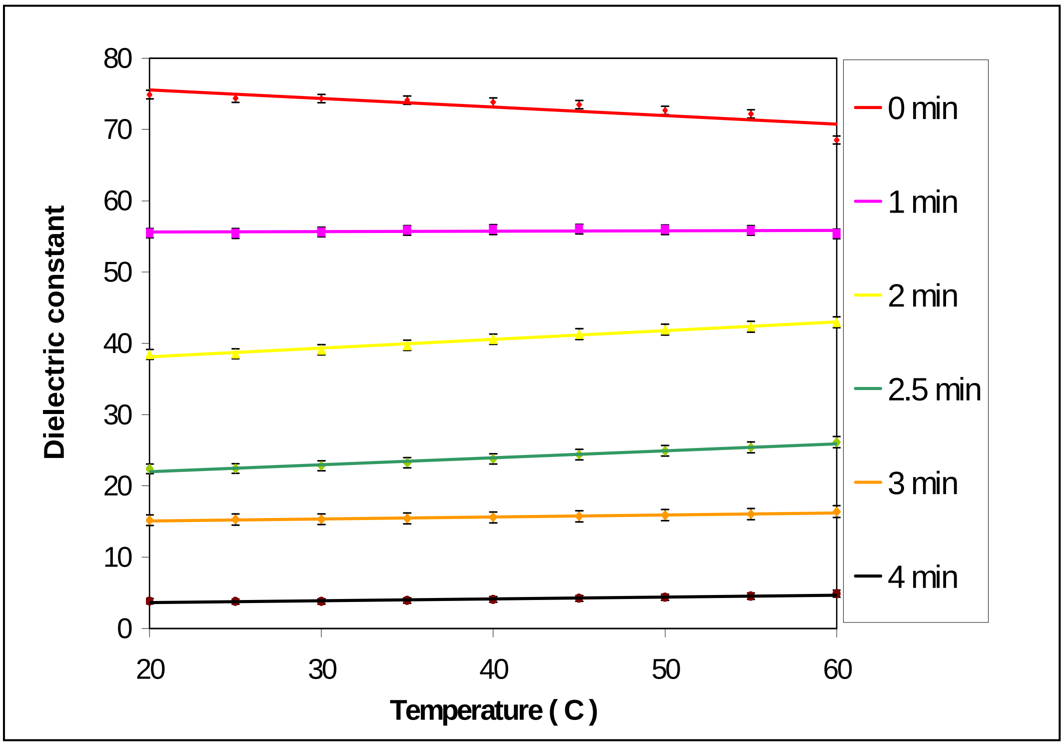


Figure 7.20: Dielectric constant of the blended fried Estima potato as a function of temperature at frying time between 0 min to 4 min at frequency 2.45 GHz.

The effect of temperature on the dielectric constant of the blended fried estima potato at different moisture contents or frying time is shown in Figure 7.20. The change of the dielectric constant with temperature is small for all moisture content of fried blended estima potato.

There are three types of behaviour of dependence of the dielectric constant on temperature are observed from Figure 7.20. In case of the high moisture content, the dielectric constant for the raw estima potato with 78.4 % moisture content is shown to decrease slightly with temperature. The decrease of dielectric constant of raw estima is around 3 from temperature 20 C to 60 C. The gradual decrease in the dielectric constant with increasing temperature is due to high moisture content (78.4%), although less temperature dependence is noted at this moisture level.

For the intermediate moisture range between 14 % to 38 % moisture content, the dielectric constant increases slightly with an increase in the temperature. The dielectric constant of 21.8 % moisture content is increased from 35 at temperature 20 C to 39 at the temperature 60 C. The effect of temperature on the dielectric constant is marginal and small.

For the low moisture content which is around 3 % or at the 4 minutes of frying time, the dielectric constant remains unchanged with an increase in the temperature. It is shown that the dielectric constant is less temperature dependence at the microwave heating frequency 2.45 GHz.

The finding for the 78.5 % moisture content is similar to the plot of water over temperature range 20 C to 60 C at frequency 3 GHz where the dielectric constant decreases as the temperature is increased [91]. The main constituent of Estima raw potato is water and the percentage of moisture content is high (78.5%) and then the dielectric properties behaviour of raw Estima potato follows the dielectric properties of free water. The dielectric constant of free water is increased with the increase in the temperature. This result follows the study conducted by Funebo showing that at the frequency 2.8 GHz, dielectric constant of apple, chervil, mushroom, parsley, and strawberry with highest moisture content decreases with increasing temperature [106].

For the intermediate moisture content from 1 minute to 3 minutes of frying time, the dielectric constant increases as the temperature is increased. This is probably due to the reduced amount of water and increased amount of lipid or cooking oil in the fried potato. The moisture content of the blended estima potato for 1 to 3 minutes frying time is from 11 % to 38 % and then the trend of the dielectric constant against temperature follows the behaviour of the dielectric properties of the ionic conduction for the elevated temperature. The dielectric constant of the ionic conduction increases as the temperature is increased. The studies conducted by Wang and Sipahioglu [92, 93] on the maraconi and ham shows that the dielectric properties are not only affected by temperature but also affected by frequency and moisture content. They found that dielectric properties increased with temperature at the higher frequency 2.45 GHz for the moisture content (45% and 56 %) food sample. In the study conducted by Feng [94] on the dielectric properties of dehydrated red apples, he found that at the medium moisture content level which is around 23 %, the ionic conduction has the major effect on the dielectric properties. Funebo also reported at the intermediate moisture content, dielectric constant of apple, chervil, mushroom, parsley, and strawberry increases with increasing temperature at the frequency 2.8 GHz [106].

For the lower moisture content (4%) which is at the 4 minutes frying time, the change in the dielectric constant is small as the temperature is increased. At this frying time, cooking oil is major constituent of the fried potato. Dielectric behaviour of fried potato against temperature follows the behaviour of the dielectric properties of the cooking oil against temperature. Cooking oil is non polar material where by its dielectric properties are not affected by the changing of temperature [95].

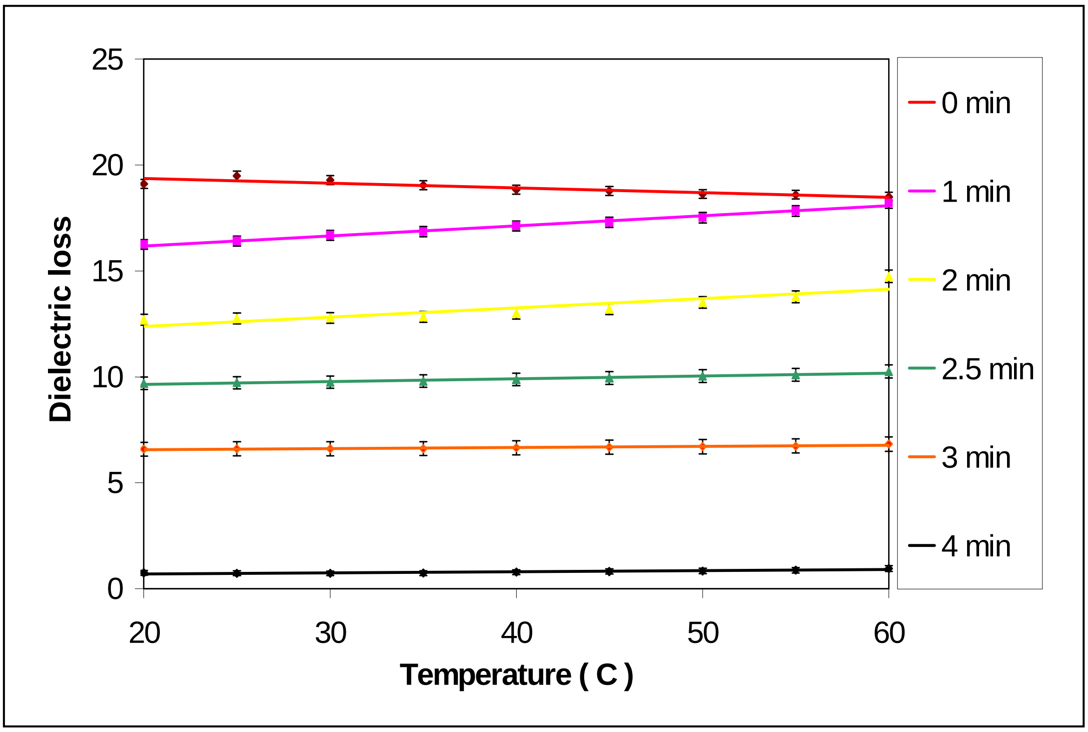


Figure 7.21: Dielectric loss of the blended fried estima potato as a function of temperature at frying time between 0 min to 4 min at frequency 2.45 GHz.

The effect of temperature on the dielectric loss of blended estima potato at different moisture content is shown in Figure 7.21. As observed for the dielectric constant, the dielectric loss of the estima potato for 78.5% moisture content decreases slightly with an increase in the temperature. However, the dielectric loss increases with an increase in the temperature for the intermediate moisture content (14 % to 38 %). At the lowest moisture content (3 %), the change dielectric loss is very small with an increase in the temperature. The amount of the dielectric loss value that has been decreased or increased over temperature range 20 C to 60 C for all moisture content is small. It is noted that the dielectric loss fried estima potato is less temperature dependence at the microwave heating frequency 2.45 GHz. The effect of moisture content on the dielectric loss is higher than the temperature. The dielectric loss increases from 2.4 for 3% moisture content to 19 for 78.5 % moisture content. The change in dielectric loss is higher with the change of moisture content in comparison to the change of temperature. It is much more dependent on the moisture content than the temperature. The effect of the temperature on the dielectric loss is related with the moisture content as discussed on the effect of temperature on the dielectric constant of Estima potato.

7.3.3.1.2 Blended fried King Edward potato.

The result of the dielectric constant for the blended fried King Edward potato at different temperatures and moisture content is presented in Figure 7.22. The effect of the temperature on the dielectric constant of the fried King Edward potato with the different moisture content follows the similar trend of the behaviour of the fried Estima potato with temperature. At the higher moisture content (77%), the dielectric constant decreases slightly with an increase of temperature. The opposite effect is seen at the intermediate moisture content in between 14% to 36% where by the dielectric constant increases slightly with an increase of temperature. For lowest moisture content (3 %), the change in the dielectric is small as the temperature is increased. The change of dielectric constant with temperature is small, and it is less dependent on the temperature as compared to the moisture content.

The similar explanation of the behaviour for the dielectric constant of fried King Edward potato against temperature is presented at the previous section 7.3.3.1

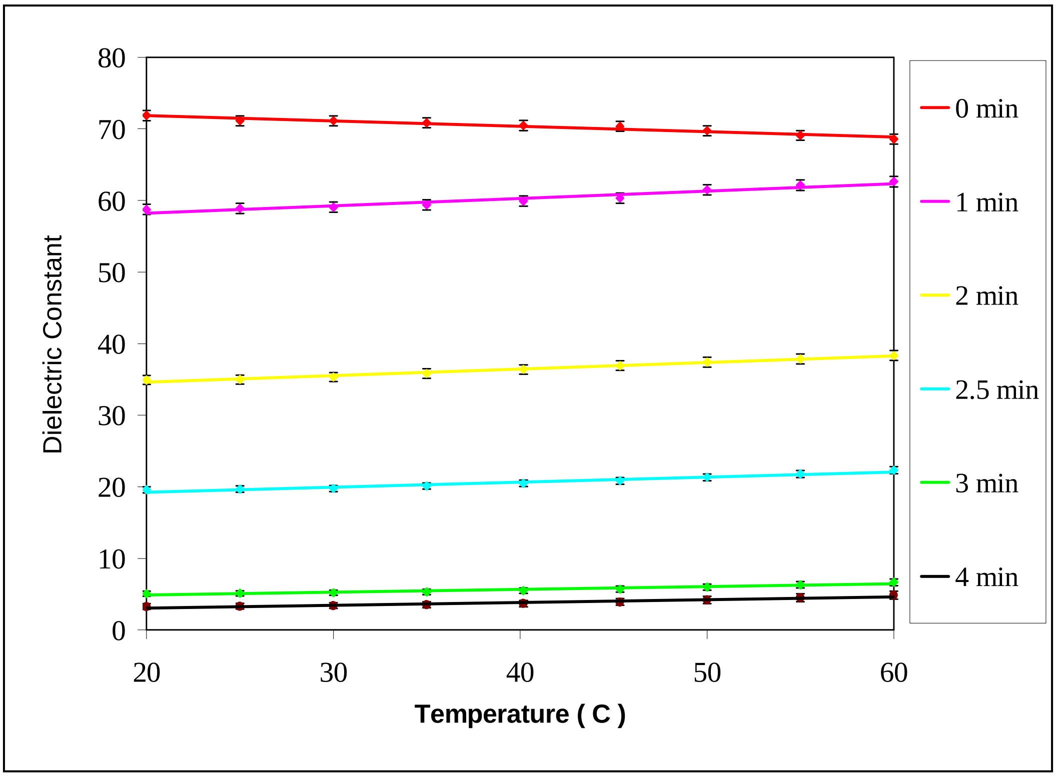


Figure 7.22: Dielectric Constant of the blended fried King Edward potato as a function of temperature at frying time between 0 min to 4 min at frequency 2.45 GHz.

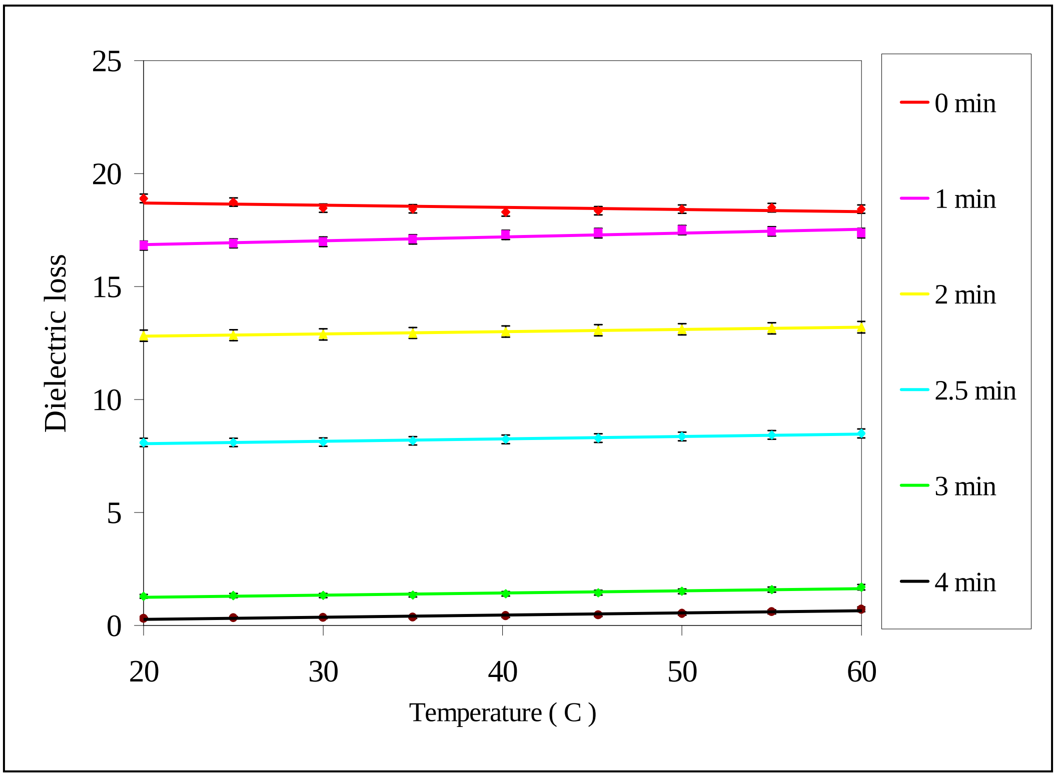


Figure 7.23: Dielectric loss of the blended fried King Edward potato as a function of temperature at frying time between 0 min to 4 min at frequency 2.45 GHz.

The result of the effect of temperature on the dielectric loss of the blended fried King Edward potato is shown in the Figure 7.23. All results are presented at the microwave heating frequency 2.45 GHz with different moisture content or frying time. The dielectric loss of the raw King Edward potato with 77 % of moisture content is decreased slightly with an increase in the temperature. The dielectric loss is increased from 19 at the temperature 20 C to 17 at the temperature 60 C. The change of dielectric loss with temperature is small, and it is noted that the dielectric loss is less dependent on the temperature. For the higher moisture content food material, this is mainly attributed from the dielectric behaviour of the free water against temperature. This agrees with the experimental result reported by Nelson [91] and Feng [94].

The dielectric loss of the moisture content in between 14% to 36% is increased slightly with the increase of temperature. The amount of increases in the dielectric loss is small and less temperature dependence.

The change in the dielectric loss of the low moisture content of fried King potato (~3%) is small with the change in temperature. This is mainly caused by the higher amount of the cooking oil in the fried potato at the 4 minutes frying time. Then dielectric loss of fried King Edward potato follows the behaviour of the dielectric properties of cooking oil against temperature. The study conducted by Pace[95] shows that the dielectric properties of fat and cooking oil are constant with the change of frequency or temperature.

7.3.3.1.3 Blended fried Maris Piper.

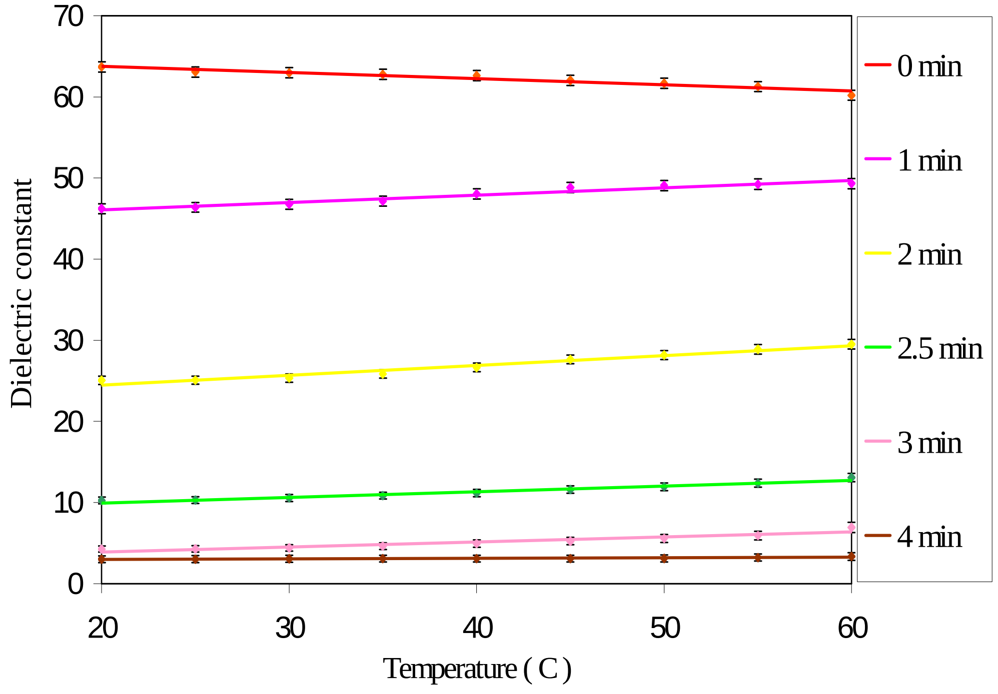


Figure 7.24: Dielectric constant of the blended fried Maris Piper potato as a function of temperature at frying time between 0 min to 4 min at frequency 2.45 GHz.

Experimental data of the dielectric constant for the blended Maris Piper potato against temperature is presented in the Figure 7.24. The dielectric constant behaviour of the fried Maris Piper potato follows the similar trend of the dielectric constant of fried Estima and King Edward potato against temperature. The dielectric constant of the raw Maris Piper potato with 66.9 % moisture content decreased slightly with the increase in temperature. This is expected as the raw potato contains high moisture and its dielectric behaviour follows the behaviour of the dielectric properties of free water against temperature. It is noted that the change of dielectric constant of raw Maris Piper potato with the temperature is small and it is not much depending on the temperature.

The dielectric constant of the intermediate moisture content in between 10 % to 30 % increases slightly with an increase in temperature. The incremental amount of the dielectric constant with temperature is small, and it is considered as less temperature dependence.

For the lowest moisture content (~3 %), the change in dielectric constant is small with the increase in the temperature. This follows the similar trend with the dielectric constant of fried Estima and King Edward potato at the lowest moisture content. This is probably due to the influence of the high content of cooking oil in the fried Maris Piper potato at the higher frying time. The dielectric properties of the cooking oil are not changed with the change in the temperature [95].

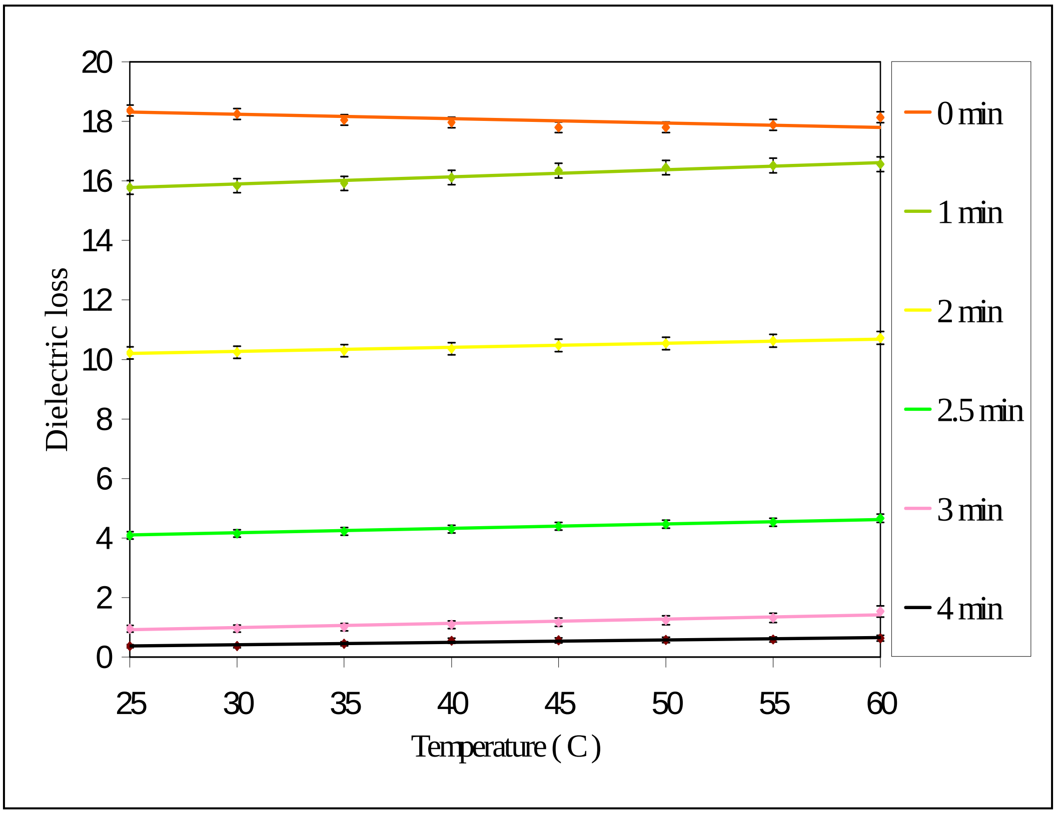


Figure 7.25: Dielectric loss of the blended fried Maris Piper potato as a function of temperature at frying time between 0 min to 4 min at frequency 2.45 GHz.

The dielectric loss of the different moisture content for the blended fried Maris Piper potato against the temperature at the 2.45 GHz is presented in the Figure 7.25. The effect of the temperature on the dielectric loss is related with the moisture content of the fried Maris Piper potato. For the high moisture content (66.9 %), the dielectric loss is slightly decreased with the increase in the temperature. On the other hand, for the intermediate moisture from 10 % to 30 %, the dielectric loss increases slightly with the increase in the temperature. At the lowest moisture content (~ 3 %), the change in dielectric loss is minimal with the increase in the temperature.

The detailed explanation of the effect of the different moisture content on the dielectric loss against temperature is presented in the previous section (7.3.3.1 and 7.3.3.2).

7.3.3.2 The effect of temperature on the dielectric properties of fried potatoes at the microwave heating frequency 915 MHz.

7.3.3.2.1 Blended Fried Estima Potato.

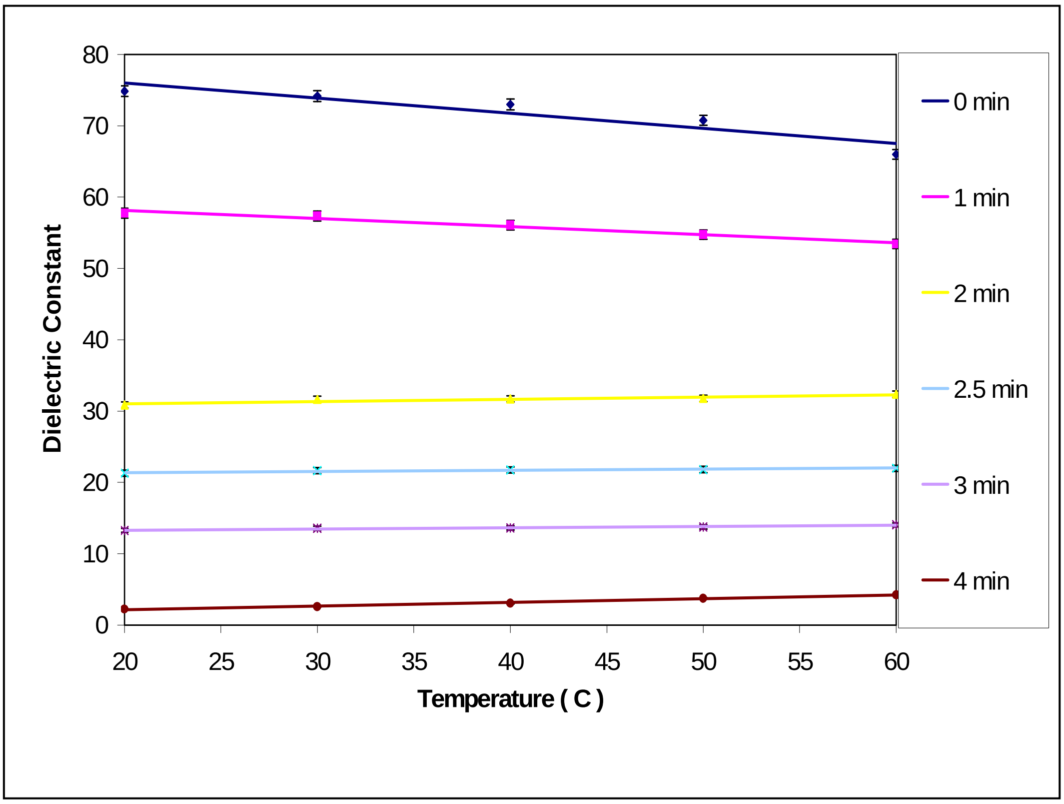


Figure 7.26: Dielectric constant of the blended fried Estima as a function of temperature at frying time between 0 min to 4 min at frequency 915 MHz.

Experimental data on the effect of temperature on the dielectric constant of the blended Estima potato is shown in the Figure 7.26. The data is presented for the different of moisture content at the frequency 915 MHz. The blended fried

Estima potato with the moisture content 78% and 38 % shows an increase in the dielectric constant as the temperature is increased. The effect of the temperature on the dielectric constant of the raw potato agrees with the data on the dielectric constant of mangoes against temperature reported by Sosa [96]. Dielectric constant of mangoes with 86 % of moisture content decreases with the increase in the temperature at the frequency 915 MHz.

For the medium moisture content between 12% to 22%, the dielectric constant increases slightly with the increase in temperature. The reduced amount of water reduces the effect of the free water in the blended Estima potato. Then the effect of temperature on the dielectric constant is dominated by the ionic conductivity.

The change in the dielectric constant is minimal as the temperature increased at the lowest moisture content 2.4 %.

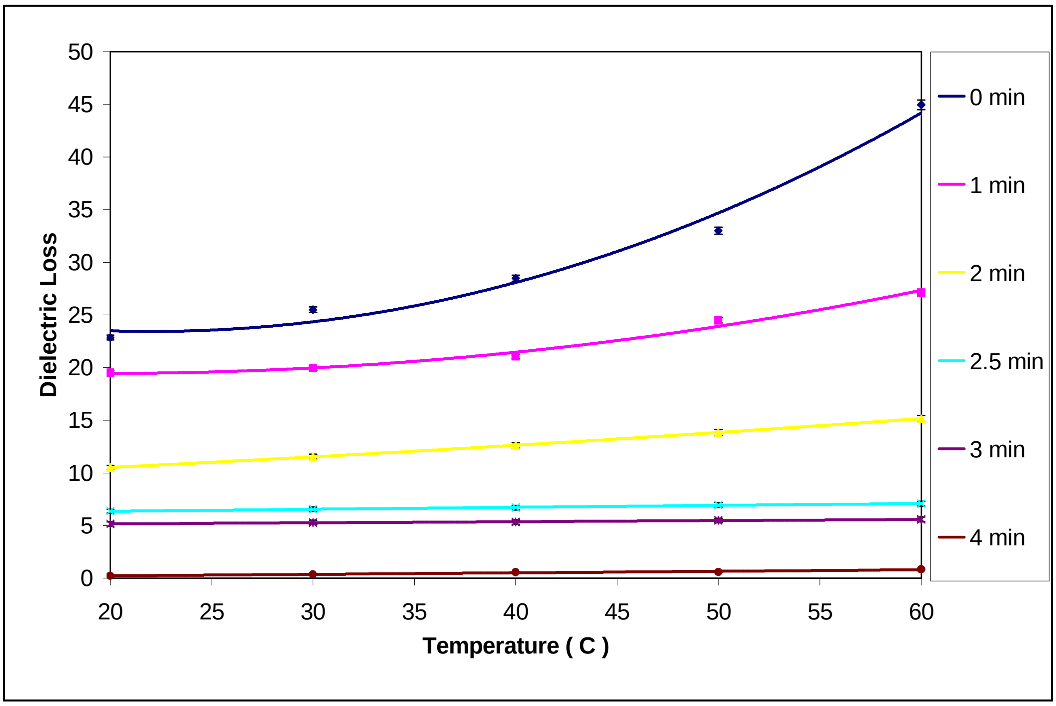


Figure 7.27 : Dielectric loss of the blended fried Estima potato as a function of temperature at frying time between 0 min to 4 min at frequency 915 MHz.

Figure 7.27 shows the effect of the temperature on the dielectric loss of the different moisture content for the blended fried Estima potato at the frequency 915 MHz. The increase in the dielectric loss is higher as the temperature is increased especially at the higher moisture content. As the moisture content is decreased, the increase in the dielectric loss against temperature is minimal and become less temperature dependence. At the lower frequency measurement (915 MHz), the effect of the ionic conduction is more dominant than the effect of the free water. The dielectric loss behaviour of the blended fried potato Estima follows the behaviour of the dielectric loss of the ionic conduction against temperature. In a study conducted by Roebuck [97] the ionic conduction dominates the effect of the temperature on the dielectric loss at frequencies lower than 1 GHz. In another study, Trump [98] found that the ionic conductivity (σ) increases with the increase in temperature as a result of reduced viscosity at a high temperature. Therefore, with reference to equation 3, the dielectric loss of the ionic conduction is increased with the temperature. Then the dielectric loss of Estima potato increases accordingly with temperature.

Ryyananen [3], Guan[99] and Wang[100] reported that the ionic conductivity dominated the loss at the lower frequency while at the higher frequency dipolar relaxation losses caused by the free water are more important. As a result, at the higher frequency, the effect of the temperature on the dielectric loss is dominated by the free water and while at the lower frequency is dominated by ionic conduction. The effect of the ionic conduction on the dielectric loss becomes lesser as the moisture content is decreased. This is due to the reduced amount of the dissolved ionic ion in the fried potato as the moisture is evaporated during the frying process.

7.3.3.2.2 Blended Fried King Edward potato.

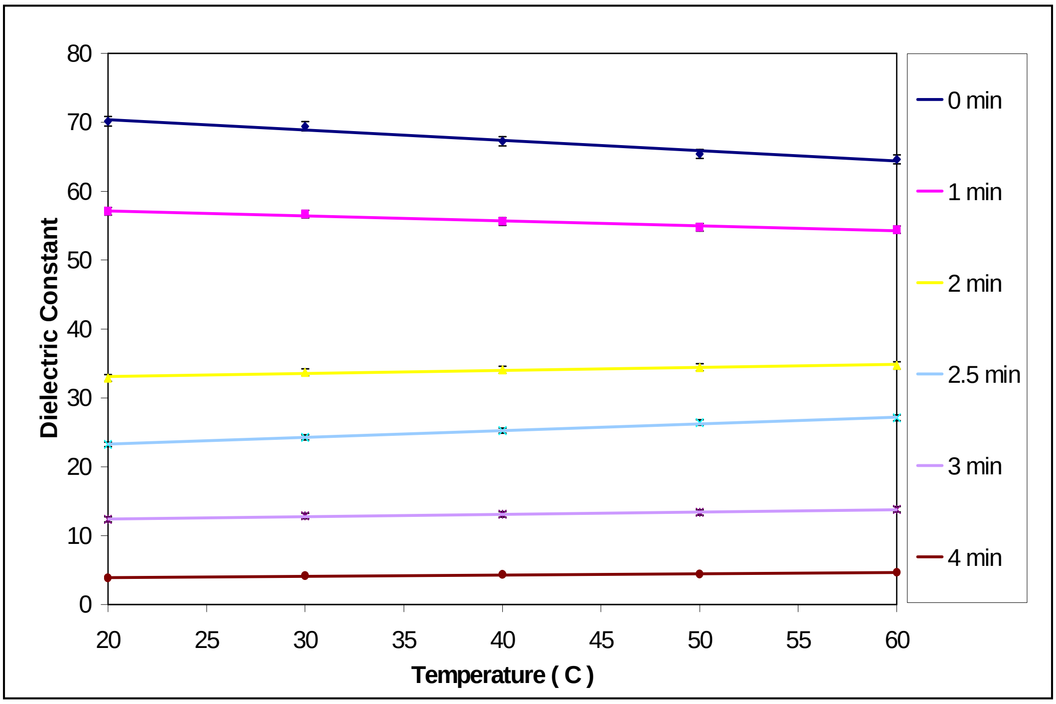


Figure 7.28: Dielectric constant of the blended fried King Edward potato as a function of temperature at frying between 0 min to 4 min at frequency 915 MHz.

The result of the effect of temperature on the dielectric constant of the blended fried King Edward potato at the different moisture content is shown in Figure 7.28. The raw King Edward potato with 76.9 % moisture content and blended King Edward potato with 35.8% moisture content shows a decrease in dielectric constant with increasing temperature from 20 C to 60 C. Most of the water in the high moisture fruits and vegetables exists as free water and the dielectric constant of free water decreases with temperature [101], thus, this is anticipated. It has been known that for the free water, increase in temperature causes a decrease in dielectric relaxation time which results in a lower dielectric constant [102]. The raw potato shows more decrease in the dielectric constant compared to the blended potato with the moisture content 35.8 %. This is probably due to the lower amount of moisture content in the fried potato.

The dielectric constant of the medium moisture content King Edward such as 22.7 % MC, 16.3 % MC and 5.9 % MC shows the increase in the dielectric constant with increasing temperature. This is probably due to the reduced moisture content of the fried potato during the frying process. The amount of free water will reduce and the ionic conduction dominates the effect of the temperature on the dielectric constant. Dielectric constant behaviour follows the trend of the dielectric constant of the ionic conduction against temperature. Dielectric constant of ionic conduction increases with temperature. This trend follows the study on the effect of the moisture content and temperature on the dielectric properties of the dehydrated apples [94]. Feng found that at the medium moisture content level which is around 23 %, the ionic conduction has the major effect on the dielectric properties. Dielectric constant of the dehydrated apples with moisture content 23 % decreases with temperature.

The change in the dielectric constant of fried King Edward potato with 3.3 % moisture content with temperature is small. The amount of water is low and then dielectric constant of low loss food materials is less affected by temperature.

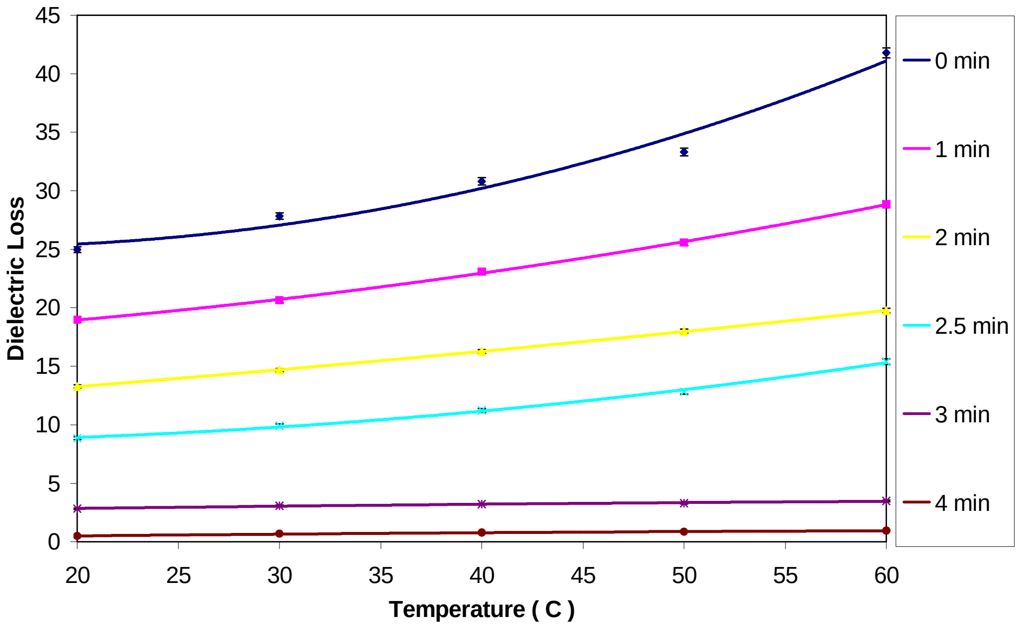


Figure 7.29: Dielectric loss of the blended fried King Edward potato as a function of temperature at frying time between 0 min to 4 min at frequency 915 MHz.

Figure 7.29 shows the effect of the temperature on the dielectric loss of blended King Edward potato with the different of moisture content at the frequency 915 MHz. The dielectric loss of the high moisture content King Edward potato increases with increasing temperature. The dielectric loss is elevated towards higher temperature 60 C especially for the raw King Edward potato with the moisture content 76.9 %. The increase in the dielectric loss against temperature becomes smaller as the moisture content is decreasing. This is expected as the water content is polar solvent, as the moisture content decreases the dissolved ionic ion is decreased accordingly. Then the dielectric loss caused by ionic loss is decreased. The increase in the dielectric loss against temperature is expected at the frequency 915 MHz. Dielectric loss factor consists of two components; dipolar loss and ionic loss. Dipole loss results from the effect of the electromagnetic wave with the free water, while ionic loss results from migration of ionic conductivity. Ryyananen [3], Guan[99] and Wang[100] reported the ionic conductivity dominates the effect on the dielectric loss at the lower frequency, especially for the frequency below than 1 GHz[97]. Furthermore, the ionic conductivity (σ) increases with the increase in the temperature [98]. Dielectric loss caused by ionic conductivity increases accordingly.

7.3.3.2.3 Blended Fried Maris Piper potato.

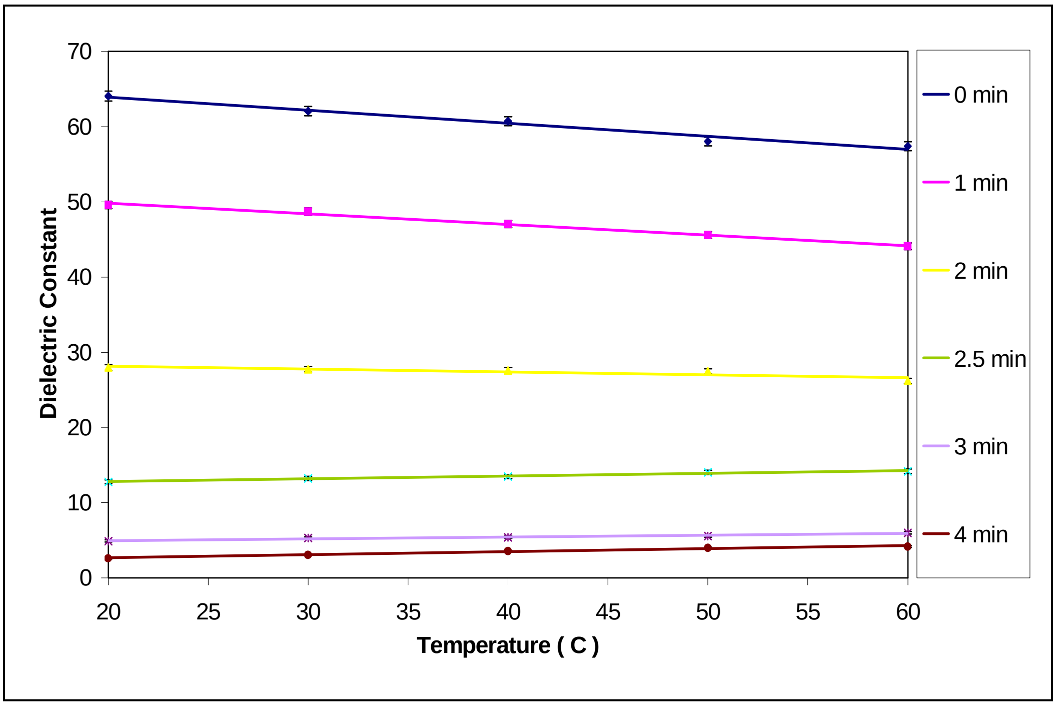


Figure 7.30: Dielectric constant of the blended fried Maris Piper potato as a function of temperature at frying time between 0 min to 4 min at frequency 915 MHz.

Figure 7.30 shows the dielectric constant of the blended fried Maris Piper potato against temperature at the frequency 915 MHz with different moisture contents. The effect of the temperature on the dielectric constant follows the similar trend in the Estima and King Edward potato. The dielectric constant of the raw potato and blended fried potato with moisture content 66.2 % and 30.7 % is decreased with the increase in temperature. On the other hand, the dielectric constant of the blended potato with the moisture content 17 % and 9.8 % is increased mildly with the increase in the temperature. While the effect of the temperature on the dielectric constant for the 4.2 % and 1.6 % moisture content blended Maris Piper potato is low and not temperature dependence. At the 3 and 4 minutes frying time, most of the moisture content has been evaporated and the major of its constituent is cooking oil. The dielectric properties of the fried potato are dominated by the cooking oil. Cooking oil is non polar material and not temperature dependence. The dielectric constant of the free water is decreased with increased in the temperature.

As discussed in the previous section, whether the dielectric constant of the fried potato increases or decreases is not only affected by the temperature but also affected by moisture content. For the moisture content 66.2 % and 30.7%, dielectric constant decreases with the increase in temperature, but dielectric constant increases mildly with the increase in temperature for the moisture content 17 % and 9.8 %. Most of the water exists as free water in the high moisture content Maris Piper potato. The dielectric constant of the free water is decreased with increased in temperature.

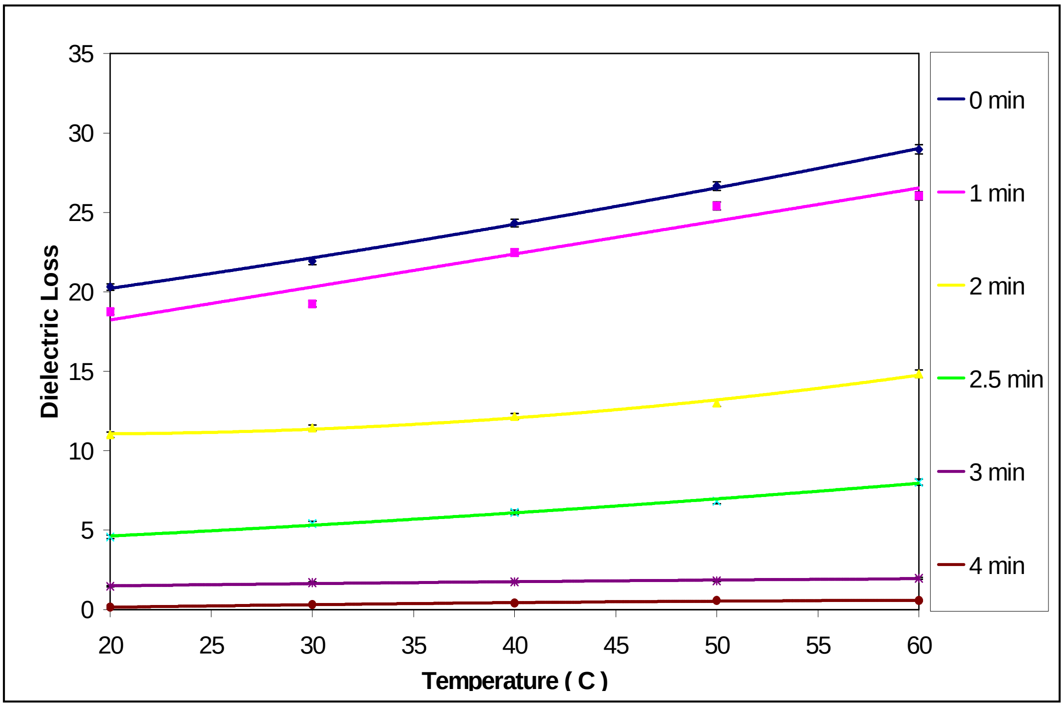


Figure 7.31: Dielectric loss of the blended fried Maris Piper potato as a function of temperature at frying time between 0 min to 4 min at frequency 915 MHz.

The rate of the decrease in the dielectric constant becomes lesser at the moisture content 30.7 % due to the reduction of moisture content.

Figure 7.31 shows the dielectric loss of the fried Maris piper potato increases as the temperature increases, with this trend more pronounced at the higher moisture content 30.7 % and 66.2 %. The increase of the dielectric loss with the increase in temperature is attributed to the reduction of viscosity of fried potato and increase mobility of ion and increase electrical conductivity. The increase of dielectric loss is more contributed by the ionic loss. As the moisture content is decreasing, the dielectric loss of the fried Maris Piper potato becomes less dependent on the temperature. At the lowest moisture content 1.6 % and 4.2 %, the change in the dielectric loss is small with the increase in the temperature. This is expected trend as the dielectric loss of the low loss material not depends on the temperature.

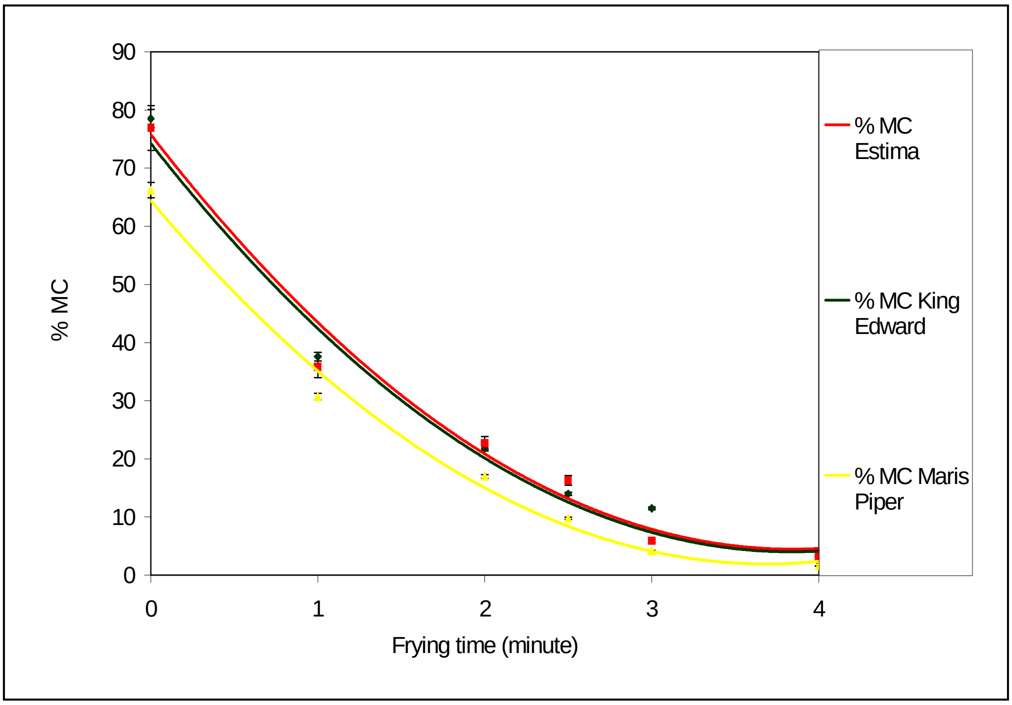


Figure 7.32 : Moisture content of Estima, King Edward and Maris Piper as a function of frying time.

Figure 7.32 shows the moisture content of the Estima, King Edward and Maris piper potato decreases as the frying time increases. The decrease of the moisture content with the increase in frying time is caused by the evaporation of moisture from potato in the frying process. The graph shows that there is an exponential of moisture content loss occurs from 0 minute to 4 minutes frying time.

7.4 Conclusion.

The dielectric properties of the blended fried Estima, King Edward and Maris Piper potatoes are much more influenced by the moisture content than temperature. The major decrease in the moisture content between frying time 0 minute to 4 minutes has resulted in a decrease of the dielectric properties. The change in the dielectric properties with the change in temperature is higher for the microwave heating frequency 915 MHz than the frequency 2.45 GHz, especially for the dielectric loss. The effect of the temperature on the dielectric properties of these 3 varieties of fried potatoes at the microwave heating frequency 2.4 GHz is small, marginal and less temperature dependence. The dielectric loss is generally increased with increasing temperature at the frequency 915 MHz. The dielectric loss increased with increasing temperature at the frequency 2.45 GHz, except for the highest moisture content or raw potato, where the loss factor tended to decrease with increasing temperature. Dielectric constant generally decreased and then increased with the decrease in the moisture content and increasing temperature at both microwave heating frequencies. The increase or decrease in the dielectric properties of the fried potatoes with increasing temperature depends on the moisture content and frequency measurement. These measurements provide new information concerning frequency, moisture content and temperature dependence behaviour of the fried Estima, King Edward and Maris Piper potatoes dielectric properties that may be useful in dielectric heating and sensing application.

The summarised of the finding in the study is presented in the table 7.4 and 7.5

Table 7.4 : The effect of the temperature on the dielectric properties of the fried Estima, King Edward and Maris Piper potatoes.

	915 MHz		2.45 GHz	
	Dielectric Constant	Dielectric Loss	Dielectric Constant	Dielectric Loss
High moisture content (~> 70%)	Moderate decrease with the increase in temperature	High increase with the increase in temperature	Moderate decrease with the increase in temperature	Moderate decrease with the increase in temperature
Intermediate moisture content (10% < MC < 70%)	Moderate increase with the increase in temperature	Moderate increase with the increase in temperature	Moderate increase with the increase in temperature	Moderate increase with the increase in temperature
Low Moisture content (10 % <~)	Low increase with the increase in temperature	Low increase with the increase in temperature	Low increase with the increase in temperature	Low increase with the increase in temperature

Table 7.5 : Comparison between the effect of the moisture content and temperature on the dielectric properties of the fried Estima, King Edward and Maris Piper potatoes.

	Frequency range 500 MHz to 1 GHz		Frequency range 2.4 GHz to 3.5 GHz	
	Dielectric constant	Dielectric loss	Dielectric constant	Dielectric loss
Temperature	Low effect	High effect for the higher moisture content potatoes and low effect for the intermediate and low moisture content	Low effect	Low effect
Moisture content	High effect	High effect	High effect	High effect

Chapter 8

Conclusion and future work.

8.1 Conclusion.

The objective of this PhD study was to utilise microwave sensors for efficient characterisation of raw potatoes, partial cooked and cooked fried potatoes. The dielectric properties of foodstuffs and the microwave measurement techniques were discussed and further elaborated on this study.

Two microwave measurement methods were investigated in this research study. The first one utilised the open ended coaxial probe to obtain the dielectric properties of fried potatoes in the frequency range 500 MHz to 1 GHz. The sample holder was specially designed to contain the paste form of the blended fried potato and to have good contact between the paste samples and the coaxial probe. Furthermore, an adapted sample holder was successfully used to measure the temperature dependence of fried potatoes. The second microwave measurement method used in this study was a waveguide cell that incorporates two Perspex windows to obtain the dielectric property measurements in the frequency range 2.4 GHz to 3.5 GHz. The two Perspex windows were used to contain the non supporting sample pastes and liquid form samples. The sample holder with 2 Perspex windows was also successfully adapted to measure the dielectric properties at different temperatures. The temperature control chamber was used to measure the dielectric properties of fried potato at the elevated temperature. This temperature control chamber was successfully designed with the double layer of 0.5 mm thick Perspex to minimise the heat loss through its structure. The heating and cooling system are generated by a Peltier thermoelectric air cooler. Its temperature is controlled by Thermoelectric Cooler Temperature controller. It is suitable to be used with waveguide 10, waveguide 12, waveguide 14 and waveguide 16. It also successfully used to control the temperature for the sample holder of an open ended probe.

It was concluded that microwave measurement methods are unable to discriminate the effect of different temperature storage on the dielectric properties of raw Saturna potato. This is probably due to the low reaction of the reducing sugar content with water when the raw Saturna is stored at different storage temperatures. The reducing sugar content is not ionic substances but organic hydrocarbon substance. It does not have positive or negative ion that are attracted to positive ion hydrogen and negative ion oxygen of water. The reducing sugar in water does not reduce the number of mobilised ion of water then the dielectric properties of water are not changed. Raw Saturna potato contains high moisture content and has high value dielectric properties; its microwave dielectric spectrum is mainly formed by water.

In this thesis microwave measurement techniques are successfully used to discriminate the dielectric properties of raw potatoes, partial cooked and cooked fried potatoes. Both real and imaginary parts of the dielectric properties are useful in characterising the moisture content of potato crisps at different frying times. Dielectric properties of fried Estima, King Edward and Maris Piper potatoes are highly affected by the moisture content. Dielectric constant and loss of Estima, King Edward and Maris Piper at temperature 20 C, frequency 915 MHz and 2.45 GHz decrease in the value of 70 and 16 when its moisture content decreases from 70% at the beginning of frying time to 2% at the 4 minutes frying time.

Measurements of the dielectric properties of Estima, King Edward and Maris Piper fried potatoes over the temperature range from 20 C to 60 C at frequency 2.45 GHz and 915 MHz revealed that the effect of temperature on the dielectric properties is lower than moisture content, especially for the cooked and partial cooked fried potatoes with the moisture content lower than 30%. The effect of temperature on the dielectric properties is higher for the raw potatoes at the frequency 915MHz. The dielectric constant and loss of raw Estima, King Edward and Maris Piper at 915 MHz decrease to a value of 4 and 6 (dielectric constant) and 10 to 21 (dielectric loss) when its temperature was increased from 20 C to 60 C.

Furthermore, when the effect of temperature was studied, it was found that the dielectric properties of fried Estima, King Edward and Maris Piper potatoes not only depend on temperature but also depend on frequency measurement and moisture content. For the high moisture content, the dielectric constant and loss decrease with temperature except at 915 MHz where dielectric loss increased with temperature. The detailed explanation on this matter is discussed in chapter 7. For the intermediate moisture content, dielectric constant and loss increases with temperature at both 915 MHz and 2.45 GHz. For the low moisture content, the increase in dielectric loss is small with temperature. These measurements provide new information on the moisture content and temperature dependence behaviour of the dielectric properties of Saturna, Estima, King Edward and Maris Piper potatoes. This data is useful for the microwave heating system for frying potatoes and sensing applications.

8.2 Future Work.

This study showed very promising outcomes and has demonstrated the capability of microwave sensor for measuring the dielectric properties of fried potato. However, there are still potential research areas for further investigations. Some of these further works are suggested below:

Waveguide cells provide useful methods for measuring the dielectric properties of the fried potato but it required proper sample preparation. The microwave measurement method can be improved by introducing the free space and non contact measurement. This will allow for contact less and non-destructive microwave measurements for the fried potato.

This research suggests that there is a great potential for the use of microwave sensors for characterising the dielectric properties of fried potato; however, this research only concentrates on fried potato. A broad range of agricultural products such risen and grain is needed to explore their dielectric properties when it gets dried. This data is very useful to design microwave heating system to dry this products.

The moisture is an essential parameter to determine the quality of potato crisps during the frying process. Level of moisture content in potato crisps determines their quality such crispness and hardness. The research study on the dielectric properties of fried potatoes can be used to determine the quality of the potato crisps. The microwave measurement techniques can be used to determine the moisture content and quality of potato crisp.

The research on the microwave measurement is needed to determine the flavour content for potato crisp products. It needs a rapid method to ensure a consistent and even coating of flavour (salt based flavour) throughout the whole batch of the products. Samples can be taken periodically from the manufacturing line and measured using microwave sensor.

Cooking oil is absorbed into fried potato during frying process. Further research study on the microwave sensors is needed to produce rapid and accurate measuring technique which gives closer control and monitoring on the cooking oil content in potato crisps.

Through the findings of this research, it is obvious that this method is destructive methods whereby the potato sample needs to be blended. This could be improved if a non-destructive microwave measurement is developed so that measurement can be carried out directly to the potato crisp on the manufacturing and production lines.

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