Effect of Moisture Content in Beef on Reflection and Dielectric Measurement using Coaxial Reflection Probes

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***Abstract*—Open-ended coaxial probe and Agilent 85070E High Temperature Probe were used in conjunction with Agilent E8362B PNA Network Analyzer from 200 MHz to 20 GHz for moisture detection in beef. The open-ended coaxial probe was fabricated from SMA stub contact. A high-temperature probe was used to measure dielectric properties, ε^* viz. dielectric constant, ε' and loss factor, ε'' of beef. Complex reflection coefficient, Γ was measured for different moisture content (mc) of beef. It would be compared with the measured Γ from High Temperature Probe to verify the performance of coaxial probe. ε' increases when mc increases. However, ε'' exhibit opposite response with *mc*. Measured $|\Gamma|$ via both probes decreases when frequency and mc increases. Meanwhile, negative phase, - ϕ increases due to the increment of frequency or *mc*. The results show that measured ε and Γ provides significant results for predicting *mc*. However, ϕ is indistinguishable among different mc of beef.**

***Index Terms*—Dielectric Constant; Loss Factor; Moisture Content; Complex Reflection Coefficient.**

I. INTRODUCTION

The meat from bovine or cattle, i.e. beef has been widely used in cuisine. Beef is originated from cattle, bulls, buffalo and etc. It is widely accepted by the majority of countries due to its nutrition value. Beef has an abundant source of protein and minerals, e.g. zinc, selenium, phosphorus and iron, and B vitamins [1]. As a result, it has high commercial value and it becomes an important poultry industry for some countries, e.g. Pakistan, Australia, Brazil, India, United States, New Zealand and etc. Due to its high earning power, the quality control and assurance should be tenacious. One of the parameter to determine its quality is mc in beef. Moisture is a very crucial parameter in agriculture. It brings much useful information, e.g. lifespan of agricultural or poultry product, ripeness of fruits, the freshness of products and etc. As a result, moisture analysis usually becomes very popular research in many fields [2,3]. Aishah et al. [4] explore the use of a microwave approach in association with moisture detection in animal fats in 2016. The moisture in liquid and solid state (ice) reflects the freshness and quality of beef, especially juiciness and tenderness of beef is the major concern among consumers. Beef consists of water, muscle, connective tissue, fat, and bone [5,6]. The muscle contains approximately 75% water. The percentage of water in beef may vary due to its type of muscle, meat, the season, and the pH of the meat. In addition, fat content is one of the quality indicators for beef. The fat content increases when moisture content decreases. Hence, *mc* can be used to deduce fat content in beef [7]. Suffice to say, moisture monitoring in beef is important and associated with company profitability, the efficient and fast moisture detection system water is crucial to maximize yield and quality.

The conventional or traditional methods used for moisture determination in poultry product are oven drying method [8], distillation method [9], Karl Fischer Titration [10], and etc. These methods are time-consuming and lab scale measurement is necessary. As a result, these methods are always hindering production process to maintain at optimal efficiency. Additionally, these methods tend to increase the cost of production as it needs bulky and expensive equipment. The recent researches have been widely conducted by using the electrical method, e.g. electromagnetic approaches [11,12].

The measurement of moisture in poultry is crucial for quality assurance, pricing, raw material acceptance and etc. In this study, an open-ended coaxial probe was designed and fabricated for fast and efficient detection of moisture in beef via microwave approach.

An open-ended coaxial probe consists of an inner and outer conductor, with radius *a* and *b*, respectively. An equivalent circuit can be used to represent the open-ended coaxial probe. The radius of the inner and outer conductor, *a* and *b* obeys the inequality a, $b << \frac{\lambda_0}{\sqrt{\varepsilon_r}}$, λ_0 is operating wavelength in air, $G(\varepsilon_r)$ is the radiation conductance, C_f is the capacitance of the fringing field in the coaxial line, and $C(\varepsilon_r)$ is the capacitance of the field in the sample with ε_r. Both C and G are a function of ε_r^*, which depends on the permittivity of the sample. Meanwhile, C_f, C and G (conductance) depend on the dimensions of the coaxial line, i.e. radius of the inner conductor, a and radius of the outer conductor, b as well as the permittivity of the dielectric filling the line. C_f, C_0 and G_0 in free space can be obtained through [13]. The total end capacitance, C_T ($C_T = C_f + C_0$ for the case in air) and C_f can be obtained numerically [13] or simply measured both of capacitances [14]. On the other hand, it can also be determined approximately through quasi-static analysis [15]. The total capacitance, C_T ($= \frac{B_0}{\omega}$) and radiation conductance, G_0 in the air can be predicted [16]. C_f and G_0 can be neglected at first approximation [17].

The expression that represents the aperture load impedance, $Z_L(\omega,\varepsilon^*)$ in terms of the *in vivo* measurement of the relative permittivity of the external medium [18] is:

$$Z_L(\omega,\varepsilon^*) = -j\frac{1}{\omega(\varepsilon^* C_0)} = -j\frac{1}{\omega C(\varepsilon^*)} \tag{1}$$

in which

$$C(\varepsilon^*) = \varepsilon^* C_0 = (\varepsilon' - j\varepsilon'')C_0 \tag{2}$$

$$C_0 = C(\varepsilon^* = 1) = 2.38\varepsilon_0(b-a) \tag{3}$$

$$\varepsilon_0 = \frac{10^{-9}}{36\pi}\ \text{F/m} \tag{4}$$

where ω is the angular frequency, ε_0 is the permittivity of free space, ε^* is the complex permittivity of the sample that occupies the space outside the coaxial line, and C_0 is the capacitance in free space. The fringing capacitance, $C(\varepsilon^*)$ at the aperture of the probe consists of a part that is dependent on the relative permittivity of the sample and the filling of the coaxial line. ε' is related to the ability of the material to store energy (dielectric constant) and ε'' is the loss factor which is the dissipation of energy in the material. Then, the reflection coefficient is

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{5}$$

where Z_0 is characteristic impedance (50 Ω).

The permittivity of beef can be expressed using mixture model [19].

$$\sqrt{\varepsilon^*} = v_w\sqrt{\varepsilon_w^*} + v_f\sqrt{\varepsilon_f^*} + v_m\sqrt{\varepsilon_m^*} \tag{6}$$

where v_w, v_f, and v_0 are the volume fraction of water, fat, and muscle, respectively, and ε_w^*, ε_f^*, and ε_m^* are the corresponding complex permittivities. The values of ε_w^* are obtained from the Cole-Cole model [18]:

$$\varepsilon_w^* = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + (j\omega\tau)^{1-\alpha}} \tag{7}$$

where α is the distribution parameter, which is an empirical constant and τ is time constant. Fraction volume v_w, v_f, and v_0 for water, fat and muscle, respectively in beef can be easily found through some experimental works. The relationship between moisture and fat content in beef as reported in [7] implies that v_w and v_f is a function of mc. Fraction volume of beef consists of v_o, v_w, and v_f, and their relationship is

$$v_0 + v_w + v_f = 1 \tag{8}$$

v_w can be calculated as

$$v_w = \frac{(m.c.)(\rho_f v_f + \rho_m v_m)}{(100 - mc)\rho_w} \tag{9}$$

and

$$mc = \frac{m_w}{m_w + m_m + m_f} \times 100 = \frac{\rho_w v_w}{\rho_w v_w + \rho_m v_m + \rho_f v_f} \times 100 \tag{10}$$

where ρ_w, ρ_m and ρ_f is the density of water, muscle and fat, respectively. Hence, the relationship between mc and permittivity can be related using mixture model [20].

II. METHODOLOGY

A. Materials

The beef was collected from butchery after slaughter. It must be fresh to ensure its maximum mc at first place. The collected part is T-bone steak which is one of a popular household and restaurant food ingredients in western and oriental cuisine. The beef is sliced into smaller sample where each sample is approximately same weight, i.e. 50 grams. In order to study the variation of mc in the sample, the prepared samples were heated with 50 °C to avoid overheating or scorch. The different sample was heated with a different heating period at the same temperature. Hence, samples with different mc can be prepared through this procedure.

B. Sensing Probes

The coaxial probe was fabricated from a square flange (12.7 mm × 12.7 mm), SMA stub contact panel. The diameter of the inner and outer conductors is $2a = 1.3$ mm and $2b = 4.1$ mm, respectively. a is the radius of the inner conductor and b is the radius of the outer conductor. It has a stainless steel body with gold plating. In the meantime, a comparison of the measured reflection coefficient, Γ between the fabricated open-ended coaxial probe and Agilent 85070E High Temperature Probe with glass filled was conducted in conjunction with Agilent E8362B PNA Network Analyzer to verify the efficiency of the fabricated probe in studying *mc* in beef. 85070E High-Temperature probe is well known as a high accuracy of the dielectric probe which is the product of Agilent Technologies. Inner diameter, 2*a* and outer diameter, 2*b* for High Temperature Probe are 4.8 mm and 3.0 mm, respectively. Aspect ratio, b/a is defined as the ratio of the radius of the outer conductor to the radius of the outer conductor. This aspect ratio can be used to elucidate the sensitivity of a coaxial probe in measurement. The aspect ratio for open-ended coaxial probe and Agilent 85070E High Temperature Probe is 3.15 and 1.60, respectively. It is apparent that aspect ratio of the open-ended coaxial probe is larger than High Temperature Probe.

C. Oven drying method

The actual *mc* of the sample was determined by oven drying method. Before drying process using the oven, the weight of the sample was measured by digital weighing and recorded. The samples were then dried at 50 °C in an oven for different drying period to prepare a sample in different *mc*. The weights of dried samples were measured again to determine its relative *mc*, in percentage (wet basis). It can be calculated from:

$$m.c = \frac{m_{Before\_Dry} - m_{After\_Dry}}{m_{Before\_Dry}} \times 100\% \qquad (11)$$

where m_{Before_Dry} and m_{After_Dry} are the weight of the sample before and after drying process, respectively.

D. Dielectric and Reflection Measurement

The collected beef from butchery was needed to be prepared and measured immediately, so that the effect of moisture in fresh beef on reflection coefficient can be investigated through reflection measurement. A one-port calibration on both High Temperature Probe and the fabricated open-ended coaxial probe must be performed prior to reflection measurement for systematic errors removal. A procedure with a one port calibration method was conducted on a coaxial cable that connects the PNA with the probe from 200MHz to 20GHz, i.e., Short-Open-Load calibration (SOL). Three known calibration standards were used in calibration: Short, Open, and a 50 Ω Broadband Load. After calibration, the reflection measurement can be carried out for reflection coefficient in terms of magnitude and phase. Before the dielectric measurement is conducted using Agilent 85070E High Temperature Probe, calibration of the probe must be conducted to remove systematic measurement errors. Three calibration standards: air, a short circuit, and water were used in calibration. The dielectric measurement was conducted using 85071E Material Measurement Software attached to an Agilent 85070E High Temperature Probe in conjunction with Agilent E8362B PNA Network Analyzer. The dielectric measurement is conducted over a frequency range from 200 MHz to 20 GHz.

III. Results and Discussions

A. Measured dielectric constant (ε') and loss factor (ε") using Agilent 85070E High Temperature Probe

Proteins are long chains of amino acids. Amino acids contain an acidic -*COOH* group (carboxyl acid) and basic -NH_2 group (amine). The amino acids exist in zwitter ion form due to the presence of negatively charged COO^- and positively charged NH_3^+. When COO^- is excessive, it is negatively charged. On the contrary, it is positively charged when NH_3^+ are excessive. Summarily, the amino acid can be classified into two different groups, i.e. polar and non-polar amino acid. The polar amino acid in the protein of beef is isoleucine, leucine, methionine, phenylalanine, tryptophan, and valine. Non-polar acid amino (Hydrophobic) in beef is arginine, histidine, lysine, and threonine [21]. These polar amino acids participate in hydrogen bond to bind with a water molecule. When the mobility of water molecule is fully restricted, this water molecule is served as bound water. Bound water is the water that is directly held by chemical bonds to the beef proteins in muscle.

Dielectric constant, *ε'* significantly decreases when frequency increases. It occurs on *mc* exceeding 22% (Figure 1(a)). However, *ε'* is level off for 0 % (dried sample) and 11 % *mc*. This might be due to the presence of free water molecules in a compartment of the sample. When frequency increases, free water molecules fail to oscillate synchronously with the frequency of applied field and causes an incomplete cycle of dipolar polarization in a water molecule occurs at high frequency. As a result, *ε'* decreases when frequency increases. In addition, the mass of the ionic substances in amino acid, e.g., carboxyl acid, anime, and etc., prevents free water molecules in a compartment of muscle from responding to the variation of the frequency-dependent electric field at a high-frequency range. On the other hand, *ε'* increases with *mc* in the sample. It implies that higher *mc* provide sufficient free water molecules in the sample. Hence, *ε'* increases when free water molecules are able to perform full dipolar polarization. Since free water molecule can be freely moved, it can work with applied field synchronously at high frequency.

At low *mc* (< 11%), water molecules are presented as bound water in a compartment of beef due to the attraction force between the positive side of the water and negative side of acid amino. The generated attraction force leads to immobility of polar molecules in beef and inhibits complete dipolar polarization. As a result, low *ε'* can be noticed at low *mc* range as shown in Figure 1(a). In other words, *ε'* is higher at high *mc*. It is due to the presence of sufficient moisture molecules in the sample. It yields free water molecules in the sample as most of the polar amino acid have been bound with water molecules. The excessive water molecules can act as free water molecules. A free water molecule is unlike bound water molecule where free water molecules can perform a complete cycle of dipolar polarization synchronously with the frequency of applied field due to its high mobility.

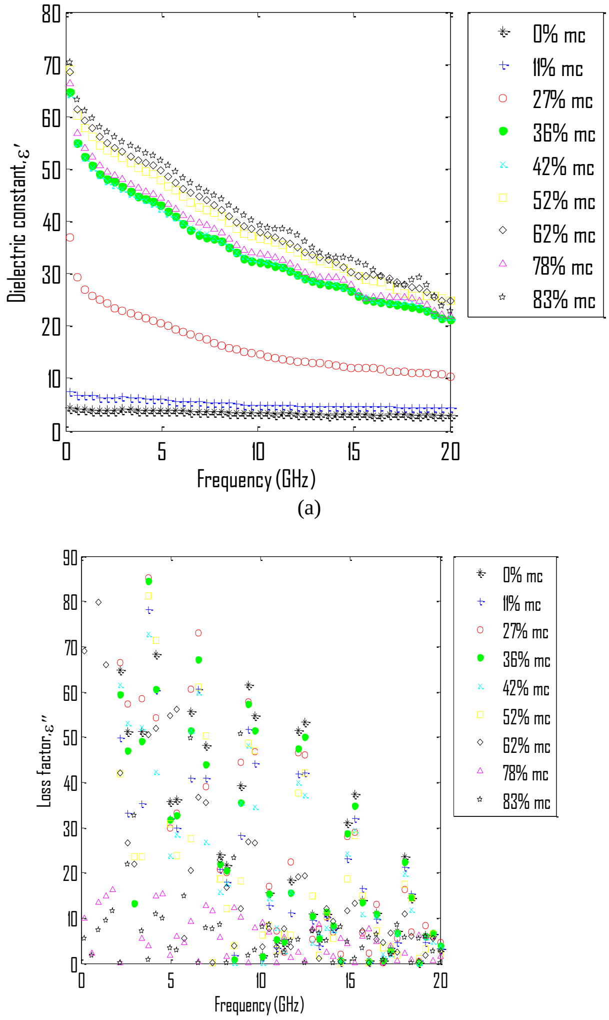
The variation of loss factor, *ε"* could be attributed to the frequency of applied field and *mc* in the sample as shown in Figure 1(b). It can be clearly noticed that the *ε"* exhibits a decrement when the frequency increases. The decrement of *ε"* above 78% *mc* can be observed in Figure 1(b). This decrement of *ε'* leads to the decrement of *ε"*. When operating frequency of applied field increases, the water molecules orient asynchronously during dipolar polarization with the frequency-dependent applied field. The orientation is inhibited and cause the frequency of friction decreases. Massive heat is generated through friction among water molecules and the amino acids in the sample when the dipolar polarization is conducted if polarizations work synchronously with operating frequency. Heat dissipation or heat loss is a major factor of *ε"*. Suffice to say, the *ε"* decreases when heat loss decreases due to asynchrony between dipolar polarization and operating frequency of the applied field. At high frequency, *ε'* and *ε"* experience same phenomenon where the movement of polar molecules during polarization become stagnant. It may due to relaxation frequency which owns naturally by polar molecules in beef is low.

In addition, the increment of *mc* leads to the decrement of *ε"*. When a number of free water molecules exceed polar amino acids, free water molecules are presented in a compartment of beef. However, excessive free water molecules do not fill the compartment fully due to a massive number of the compartment in the muscle of beef, even though *mc* is high (> 78%). As a result, free water molecules might still far apart and frequency of friction is low, even full dipolar polarization is carried out. In other words, *ε"* is low when *mc* is high. It can be justified by comparison between Figure 1(a) and Figure 1(b) where *ε'* increases, but *ε"* decreases when *mc* increases. In the meantime, it can be observed that *ε'* and *ε"* are clumped together and become indistinguishable at high frequency. The scattered *ε"* over frequency might due to compartmental of muscle in beef. The heat is unevenly dissipated due to friction in compartmental muscle.

B. *The variation of the magnitude of the reflection coefficient, |Γ| over frequency for different moisture content in beef*

Figure 2(a) exhibit frequency responses on |*Γ*| due to the variation of *mc* in beef. In Figure 2(a), it can be noticed that |*Γ*| decreases when frequency increases for all *mc*. The electromagnetic field is directed along the coaxial line to sample. When aperture of coaxial line contact with the sample without an air gap, a mismatch in impedance take place due to the different impedance presented between two different media on the interface, i.e. coaxial line and beef. Incident field is partially reflected based on the degree of mismatch in impedance which takes place on the interface. The reflection occurs attributed to a mismatch in impedance. The impedance of sample is determined indirectly through *mc* in beef. The relationship between reflection coefficient and mismatch in impedance are described by Equation (1)-(5). The mismatch in impedance decreases when the impedance of the sample discrepant from the characteristic impedance of the coaxial line becomes lesser. Subsequently, it leads to a decrement in the reflection coefficient. In other words, the mismatch in impedance decreases progressively when frequency increases. This can be noticed that |*Γ*| increases with frequency. In the meantime, Figure 2(b) show similar frequency response as Figure 2(a) where measured |Γ| is presented in descending form too when frequency increases.

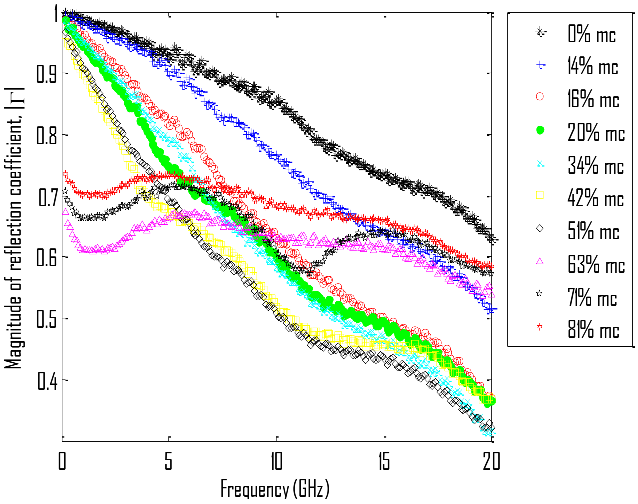
When the sample is fully dried to remove mc completely (0 % mc), it can be noticed that measured |Γ| by both probe as shown in Figure 2(a) and Figure 2(b) are at a highest level when comparing with other *mc* percentage in the sample. It can be associated with nature characteristic of the water molecule, H_2O. H_2O is dipolar molecule where it has an electronic charge due to non-uniform electrons distribution. Area of hydrogen inclines to a positive charge. Meanwhile, the area of oxygen inclines to a negative charge. The macro and microstructure of muscle in the sample have many compartments where water may be held. The proteins of beef have the excessive negative charges in polar acid amino where it has a natural attraction for positive charged areas of H_2O. When frequency-dependent applied field interacts with molecule H_2O, it conducts dipolar polarization. Since H_2O is bound with polar acid amino in protein at low *mc*, its mobility is restricted and leads to inhibition of the polarization. Subsequently, it causes low *ε'*. In the meantime, bound water at low frequency has intimate interaction with acid amino. If sufficient energy is owned by a water molecule, friction still occurs and cause high *ε"*. Meanwhile, contrast dielectric response can be seen at high frequency. It causes constant and loss factor of beef can be seen in Figure 1(a) and Figure 1(b). This dielectric relationship among component in beef can be described using Equation (6) to Equation (10). The reduction of *ε'* and *ε"* results in an increment of mismatch in impedance and it is expressed by Equation (1) to Equation (7). Subsequently, the increment of mismatch in impedance triggers increment of |*Γ*|. When comparing Figure 2(a) with Figure 2(b), it can be noticed that Agilent 85070E High Temperature Probe is not sensitive with a variation of *mc* when *mc* > 36%. In literature [22], it reported that higher sensitivity could be obtained for a probe with higher aspect ratios. Apparently, the open-ended coaxial probe is more sensitive than High Temperature probe in reflection measurement.



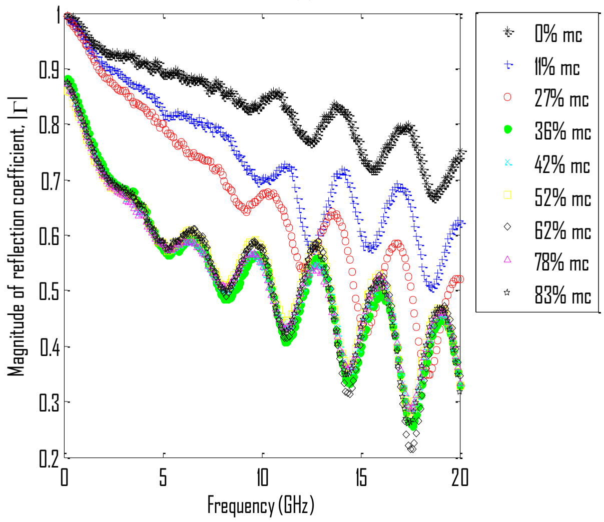
(a)

(b)

Figure 1: Frequency response of (a) dielectric constant, ε' and (b) loss factor, ε" with various mc.



(a)



(b)

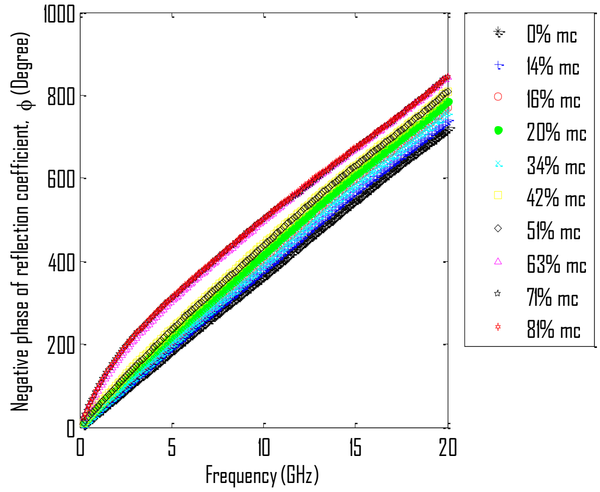
Figure 2: The variation of measured |Γ| with frequency using (a) open-ended coaxial probe and (b) Agilent 85070E High Temperature Probe for different moisture content (mc) in beef.

C. The variation of the phase of the reflection coefficient, over frequency for different moisture content in beef

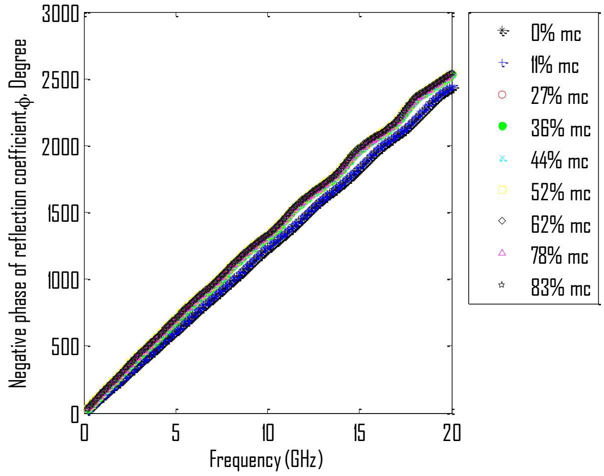
Negative phase, $-\phi$ increase as frequency increases as shown in Figure 3(a) and Figure 3(b). Negative phase implies that the reflected wave is lag behind the incident wave. When the incident wave transmits from probes impinges on the interface, the time delay is occurred due to the phenomenon of conductivity that determines the penetration depth. Higher conductivity results in greater loss factor, since loss factor is proportional to conductivity. In Figure 1(b), it is clearly stated that ε'' decreases when frequency increases. In other words, conductivity decreases over frequency. Lower conductivity suggests higher penetration depth, as the sample is less reflective and allow the applied field to propagate farther in the sample. Time delay during the reflection on interface increases over frequency. It is probably due to increment of penetration depth over frequency lengthen time delay (or lag phase of the reflected field behind incident field) when reflection occurs. The penetration depth of applied field might be longer causes the resultant phase shift due to reflection on the surface and internal depth of sample becomes longer.

On the other hand, the measured ϕ for all percentage *mc* using both probes cannot be distinguished significantly. It seems that measured ϕ is insensitive with *mc*. It might due to the insignificant time delay between the incident wave and reflected wave. The compartmental structure of beef causes water molecules to split apart. Hence, the role played by water molecules in enhancing the conductivity might be insignificant. Hence, penetration depth seems alike, even *mc* increases.

Withal, the sensitivity of Agilent 85070E High Temperature Probe in measuring ϕ is higher than the open-ended coaxial probe. It is in contrast with measured $|\Gamma|$ when comparing Figure 2(a) and Figure 2(b). It is probably attributed to the larger surface area of the flange at an aperture of High Temperature Probe. It provides wider coverage fringing field to interact with water molecules in the sample.



(a)



(b)

Figure 3: The variation of measured negative phase, ϕ with frequency using (a) open-ended coaxial probe and (b) Agilent 85070E High Temperature Probe for different moisture content (mc) in beef.

IV. CONCLUSION

A microwave reflection measurement system which consists of Agilent 85070E High Temperature Probe and open-ended coaxial probe in conjunction with PNA is developed for the sake of reflection coefficient and dielectric properties in beef with various *mc*. The dielectric mechanism was conducted when water molecules in sample interacted with a time-varying field. Then, the complex reflection coefficient in terms of magnitude ($|\Gamma|$) and phase (ϕ) was measured using both probes. The measured ε' increases with *mc*. Meanwhile, ε” exhibit lower when *mc* > 62%. . The measured |Γ| and ϕ decrease when *mc* increases. The effect of *mc* on the dielectric properties is major factor leading to the variation of $|\Gamma|$ and ϕ. Nevertheless, the phase has no significant response towards the variation of *mc*. In summary, the dielectric and reflection measurement present good agreement in assessing the *mc* in beef.

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