

**OPTIMIZATION IN THE COMPUTATION OF DIELECTRIC
CONSTANT OF METHANOL USING DEBYE RELAXATION
METHOD**

ABSTRACT

The Debye relaxation equation and its derivatives were used to analyze dielectric constant and loss factor of pure methanol in megahertz and gigahertz over the temperature range of 10°C to 50°C. This was done in order to ascertain which of the frequency ranges has the highest dielectric constant and least loss factor. The graphs of dielectric constant and loss factor were plotted against the frequency. The results were also used to plot Cole-Cole diagrams. The results revealed that the dielectric constant of methanol is higher at frequency 0.05GHz and decrease as both frequency and temperature increases. However, as the frequency increases beyond 1.0GHz the dielectric constant increase as the temperature increases. The results also showed that methanol actually formed a semi-circle which suggested that the solvent indeed exhibits Debye relaxation model. There were some discrepancies observed in the Cole-Cole plots which may just be attributed to the distribution of the relaxation times in the methanol. The researchers conclude that dielectric constant of methanol is higher in megahertz than those in gigahertz. The loss factor on the other hand was small at lower frequencies but as the frequency increases the loss factor also increases to a maximum value. The loss factor however decreased when the frequency increases after attaining its maximum.

KEYWORDS: Debye relaxation, dielectric constant, loss factor, megahertz gigahertz and Cole-Cole plot.

INTRODUCTION

Methanol is one of the most widely traded chemical commodities in the world today. The estimated global demand for methanol also known as methyl alcohol, wood alcohol, wood naphtha, methyl hydrate, or wood spirit is around

33 27 to 29 million metric tons [1-2]. Recently, the production capacity of
34 methanol has increased considerably. The coming on stream of new plants in
35 South- America, China and the Middle East is a clear cut example.

36 Methanol was first produced cheaply as a byproduct of the destructive
37 distillation of wood but today industrial methanol is produced in a catalytic
38 process directly from carbon monoxide, carbon dioxide and hydrogen [3-4]. It is
39 a light, volatile, colourless, flammable liquid with a distinctive odour very
40 similar to that of ethanol [5]. However, unlike ethanol, methanol is highly toxic
41 and unfit for consumption. Methanol is a traditional denaturant for ethanol, the
42 product known as denatured alcohol or methylated spirit. This was commonly
43 used during the prohibition to discourage consumption of bootlegged liquor,
44 and ended up causing several deaths [6-7].

45 Organic methanol, produced from wood or other organic materials
46 (bioalcohol), has been suggested as a renewable alternative to petroleum-based
47 hydrocarbons [8, 1]. Low levels of methanol can be used in existing vehicles
48 with the addition of co-solvents and corrosion inhibitors. Methanol fuel has
49 been proposed for ground transportation. The chief advantage of a methanol
50 economy is that it could be adapted to gasoline internal combustion engines
51 with minimum modification to the engines and to the infrastructure that delivers
52 and stores liquid fuel [10-11].

53 The solvent is primarily used as feedstock for the manufacture of
54 chemicals and as a fuel for specialized vehicles. At about 40% of methanol is
55 converted to formaldehyde and from there into products as diverse as plastics,
56 plywood, paints, explosives, and permanent textiles [1]. Other chemical
57 derivatives of methanol include dimethyl ether (DME), which has replaced
58 chlorofluorocarbons as an aerosol spray propellant, and acetic acid. Dimethyl
59 ether can be blended with liquefied petroleum gas (LPG) for home heating and

cooking, and can be used as a replacement for transportation diesel fuel [12]. It is because of the increasing demand and the market value of methanol that the researchers have decided to optimize the dielectric constant of methanol. This was done in order to ascertain which frequency value and temperature one can obtain the highest dielectric constant.

MATHEMATICAL DERIVATION OF THE DEBYE EQUATIONS

Consider a capacitor that consists of two plane parallel electrodes in vacuum having an applied alternating voltage represented by the equation;

$$V = V_m \cos \omega t \quad (1)$$

Where V = instantaneous voltage, V_m = maximum voltage, ω = angular frequency in radians per second = $2\pi f$. The current through the capacitor, i_1 is given by

$$i_1 = I_m (\cos \omega t + \pi/2) \quad (2a)$$

$$\text{Where } I_m = \frac{V_m}{Z} = \omega C_0 V_m \quad (2b)$$

C_0 = vacuum capacitance, sometimes referred to as geometric capacitance.

In an ideal dielectric, the current leads the voltage by 90° or $\pi/2$ rads. There is no component of the current in phase with the voltage. If a material of dielectric constant ϵ is now placed between the plates, the capacitance increases to $C_0\epsilon$ and the current is given by

$$i_2 = I_m \cos [\omega t + (\pi/2 - \delta)] \quad (3a)$$

$$\text{where } = \omega C_0 \epsilon V_m \quad (3b)$$

δ = loss angle

The usual symbol for the dielectric constant is ϵ_r , but the subscripts was omitted for the sake of clarity, noting that ϵ is dimensionless. The current phasor will now, not be in phase with the voltage but an angle $(90^\circ - \delta)$. The dielectric constant is a complex quantity represented by

$$\epsilon^* = \epsilon' - j\epsilon'' \quad (4)$$

The current can be resolved into two components; the component in phase with the applied voltage is $I_x = V\omega\epsilon''C_0$ and the component leading the applied voltage by 90° is $I_y = V\omega\epsilon'C_0$. This component is the charging current of the ideal capacitor.

90 The component in phase with the applied voltage gives rise to dielectric
91 loss. The loss angle δ is given by

$$92 \quad \delta = \tan^{-1} \frac{\epsilon''}{\epsilon'} \quad (5a)$$

93 Note that $I_x = V\omega C_0 \epsilon''$, but since $C_0 = \frac{\epsilon_0 A}{d}$

$$94 \quad I_x = V\omega \epsilon'' \frac{\epsilon_0 A}{d} = \frac{V\omega \epsilon_0 \epsilon'' A}{d} = A\omega \epsilon_0 \epsilon'' E \quad (5b)$$

95 Where $E = \frac{V}{d}$

$$96 \quad J_x = \frac{I_x}{A} = \frac{A\omega \epsilon_0 \epsilon''}{A} \therefore J_x = \omega \epsilon_0 \epsilon'' E.$$

97 **NOTE:** ϵ' = the real part of the complex dielectric constant

98 ϵ'' = The imaginary part of the complex dielectric constant

99 J_x = The current density

100 The alternating current conductivity is given by

$$101 \quad \sigma_{ac} = \sigma' + j\sigma'' = \omega \epsilon_0 [\epsilon'' + j(\epsilon' - \epsilon_\infty)] \quad (6)$$

102 The total conductivity is given by

$$103 \quad \sigma_T = \sigma_{ac} + \sigma_{dc} = \omega \epsilon_0 \epsilon'' + \sigma_{dc} \quad (7)$$

104 σ_{dc} is the direct current conductivity

105 When a direct voltage applied to a dielectric for a sufficiently long
106 duration is suddenly removed, the decay of polarization to zero value is not
107 instantaneous but takes a finite time. This is the time required for the dipoles to
108 revert to a random distribution, in equilibrium with the temperature of the
109 medium, from a field oriented alignment. Similarly, the build-up of polarization
110 following the sudden application of a direct current takes a finite time interval
111 before the polarization attains its maximum value. This phenomenon is
112 described by the general term “dielectric relaxation”.

113 When a dc voltage is applied to a polar dielectric, let us assume that the
114 polarization builds up from zero to a final value according to an exponential law
115 such that

$$116 \quad P(t) = P_\infty (1 - e^{-\frac{t}{\tau}}) \quad (8)$$

117 Where $P(t)$ is the polarization at a time, t and τ is called the relaxation time. τ is
118 a function of temperature and it is independent of the time.

119 If $\omega = 2\pi f$, $\omega\tau = 2\pi f\tau$

120 Differentiating equation (8) with respect to t, yields

121
$$\frac{dP(t)}{dt} = \frac{P_{\infty}e^{-t/\tau}}{\tau} \quad (9)$$

122 Expanding the right hand side of (8) yields

123
$$P_{\infty}e^{-t/\tau} = P_{\infty} - P(t) \quad (10)$$

124 Which upon dividing both sides by P_{∞} yields

125
$$e^{-t/\tau} = \frac{P_{\infty} - P(t)}{P_{\infty}}$$

126 Substitute equation (10) into (9) we obtained

127
$$\frac{dP(t)}{dt} = \frac{P_{\infty} - P(t)}{\tau} \quad (11)$$

128 This by assuming that the polarization is due to the dipoles yields

129
$$\frac{dP(t)}{dt} = \frac{P_{\infty} - P(t)}{\tau} \cong \frac{P_{\mu} - P(t)}{\tau} \quad (12)$$

130 Neglecting atomic polarization, the total polarization $P_T(t)$ can be
131 expressed as the sum of the orientation polarization at that instant $P_{\mu}(t)$ and
132 electronic polarization, P_e which is assumed to attain its final value
133 instantaneously because the time required for it to attain saturation value is in
134 the optical frequency range. Further, it is assumed that the instantaneous
135 polarization of the material in an alternating voltage is equal to that under dc
136 voltage that has the same magnitude as the alternating voltage at that instant.

137 We can express the total polarization, $P_T(t)$ as

138
$$P_T(t) = P_{\mu}(t) + P_e \quad (13)$$

139 The final value attained by the total polarization is

140
$$P_T = \epsilon_0(\epsilon_s - 1)E \quad (14)$$

141 Under steady voltages;

142
$$P_e = \epsilon_0(\epsilon_{\infty} - 1)E \quad (15)$$

143 where ϵ_s and ϵ_{∞} are the dielectric constants under direct voltage and at infinity
144 frequency respectively. Also note that Maxwell's relation holds

145
$$\epsilon_{\infty} = n^2$$

146 Substituting (14) and (15) into (13) to have

$$147 \quad P_{\mu} = \varepsilon_0 E (\varepsilon_s - \varepsilon_{\infty}) \quad (16)$$

148 Representing the alternating electric field as

$$149 \quad E = E_{max} e^{j\omega t} \quad (17)$$

150 Substituting (16) into (12), we have

$$151 \quad \frac{dP(t)}{dt} = \frac{\varepsilon_0 (\varepsilon_s - \varepsilon_{\infty}) E - P(t)}{\tau} \quad (18)$$

152 Substituting (17) into (18); yields

$$153 \quad \frac{dP(t)}{dt} = \frac{1}{\tau} [\varepsilon_0 (\varepsilon_s - \varepsilon_{\infty}) E_{max} e^{j\omega t} - P(t)] \quad (19)$$

154 By using the idea of solving linear equations by the use of integrating factors,

$$155 \quad P(t) = \frac{\varepsilon_0 (\varepsilon_s - \varepsilon_{\infty}) E_m e^{j\omega t}}{1 + j\omega\tau} + C e^{-t/\tau} \text{ or}$$

$$156 \quad P(t) = C e^{-t/\tau} + \varepsilon_0 \frac{(\varepsilon_s - \varepsilon_{\infty}) E_m e^{j\omega t}}{1 + j\omega\tau} \quad (20)$$

157 Where C, is a constant. At time, t sufficiently large when compared with τ , the
 158 first term on the right hand side of equation (20) becomes so small that it can be
 159 neglected, so the solution for P (t) becomes

$$160 \quad P(t) = \varepsilon_0 \frac{(\varepsilon_s - \varepsilon_{\infty}) E_m e^{j\omega t}}{1 + j\omega\tau} \quad (21)$$

161 Substituting (15), (17) and (20) into (14) and let

$$162 \quad P(t) = P_{\mu}(t) = \varepsilon_0 \frac{(\varepsilon_s - \varepsilon_{\infty}) E_m e^{j\omega t}}{1 + j\omega\tau};$$

163 We have upon simplification

$$164 \quad P(t) = \left[\varepsilon_{\infty} - 1 + \frac{(\varepsilon_s - \varepsilon_{\infty})}{1 + j\omega\tau} \right] \varepsilon_0 E_m e^{j\omega t} \quad (22)$$

165 Equation (22) shows that P (t) is a sinusoidal function with the same
 166 frequency as the applied voltage. The instantaneous value of flux density, D is
 167 given by

$$168 \quad D(t) = \varepsilon_0 \varepsilon^* E_m e^{j\omega t} \quad (23)$$

169 But flux density is also equal to

$$D(t) = \varepsilon_0 E_m e^{j\omega t} + P(t) \quad (24)$$

Equate equation (23) to (24) ;

$$\varepsilon_0 \varepsilon^* E_m e^{j\omega t} = \varepsilon_0 E_m e^{j\omega t} + P(t) \quad (25)$$

Substitute (24) into (25) and simplify

$$\varepsilon_0 \varepsilon^* E_m e^{j\omega t} = \varepsilon_0 E_m e^{j\omega t} + \left[\varepsilon_\infty - 1 + \frac{(\varepsilon_s - \varepsilon_\infty)}{1 + j\omega\tau} \right] \varepsilon_0 E_m e^{j\omega t}$$

Dividing each term by $\varepsilon_0 E_m e^{j\omega t}$, the last equation reduces to

$$\varepsilon^* = 1 + \left[\varepsilon_\infty - 1 + \frac{(\varepsilon_s - \varepsilon_\infty)}{1 + j\omega\tau} \right] \quad (26)$$

Substitute equation (4) into (26)

$$\varepsilon' - j\varepsilon'' = 1 + \left[\varepsilon_\infty - 1 + \frac{(\varepsilon_s - \varepsilon_\infty)}{1 + j\omega\tau} \right] \quad (27)$$

Simplifying further produces

$$\varepsilon' = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j\omega\tau} + j\varepsilon'' \quad (28)$$

Setting $\varepsilon'' = \frac{(\varepsilon_s - \varepsilon_\infty)\omega\tau}{1 + \omega^2\tau^2}$ and substituting into equation (28) gives

$$\varepsilon' = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + \omega^2\tau^2} \quad (29)$$

From equation (28);

$$j\varepsilon'' = \varepsilon' - \varepsilon_\infty - \frac{\varepsilon_s - \varepsilon_\infty}{1 + j\omega\tau} \quad (30)$$

Substituting equation (29) into (30); we have

$$\varepsilon'' = \frac{(\varepsilon_s - \varepsilon_\infty)\omega\tau}{1 + \omega^2\tau^2} \quad (31)$$

Recall equation (5),

$$\tan \delta = \frac{\varepsilon''}{\varepsilon'} = \frac{\frac{(\varepsilon_s - \varepsilon_\infty)\omega\tau}{1 + \omega^2\tau^2}}{\varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + \omega^2\tau^2}}$$

$$= \frac{(\epsilon_s - \epsilon_\infty)\omega\tau}{\epsilon_\infty\omega^2\tau^2 + \epsilon_s} \quad (32)$$

Equations (29) and (31) are known as Debye equations and they describe the behaviour of polar dielectrics at various frequencies.

MATHEMATICAL DERIVATION OF THE RELAXATION TIME

Recall equation (31) and differentiating it with respect to $\omega\tau$ using quotient rule i.e.

$$\frac{d\epsilon''}{d\omega\tau} = \frac{(1+\omega^2\tau^2)(\epsilon_s - \epsilon_\infty) - (\epsilon_s - \epsilon_\infty)\omega\tau \cdot 2\omega\tau}{(1+\omega^2\tau^2)^2}$$

Simplifying the above expression gives

$$\begin{aligned} \frac{d\epsilon''}{d\omega\tau} &= (\epsilon_s - \epsilon_\infty) \left[\frac{1 + \tau^2\omega^2 - 2\omega^2\tau^2}{(1 + \omega^2\tau^2)^2} \right] \\ &= (\epsilon_s - \epsilon_\infty) \frac{(1 - \omega^2\tau^2)}{(1 + \omega^2\tau^2)^2} \end{aligned}$$

$$\frac{d\epsilon''}{d\omega\tau} = \frac{(\epsilon_s - \epsilon_\infty)(1 - \omega^2\tau^2)}{(1 + \omega^2\tau^2)^2} \quad (33)$$

According to Agilent [13] Basics of Measuring the Dielectric properties of materials, a material that has a single relaxation frequency as exhibited by the Debye relation will appear as a semicircle with its centre lying on the horizontal $\epsilon'' = 0$ axis and the peak of the loss factor occurring at $\frac{1}{\tau}$. Assuming that it is lying below the horizontal $\epsilon'' = 0$ axis and then equating equation (33) to zero.

$$\frac{d\epsilon''}{d\omega\tau} = \frac{(\epsilon_s - \epsilon_\infty)(1 - \omega^2\tau^2)}{(1 + \omega^2\tau^2)^2} = 0 \quad (34)$$

$$(\epsilon_s - \epsilon_\infty)(1 - \omega^2\tau^2) = 0 \quad (35)$$

In equation (35), if $(\epsilon_s - \epsilon_\infty) \neq 0$, then

$$(1 - \omega^2\tau^2) = 0 \quad (36)$$

Solving for $\omega\tau$ in equation (36), we have

$$\begin{aligned} \omega^2\tau^2 &= 1 \\ \Rightarrow \omega\tau &= 1 \end{aligned} \quad (37)$$

208 Recall

209
$$\omega = 2\pi f_r \quad (38)$$

210 Where f_r is the relaxation frequency. Now substituting equation (38) into
211 equation (37) and then solve for τ , we have

212
$$2\pi f_r \tau = 1$$

$$\tau = (2\pi f_r)^{-1} \quad (39)$$

213 The values of the complex and static permittivity of methanol used in this work
214 was adapted from National Physical Laboratory Report MAT 23 [14]. The
215 experimental data of both complex and static permittivity as adapted in [14]
216 were solved in the Debye relaxation equations (29) and (31) using Maple-13
217 and results were generated as shown in table 1 below:

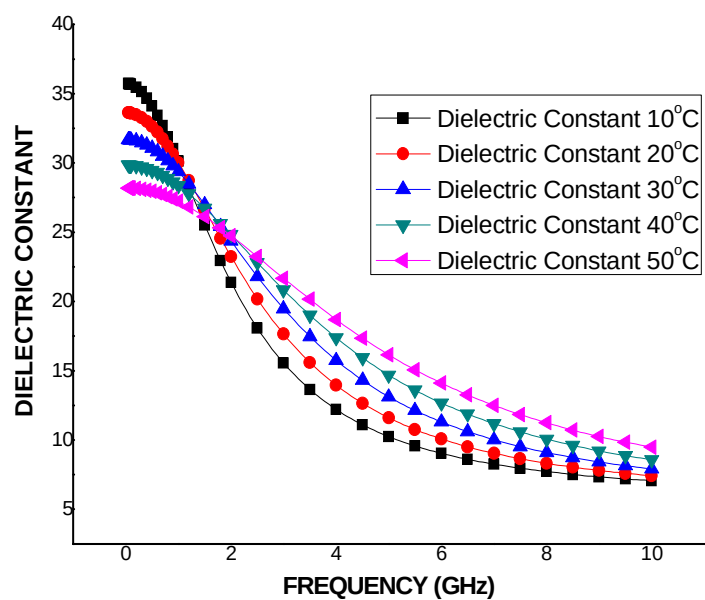
218 Table1: the static permittivity ϵ_s , complex permittivity ϵ_∞ and relaxation
219 frequency

Temperature °C	ϵ_s	ϵ_∞	f (GHz)
10	35.74	5.818	2.262
20	33.64	5.654	2.822
30	31.69	5.450	3.490
40	29.85	5.251	4.283
50	28.19	5.224	5.175

220 Source: NPL Report MAT, 2012 [14]

221 RESULTS AND DISCUSSION

222 The experimental data for static ϵ_s and complex ϵ_∞ permittivity substituted
223 in equations (29) and (31). An algorithm was written and maple-13 was used
224 to generate results for dielectric constant ϵ' and loss factor ϵ'' . The obtained
225 in this work were discussed based on the already existing theories. The effect
226 of the frequency for the dielectric constant and loss factor of methanol for
227 different temperatures are shown in the figure1 and figure2 below. The
228 results of our work are also used to plot Cole-Cole diagrams as shown in
229 figure 3a to figure 3e.



230

231 Figure1: **graph** of the dielectric constant of methanol against the frequency.
 232 The dielectric constant is higher at frequency 0.05GHz and temperature
 233 10°C. The dielectric constant then decrease as both frequency and
 234 temperature increases.

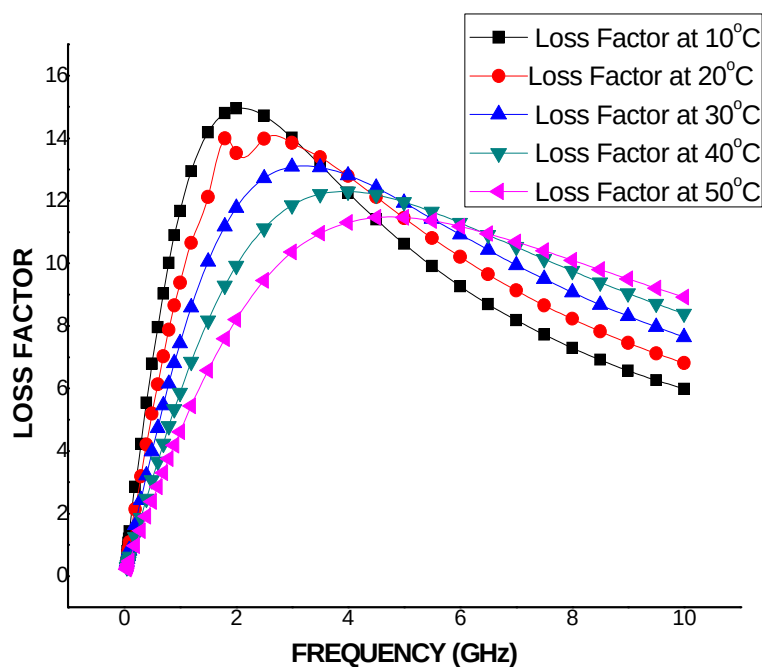
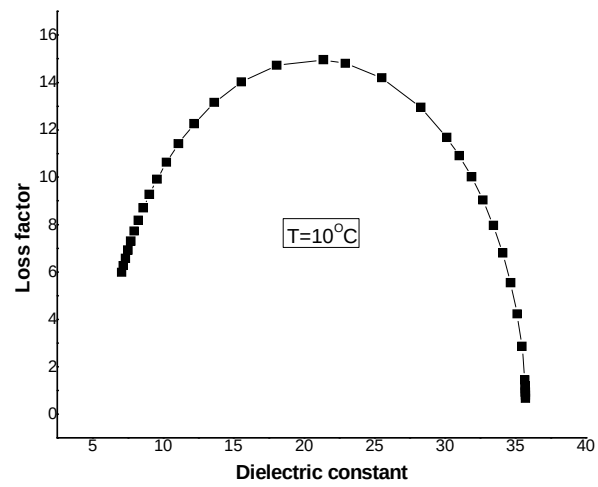
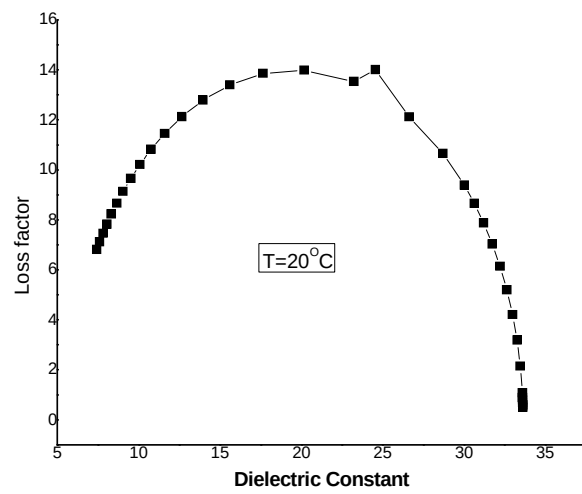


Figure2: graph of the loss factor against the frequency. The loss factor of methanol is small at low frequency (i.e. 0.66, 0.50, 0.46, 0.29 and 0.22) for temperature 10°C, 20°C, 30°C, 40°C, and 50°C respectively but as the frequency increases the loss factor also increases to a maximum value of 14.95, 14.00, 13.09, 12.30 and 11.45 respectively. The value however decreased to 5.97, 6.81, 7.64, 8.40 and 8.92 when the frequency increased to 10GHz after attaining its maximum.



246

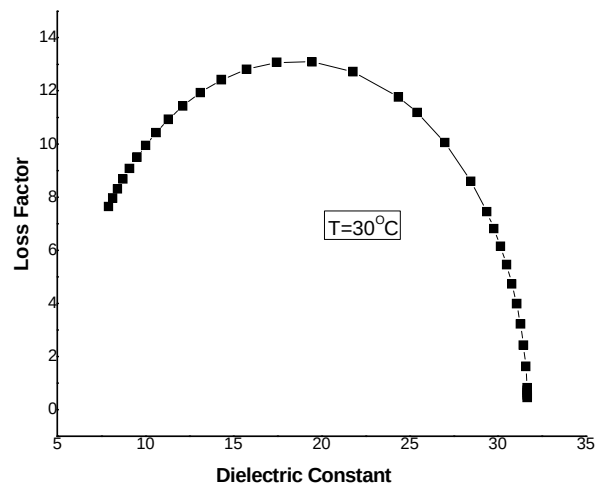
247 Figure 3a: A Cole-Cole plot at temperature 10°C



248

249

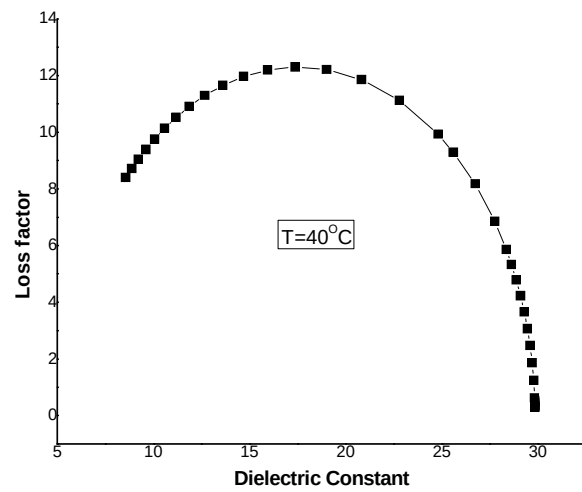
250 Figure 3b: A Cole-Cole plot at 20°C



251

252 Figure 3c: A Cole-Cole plot at 30°C

253



254

255 Figure 3d: A Cole-Cole plot at 40°C

256

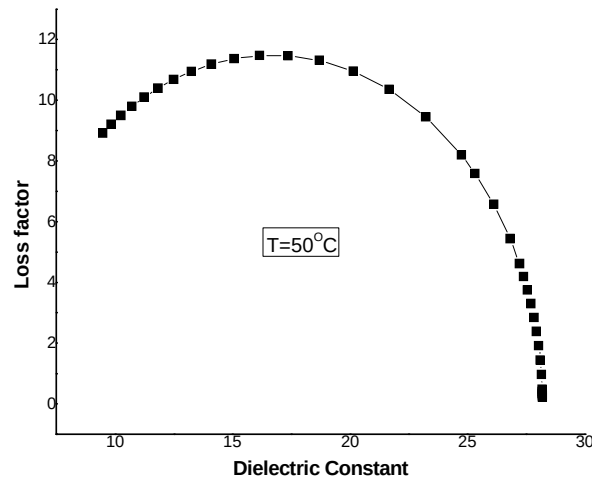


Figure 3e: A Cole-Cole plot at 50°C

Figure 3a to figure 3e shown in the above, are graphs of loss factor ϵ'' against the dielectric constant ϵ' known as Cole-Cole plot. The points on these graphs actually formed a semi-circle. However, there are some discrepancies in all the figures as shown in the above.

DISCUSSION

The dielectric constant ϵ' and the loss factor ϵ'' of methanol were fitted using the Debye relaxation model. The computation was done within the frequency range of 500MHz to 10GHz and temperature range of 10°C to 50°C. The parameters such as temperature and frequency were varied in order to ascertain which value of the frequency and temperature one can obtain the highest value of the dielectric constant. The graph of the dielectric constant ϵ' against the frequency and that of the loss factor ϵ'' against the frequency were then plotted. The results of the loss factor ϵ'' and dielectric constant ϵ' obtained in this work were used to plot Cole- Cole diagrams as shown in figure 3a to figure 3e above.

The Cole-Cole plots indeed formed a semi-circle which suggest that methanol exhibits Debye relaxation model. The discrepancies observed in our plots may just be due to distribution of relaxation times in methanol.

The dielectric constant of methanol was found to be higher at 0.05GHz and temperature 10°C (see fig.1). However, as both the frequency and

temperature increases beyond 0.05GHz and 10°C, the dielectric constant continue to decrease steadily until it reaches 1.0GHz. Beyond this frequency the dielectric constant of methanol decreases as the frequency increases. The dielectric constant however increased as the temperature increases at higher frequency values.

The higher value of the dielectric constant ϵ' at low frequencies as observed in figure1 above may be due to the overall conductivity which consists of different conduction mechanisms. The most prevalent one in moist materials is the ionic conductivity which varies inversely proportional to the frequency. The decrease in the dielectric constant as frequency increases 1.0GHz may be due to the fact that the dipoles cannot follow up the rapid variation of the applied field [15].

As the temperature increased beyond 10°C the dielectric constant decreases especially at the frequency range of $0.05 \leq f \leq 1.0GHz$. This decrease in the dielectric constant as the result of increase in the temperature may be due to the relaxation time which has been found to be fast at high temperature and increases dramatically at low temperatures. This suggest a freezing of electric dipoles at low temperature [16] and because of orientation polarization which depend on temperature and decreases with increase in temperature. This is because at higher temperature the thermal energy will increase which will try to disorient the dipoles. The results have shown a sudden increase in the dielectric constant as the temperature increased beyond 10°C between the frequency ranges of 1.2GHz to 10GHz. This increase in the dielectric constant as the result of an increase in the frequency may be due to the permanent electric dipoles possessed by methanol [15].

The loss factor on the other hand has a small value at frequency 0.05GHz and increases to reach its maximum value as the frequency increases. It then decreases steadily after attaining the maximum value (see figures 2 above). This behaviour exhibited by the loss factor may be due to the contribution from all the four types of polarization (i.e. space charge, dipole, ionic and electronic) [13]. But as temperature increases the loss factor decreases especially within the frequency range of 0.05GHz to 4.5GHz. This behaviour exhibited by methanol is contrary to the statement made by Guan et al [17] which said “Generally, the loss factor increases with increasing temperature at low frequencies due to ionic conductance and decreases with increasing temperature at high frequencies due to free water dispersion [18]”. However, beyond the 4.5GHz, the loss factor of

methanol increased as the temperature increase in line with what Guan and Wang said.

CONCLUSION

The dielectric constant of methanol has been optimized by varying the frequency and temperature. The computation was done using the Debye equation and its derivatives within the frequency range of $0.05 \leq f \leq 10\text{GHz}$. The results from our computation reveals that methanol has the highest dielectric constant at 0.05GHz at temperature 10°C. However, as both the frequency and temperature increases the dielectric constant decreases continuously except for values beyond 1.0GHz. At frequency 1.2GHz and above the dielectric constant value increased as the temperature increases. This suggests that the dielectric constant of methanol is easily polarizable at lower frequency and temperature.

The loss factor ϵ'' was also plotted against the dielectric constant ϵ' in order to decide which relaxation model methanol obeyed. The results showed that methanol at those temperatures fit in Debye relaxation model ($\alpha = 0$). This is because all Cole-Cole plots that are shown in figure 3a to figure 3e above formed a semi-circle.

REFERENCES

- [1]. Brown, W.R., Drown, D.P and Frenduto, F.S. (2000). Commercial-Scale Demonstration of the liquid phase methanol (LPMEOHTM) .process. <https://www.net/doe.gov/File%Library/.../Coal/major%/demonstrations/.../pdr.pdf>
- [2]. Eric de Place, Gruen, D and Powell, T. (2016). Fracked Fuel and Petrochemical Proposals in the Northwest. www.chemweek.com/lab/the-changing-face-of-methanol-demand-72206.html
- [3]. Deutschmann, O., Knozinger, H., Kochloefl, K., Turek, T. (2012). Heterogeneous Catalysis and solid catalysts, 3. Industrial Applications in Ullmann's Encyclopedia of industrial Chemistry, Wiley-VCH, Weinheim. doi:10.1002/14356007.o05.o03.
- [4]. Cadwell, J. (1661). Boyle discusses the distillation of liquids from the wood of the box shrub in: Robert Boyle, *The Skeptical Chemist*. London, England: 192-195.

- 347 [5]. National Institute for Occupational Safety and Health (22nd August,
348 2008). The Emergency Response Safety and Database: Methanol.
- 349 [6]. Blum, D. (2010). *The little story of how the U.S government poisoned*
350 *alcohol during prohibition*. Slate Magazine.
- 351 [7]. [http://www.methanol.org/Health-And-Safety/Safety-Resources/Health---safety/Methanex-](http://www.methanol.org/Health-And-Safety/Safety-Resources/Health---safety/Methanex-TISH-Guide.aspx)
352 [TISH-Guide.aspx](http://www.methanol.org/Health-And-Safety/Safety-Resources/Health---safety/Methanex-TISH-Guide.aspx)
- 353 [8]. Kamitani, A., Morishita, S., Kotaki, H & Arscott, S., (2008).
354 Miniaturized micromechanics and silicon microsystems techniques:
355 Performances at low fuel flow rates. Journal of Micromechanics and
356 Microengineering 18(12): 125019. [doi:10.1088/0960-1317/18/12/125019](https://doi.org/10.1088/0960-1317/18/12/125019)
- 357 [9]. Kamitani, A., Morishita, S., Kotaki, H & Arscott, S.,
358 (2011). Microfabricated microfluidic fuel cells. Sensors and Actuators B :
359 Chemical 154(2): 174. [doi:10.1016/j.snb.2009.11.014](https://doi.org/10.1016/j.snb.2009.11.014)
- 360 [10]. Berger, S. (2006). Methanol Laptop Fuel. Campus. Kiss.
- 361 [11]. Haldderman, J.D. and Martin, T. (2009). Hybrid and alternative fuel
362 vehicles. Pearson/Prentice Hall. [ISBN 978-0-13-504414-8](https://doi.org/10.1016/B978-0-13-504414-8).
- 363 [12]. Indycar.com (2005). IndyCar Series Teams Begin Use of Ethanol-
364 Blended Fuel.
- 365 [13]. Agilent (2006). Basics of Measuring the Dielectric Properties of
366 Materials. Application note.
367 Academy.cba.mit.edu/classes/input_devices/meas.pdf
- 368 [14]. Gregory, A.P and Clarke, R.N (2012). Tables of the Complex
369 Permittivity of Dielectric Reference Liquids at Frequencies up to 5GHz.
370 NPL REPORT MAT 23.
- 371 [15]. Onimisi, M.Y and Ikyumbur, T.J (2015b). Computation of Dielectric
372 constant and loss factor of water and dimethylsulphoxide from 0.1
373 to 13GHz. *Scientific Review*, 1(4): 79-85
- 374
- 375 [16]. Ahmad, M.M and Yamada, K (2007). Superionic PbSnF₄: A giant
376 dielectric constant material, *Appl. Phys. Lett.* 19(5): 052912-13.

- 377 [17]. Guan, D.M., Cheng, Y. Wang and Tang. J. (2004). Dielectric Properties
378 of Mashed Potatoes relevant to microwave and radiofrequency
379 Pasteurization and Sterilization Processes. *J. food Sci.* 69(1):30-37
- 380 [18]. Wang, Y.F., Wig, T.D., Tang, J.M & Hallberg, L.M (2003b). Dielectric
381 Properties of food related to RF and Microwave Pasteurization and
382 Sterilization. *J. of food Eng.* 57:257-268
- 383