

The Measurement of Dielectric Properties of Liquids at Microwave Frequencies Using Open-ended Coaxial Probes

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Abstract – Significant progress has been made in recent years in the development of microwave tomographic imaging systems for medical applications. In order to design an appropriate microwave imaging system for industrial applications, and to interpret the images produced, the materials under imaging need to be characterised. In this paper, we describe the use of open-ended coaxial probes for the measurement of dielectric properties of liquids at frequencies between 400MHz and 20GHz. The results obtained using the Misra-Blackham model for a number of liquids including water of different salinity are compared with those published in the literature showing a good agreement. For saline water, in particular, the frequency of the minimum loss depends on the salinity. It may change from 1.5GHz for the inclusion of 0.2% NaCl to 7GHz for the inclusion of 3.5% NaCl. The real part of the permittivity may also change by approximately 50% from 400MHz to 20GHz.

Keywords : Dielectric, Permittivity, Probe, Liquids

1. INTRODUCTION

In recent years, significant progress has been made in the development of microwave tomographic imaging systems for medical applications [1]. In order to design an appropriate microwave imaging system for the monitoring of industrial processes, the materials under imaging need to be characterised. This would also enable the images produced to be accurately interpreted. The characterisation of dielectric materials may include the measurement of complex permittivity as function of frequency at a given temperature or as a function of temperature at a given frequency. The measurement of dielectric properties at a wide frequency range can provide information on the low frequency conduction mechanism, interfacial polarisation and molecular dynamics [2]. The techniques of characterisation may include the use of cavity resonators, free space transmission, transmission lines and open-ended coaxial probes [3]-[6]. Primarily, open-ended coaxial probes were developed as a type of sensor for broad-band, non-destructive measurement of the permittivity of biological substances [6, 7]. However, they can also be used to measure dielectric properties of liquids. In this paper, we describe the use of this technique for the measurements of a number of common liquids including Methanol, 2-Propanol, Butanol, and water of different salinity. With the use of an appropriate calibration procedure and the Misra-Blackham model to describe the probe, both real and imaginary parts of the complex permittivity are measured. The results

will be compared with those available in the literature.

2. COAXIAL PROBE MODEL

Due to the extensive use of open-ended coaxial probes in the measurement of biological substances, a number of models for coaxial probes have been developed and numerous methods for permittivity calculations have been proposed with success [6]-[13]. For our study, we use the Misra-Blackham model, which is described below.

In the Misra-Blackham model, it is first assumed that only the dominant TEM mode propagates inside the coaxial line. The formulation of input admittance of the coaxial probe is then modified to take higher order modes into account which is necessary at higher microwave frequencies. For the TEM propagation, Misra [14] has shown that the input admittance of the probe can be written as

$$Y = j \frac{k^2}{pk_c \ln(b/a)} \int_a^b \int_a^b \int_0^p \cos(\mathbf{f}) \frac{\exp(-jkR)}{R} d\mathbf{f} dr dr' \quad (1)$$

with

$$\begin{aligned} k &= w \sqrt{\mathbf{e}^* \mathbf{e}_0 \mathbf{m}_0} \\ k_c &= w \sqrt{\mathbf{e}_c \mathbf{e}_0 \mathbf{m}_0} \\ R &= \sqrt{r^2 + r'^2 - 2rr' \cos(\mathbf{f})} \end{aligned} \quad (2)$$

where w is the angular frequency; a and b are the inner radius and outer radius of the probe respectively; ϵ_c is the permittivity of the dielectric material inside the probe and ϵ^* is the complex permittivity of unknown material under test. The integration in (1) is made on the aperture of probe with r and r' describing the field and source points respectively. By expanding the exponential term in the integrand into a Taylor series, (1) can be approximated to

$$Y = j \frac{k^2}{pk_c \ln(b/a)} \left[j \left(I_1 - \frac{k^2 I_3}{2} + \frac{k^4 I_5}{24} - \frac{k^6 I_7}{720} + \dots \right) + \left(I_2 k + \frac{k^3 I_4}{6} - \frac{k^5 I_6}{120} - \dots \right) \right] \quad (3)$$

where

$$I_n = \int_a^b \int_a^b \int_0^p R^{n-2} \cos(\mathbf{f}) d\mathbf{f} dr dr' \quad n = 1, 2, 3 \dots \quad (4)$$

For an accurate calculation, a total of 28 terms are used in the expansion.

To take the higher order modes into the formulation, the expansion constants I_n can be modified as proposed by Blackham [15], which then become

$$I'_n = \frac{I_n}{10^\beta} \quad (5)$$

where β is a parameter obtained by measuring the admittance of different materials with known permittivities in the range between 1 and 80 [15]. The parameter β is optimised until the admittances calculated using (3) give the best match to the measured admittances. Once β is obtained, (3) is used to determine unknown permittivities.

3. EXPERIMENTAL SET-UP

The measurement system used for the dielectric measurement consists of a computer controlled HP 8510B vector network analyser (VNA) and a probing platform, as shown in Fig.1. The coaxial probe as shown in Fig.2 is connected to Port 1 of the VNA.

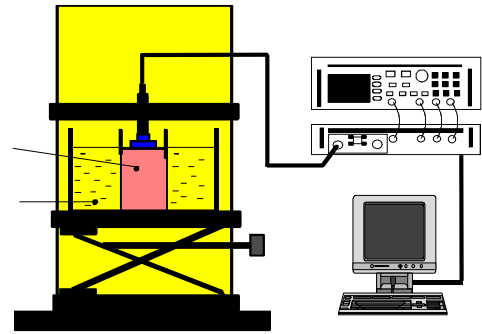


Figure 1 : The dielectric measurement system

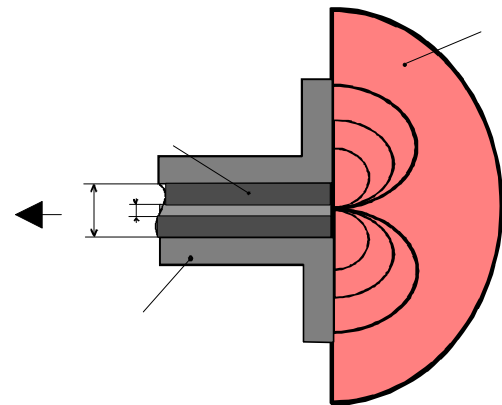


Figure 2 : Geometry of the open-ended probe for dielectric measurements

Two probes, Probe 1 and Probe 2, of different dimensions are used for measurements in order to confirm the results and to investigate the effect of the opening aperture of the probe. The dimensions of both probes are given in Table 1. They are constructed from commercially available 50Ω SMA connectors. Both probes have a flange to support the fields required, and minimise the fringing effect. The dimensions of the flange are also given in Table 1. The larger probe, i.e. Probe 1, is most suitable for measuring high permittivities, i.e. $\epsilon' \sim 80$ at lower microwave frequencies to 400MHz, and the smaller probe, i.e. Probe 2, for higher frequencies up to 20GHz.

	Probe 1	Probe 2
Connector type	Suhner 23 SMA-50-0-53	
2b (mm)	4.1	2.5
2a (mm)	1.3	0.8
Flange diameter (mm)	30	40

Table 1. Dimensions of probes.

For accurate measurements, the probes are calibrated with a short circuit, open air and de-ionised water in addition to the calibrations made to the vector network analyser at a temperature of $23 \pm 2^\circ\text{C}$. In order to minimise the frequency dependent-effect of finite volume, both water used for calibration and the liquid under test are kept in a polyethylene tube, which is mounted in a larger container containing saline water of high conductivity.

4. MEASUREMENT OF KNOWN LIQUIDS

To test the accuracy of measurements, a number of liquids of known properties including Methanol, 2-Propanol and Butanol are used. These materials are polar liquids. Their permittivities at microwave frequencies can be calculated using the Cole-Cole equation:

$$e = e_\infty + \frac{e_s - e_\infty}{1 + (j\omega\tau)^{1-a}} - j \frac{s}{\omega\epsilon_0} \quad (6)$$

where $\omega = 2\pi f$ is the radian frequency, e_∞ is the permittivity at the infinite frequency, e_s is the static permittivity, τ is the relaxation time, s is the ionic conductivity and a is an empirical parameter describing the relaxation time distribution.

The measured relative permittivities of these liquids using Probe 1 are shown in Figures 3 for the real part and in Figure 4 for the imaginary part at frequencies between 400MHz and 4GHz. Using a Levenberg-Marquardt optimisation routine for the measured results of permittivities, the Cole-Cole parameters obtained in probe can provide accurate measurements for a range of liquids. Similar results of Cole-Cole parameters are obtained for the same liquids when Probe 2 is used in the frequency range between 400MHz and 20GHz. Table 2 together with those fitted to the data available in the literature for the same type of liquids [16]. The comparison shows that the probe can provide accurate measurements for a range of liquids. Similar results of Cole-Cole parameters are obtained for the same liquids when Probe 2 is used in the frequency range between 400MHz and 20GHz.

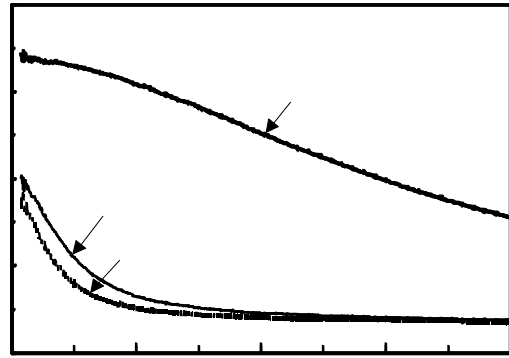


Figure 3 : Real part of relative permittivity measured on three liquids of known properties

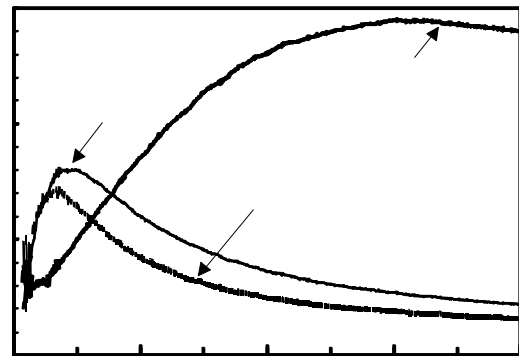


Figure 4 : Imaginary part of relative permittivity measured on three liquids of known properties

5. MEASUREMENT OF SALINE WATER

Following the validation measurements using known liquids, Probe 2 is used to measure the property of water of different salinity. The saline water solutions used for measurements are tabulated in Table 3. The salt content in the distilled water varies from 0.2 % to 3.5 % in weight. The conductivities of corresponding solutions, which are given in [17], are also listed in Table 3 for reference.

Liquid	Tabulated literature values [16]				Fitted measured values			
	e_s	e_∞	τ (ps)	a	e_s	e_∞	τ (ps)	a
Methanol	33.7	4.5	49.5	0.036	33.92	4.02	46.9	0.028
Butanol	17.1	2.95	47.7	0.08	17.49	3.44	49.3	0.06
2-Propanol	19	3.2	29.2	0	20.81	3.56	34	0.034

Table 2. Comparison of Cole-Cole parameters for measured permittivity and tabulated values in the literature for three liquids of known properties.

Solution	Salinity (% NaCl)	Conductivity (S/m)
Sol. 1	0.2	0.33
Sol. 2	0.5	0.82
Sol. 3	1	1.62
Sol. 4	1.5	2.39
Sol. 5	2	3.14
Sol. 6	2.5	3.87
Sol. 7	3.5	5.28

Table 3. Saline solutions for their reference conductivities at 22°C.

The measured relative permittivities of these saline solutions are shown in Figures 5 for the real part and in Figure 6 for the imaginary part against frequency. The effect of the salinity on the permittivity can be seen from both Figures 5 and 6. As the salinity increases, the conductivity increases. The static permittivity however decreases. The effect of conductivity dominates at lower frequencies. The frequency of relaxation of the water is around 20GHz which is not significantly affected by the conductivity. The effect of electrode polarisation can be seen from Figure 5 at frequencies below 800MHz, which becomes significant for solutions containing more than 2% of salt.

It can also be seen from Figures 5 and 6 that the real part of the permittivity may change by 50% as the frequency is changed from 400MHz to 20GHz, and the loss factor depends very much on salinity. The minimum loss occurs at a frequency of 1.5GHz for 0.2% of salt and 7GHz for 3.5% of salt.

When the results presented in Figures 5 and 6 are fitted using the Cole-Cole equation (6) with $\alpha = 0$, the Cole-Cole parameters obtained are given in Table 4 together with the parameters fitted to the data available in the literature for the same salinity [17]. A good agreement can be seen between two sets of Cole-Cole parameters, indicating the usefulness of the open-end coaxial probe for a broadband measurement of liquids.

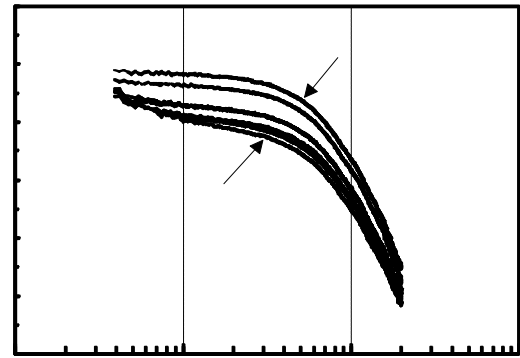


Figure 5 : Real part of relative permittivity measured on saline solutions.

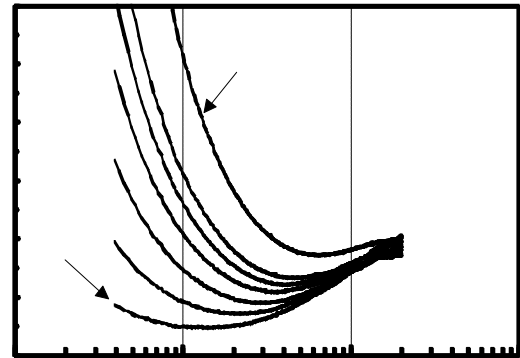


Figure 6 : Loss factor of relative permittivity measured on saline solutions.

6. CONCLUSIONS

We have demonstrated in this paper that the open-ended coaxial probe technique can provide a broadband measurement of liquids at microwave frequencies. The results obtained using the Misra-Blackham model for a number of liquids of known properties show that the designed probes can give an accurate measurement of permittivity across the frequency range from 400MHz to 4GHz for Probe 1 and to 20GHz for Probe 2.

Solution	Tabulated literature values [17]			Fitted measured values		
	ϵ_s	τ (ps)	S (S/m)	ϵ_s	τ (ps)	S (S/m)
Sol. 1	78.69	8.79	0.33	78.35	9.17	0.346
Sol. 2	77.67	8.78	0.82	76.27	8.95	0.818
Sol. 3	76.01	8.76	1.62	72.83	9.44	1.4161
Sol. 4	74.4	8.74	2.39	72.92	9.3	2.072
Sol. 5	72.83	8.71	3.14	71.17	9.7	2.644
Sol. 6	71.31	8.68	3.87	70.72	10.77	3.202
Sol. 7	68.38	8.62	5.28	69.9	10.75	5.4

Table 4. Comparison of Cole-Cole parameters for measured permittivity and tabulated values in the literature for saline water.

The measurements using Probe 2 for saline water show that the permittivity of the solutions depends very much on the salinity, as well as the frequency. The real part of the permittivity may change by approximately 50% from 400MHz to 20GHz. There also exists a frequency at which the loss in the saline water solution is minimum, as a result of the finite conductivity. This frequency may also change from 1.5GHz for 0.2% salt to 7GHz for 3.5% of salt. Such information is useful in the design of a microwave tomographic system for industrial applications.

REFERENCES

- [1] J. C. Bolomey and C. Pichot, "Some applications of diffraction tomography to electromagnetics - Particular case of Microwaves," *Inverse Problems in Scattering and Imaging*, M. Berto and E. R. Pike, Eds. New York: Adam Hilger, 1992, pp. 319-344.
- [2] A. R. Von Hippel, "Dielectric Materials and Applications", Cambridge, MA: M.I.T. Press, 1954.
- [3] M. N. Afsar, J. R. Birch, R. N. Clarke, "The measurement of the properties of materials," *Proc IEEE*, vol. **74**, January 1986, pp 183 - 199.
- [4] R. J. Cook, "Microwave cavity methods" in High Frequency Dielectric Measurement., J. Chamberlain and G. W. Chantry, eds Guildford, U.K., *IPC Sci. and Tech.*, 1973, pp 12 - 17.
- [5] D. K. Godgaonkar, V. V. Varadan, V. K. Varadan, "Free-space measurement of complex permittivity and complex permeability of magnetic materials at microwave frequencies," *IEEE Trans. Microwave Theory Tech.*, vol. **39**, n°2, April 1990, pp 387 - 394.
- [6] M. A. Stuchly, S. S. Stuchly, "Coaxial line reflection method for measuring dielectric properties of biological substances at radio and microwave frequencies - A review," *IEEE Trans. Instrum. Meas.*, vol. **29**, n°3, September 1980, pp 176 - 183.
- [7] T. Whit Athey, M. A. Stuchly, S. S. Stuchly, "Measurement of radio frequency permittivity of biological tissues with an open-ended coaxial line : Part I ", *IEEE Transactions on MTT*, vol. **30**, n°1, January 1982, pp 82 - 86.
- [8] M. A. Stuchly, T. Whit Athey, C. M. Samaras, G. E. Taylor, " Measurement of radio frequency permittivity of biological tissues with an open-ended coaxial Line : Part II - Experimental results " *IEEE Transactions on MTT*, vol. **30**, n°1, January 1982, pp 87 - 92.
- [9] T. P. Marsland, S. Evans, " Dielectric measurements with an open-ended coaxial probe ", *Proc. IEE*, vol. **134**, 1987, pp 341 - 349.
- [10] D. Misra, M. Chhabra, B. R. Epstein, M. Mirotnik, K. R. Foster, " Non-invasive electrical characterisation of materials at microwave frequencies using an open-ended coaxial line : Test of an improved calibration technique ", *IEEE Transactions on MTT*, vol. **38**, n°1, January 1990, pp 8 - 14.
- [11] D. Berube, F. M. Ghannouchi, P. Savard, " A comparative study of four open-ended coaxial probe models for permittivity measurements of lossy dielectric/biological materials at microwave frequencies ", *IEEE Transactions on MTT*, vol. **44**, n°10, October 1996, pp 1928 - 1934.
- [12] K. Folgero, T. Friiso, J. Hilland, T. Tjomsland, " A broad-band and high-sensitivity dielectric spectroscopy measurement system for quality determination of low-permittivity fluids ", *Meas. Sci. Technol.*, vol. **6**, 1995, pp 995 - 1008.
- [13] J. Hilland, " Simple sensor system for measuring the dielectric properties of saline solutions ", *Meas. Sci. Technol.*, vol. **8**, 1997, pp 901 - 910.
- [14] D. K. Misra, "A quasi-static analysis of open-ended coaxial lines," *IEEE Trans. Microwave Theory Tech.*, vol. **35**, October 1987, pp 925 - 928.
- [15] D. V. Blackham and R. D. Pollard, "An improved technique for permittivity measurements using a coaxial probe", *IEEE Trans. Instrum. Meas.*, 1997, vol. **46**, n°5, pp 1093-1099.
- [16] F. Buckley, A. A. Maryott, "Tables of Dielectric Dispersion Data for Pure Liquids and Dilute Solutions," *National Bureau of Standards Circular 589*, 1958.
- [17] A. Stogryn, "Equations for calculating the dielectric constant of saline water," *IEEE Trans. Microwave Theory Tech.*, vol. **19**, 1971, pp 733 - 736.