

Original Research Article

**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 results revealed that the dielectric constants in megahertz are higher than those in gigahertz. The dielectric constant in both megahertz and gigahertz varies inversely proportional to the frequency within the frequency ranges of $0.05 \leq f \leq 1.0\text{GHz}$. It was also found that the dielectric constant of methanol increases as the temperature is increases within the frequency ranges of $1.2 \leq f \leq 10\text{GHz}$. 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

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

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

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

48 The solvent is primarily used as feedstock for the manufacture of
 49 chemicals and as a fuel for specialized vehicles. At about 40% of methanol is
 50 converted to formaldehyde and from there into products as diverse as plastics,
 51 plywood, paints, explosives, and permanent textiles [1]. Other chemical
 52 derivatives of methanol include dimethyl ether (DME), which has replaced
 53 chlorofluorocarbons as an aerosol spray propellant, and acetic acid. Dimethyl
 54 ether can be blended with liquefied petroleum gas (LPG) for home heating and
 55 cooking, and can be used as a replacement for transportation diesel fuel [12]. It
 56 is because of the increasing demand and the market value of methanol that the
 57 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 = $2\pi ft$. 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

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

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

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.

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

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

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

$$89 \quad I_x = V\omega \epsilon'' \frac{\epsilon_0 A}{d} = \frac{V\omega \epsilon_0 \epsilon'' A}{d} = A\omega \epsilon_0 \epsilon'' E \quad (5b)$$

90 where $E = \frac{V}{d}$

$$91 \quad J_x = \frac{I_x}{A} = \frac{A\omega \epsilon_0 \epsilon''}{A} \therefore J_x = \omega \epsilon_0 \epsilon'' E.$$

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

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

94 J_x = The current density

95 The alternating current conductivity is given by

$$96 \quad \sigma_{ac} = \sigma' + j\sigma'' = \omega \epsilon_0 [\epsilon'' + j(\epsilon' - \epsilon_\infty)] \quad (6)$$

97 The total conductivity is given by

$$98 \quad \sigma_T = \sigma_{ac} + \sigma_{dc} = \omega \epsilon_0 \epsilon'' + \sigma_{dc} \quad (7)$$

99 σ_{dc} is the direct current conductivity

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

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

$$111 \quad P(t) = P_\infty (1 - e^{-\frac{t}{\tau}}) \quad (8)$$

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

$$114 \quad \text{If } \omega = 2\pi ft, \quad \omega\tau = 2\pi ft$$

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

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

Expanding the right hand side of (8) yields

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

which upon dividing both sides by P_{∞} yields

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

Substitute equation (10) into (9) we obtained

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

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

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

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

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

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

The final value attained by the total polarization is

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

Under steady voltages;

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

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

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

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

$$P_{\mu} = \epsilon_0 E(\epsilon_s - \epsilon_{\infty}) \quad (16)$$

143 Representing the alternating electric field as

$$144 \quad E = E_{max} e^{j\omega t} \quad (17)$$

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

$$146 \quad \frac{dP(t)}{dt} = \frac{\epsilon_0(\epsilon_s - \epsilon_\infty)E - P(t)}{\tau} \quad (18)$$

147 Substituting (17) into (18); yields

$$148 \quad \frac{dP(t)}{dt} = \frac{1}{\tau} [\epsilon_0(\epsilon_s - \epsilon_\infty)E_{max} e^{j\omega t} - P(t)] \quad (19)$$

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

$$150 \quad P(t) = \frac{\epsilon_0(\epsilon_s - \epsilon_\infty)E_m e^{j\omega t}}{1 + j\omega\tau} + C e^{-t/\tau} \text{ or}$$

$$151 \quad P(t) = C e^{-t/\tau} + \epsilon_0 \frac{(\epsilon_s - \epsilon_\infty)E_m e^{j\omega t}}{1 + j\omega\tau} \quad (20)$$

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

$$155 \quad P(t) = \epsilon_0 \frac{(\epsilon_s - \epsilon_\infty)E_m e^{j\omega t}}{1 + j\omega\tau} \quad (21)$$

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

$$157 \quad P(t) = P_\mu(t) = \epsilon_0 \frac{(\epsilon_s - \epsilon_\infty)E_m e^{j\omega t}}{1 + j\omega\tau};$$

158 we have upon simplification

$$159 \quad (t) = \left[\epsilon_\infty - 1 + \frac{(\epsilon_s - \epsilon_\infty)}{1 + j\omega\tau} \right] \epsilon_0 E_m e^{j\omega t} \quad (22)$$

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

$$163 \quad D(t) = \epsilon_0 \epsilon^* E_m e^{j\omega t} \quad (23)$$

164 But flux density is also equal to

$$165 \quad D(t) = \epsilon_0 E_m e^{j\omega t} + P(t) \quad (24)$$

166 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),

$$\begin{aligned} \tan \delta = \frac{\varepsilon''}{\varepsilon'} &= \frac{\frac{(\varepsilon_s - \varepsilon_\infty)\omega\tau}{1 + \omega^2\tau^2}}{\varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + \omega^2\tau^2}} \\ &= \frac{(\varepsilon_s - \varepsilon_\infty)\omega\tau}{\varepsilon_\infty \omega^2\tau^2 + \varepsilon_s} \end{aligned} \quad (32)$$

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.

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

Simplifying the above expression gives

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

$$\frac{d\varepsilon''}{d\omega\tau} = \frac{(\varepsilon_s - \varepsilon_\infty)(1 - \omega^2\tau^2)}{(1 + \omega^2\tau^2)^2} \quad (33)$$

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 $\varepsilon'' = 0$ axis and the peak of the loss factor occurring at $\frac{1}{\tau}$. Assuming that it is lying below the horizontal $\varepsilon'' = 0$ axis and then equating equation (33) to zero.

$$\frac{d\varepsilon''}{d\omega\tau} = \frac{(\varepsilon_s - \varepsilon_\infty)(1 - \omega^2\tau^2)}{(1 + \omega^2\tau^2)^2} = 0 \quad (34)$$

$$(\varepsilon_s - \varepsilon_\infty)(1 - \omega^2\tau^2) = 0 \quad (35)$$

In equation (35), if $(\varepsilon_s - \varepsilon_\infty) \neq 0$, then

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

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

$$\omega^2\tau^2 = 1$$

$$\Rightarrow \omega\tau = 1 \quad (37)$$

Recall

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

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

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

$$207 \quad \tau = (2\pi f_r)^{-1} \quad (39)$$

208 The values of the complex and static permittivity of methanol used in this work
 209 was adapted from National Physical Laboratory Report MAT 23 [14]. The
 210 experimental data of both complex and static permittivity as adapted in [14]
 211 were solved in the Debye relaxation equations using Maple-13 and results were
 212 generated as shown in table 2 below:

213 Table1: the static permittivity ϵ_s , complex permittivity ϵ_∞ and relaxation
 214 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

215 Source: NPL Report MAT, 2012 [14]

216 RESULTS AND DISUSSIONS

217 Table2: the value of the dielectric constant ϵ' at difference temperatures and
 218 frequencies

F(GHz)	ϵ' at 10°C	ϵ' at 20°C	ϵ' at 30°C	ϵ' at 40°C	ϵ' at 50°C
0.05	35.7254	33.6312	31.6820	29.8466	28.1879
0.06	35.7190	33.6274	31.6785	29.8452	28.1869
0.07	35.7114	33.6228	31.6743	29.8434	28.1858

UNDER PEER REVIEW

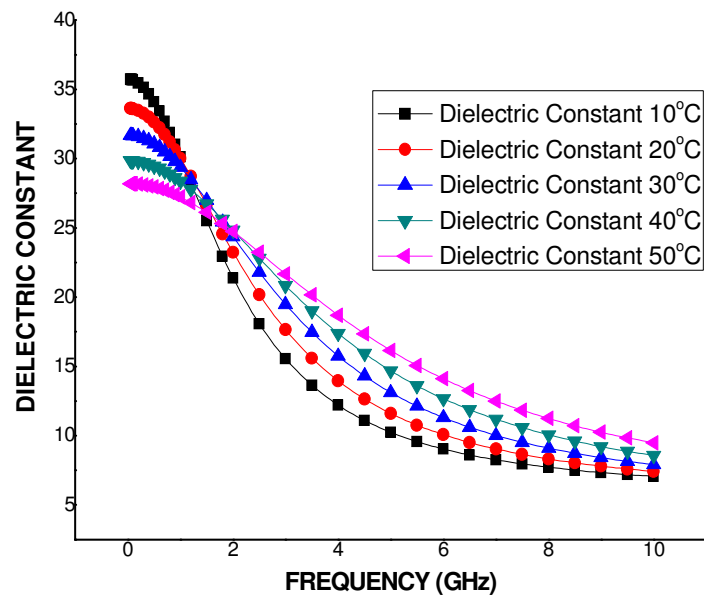
0.08	35.7026	33.6175	31.6695	29.8414	28.1845
0.09	35.6927	33.6116	31.6641	29.8391	28.1830
0.1	35.6712	33.5982	31.6646	29.8342	28.1798
0.2	35.4667	33.4752	31.5888	29.7869	28.1496
0.3	35.1320	33.2719	31.4633	29.7085	28.0993
0.4	34.6758	32.9923	31.2897	29.5996	28.0293
0.5	34.1099	32.6410	31.0698	29.4610	27.9399
0.6	33.4476	32.2237	30.8061	29.2937	27.8316
0.7	32.7038	31.7468	30.5014	29.0990	27.7050
0.8	31.8939	31.2174	30.1588	28.8782	27.5605
0.9	31.0329	30.6428	29.7816	28.6328	27.3991
1.0	30.1356	30.0305	29.3735	28.3645	27.2214
1.2	28.2841	28.7214	28.4790	27.7663	26.8206
1.5	25.5223	26.6461	26.9959	26.7423	26.1198
1.8	22.9485	24.5665	25.4237	25.6106	25.3227
2.0	21.3873	23.2298	24.3642	24.8195	24.7508
2.5	18.0791	20.1886	21.7970	22.8007	23.2337
3.0	15.5513	17.6514	19.4711	20.8356	21.6719

3.5	13.6444	15.5996	17.4528	19.0143	20.1488
4.0	12.2014	13.9604	15.7431	17.3798	18.6977
4.5	11.0981	12.6531	14.3125	15.9396	17.3647
5.0	10.2433	11.6061	13.1209	14.6878	16.1560
5.5	9.5719	10.7616	12.1284	13.6063	15.0723
6.0	9.0365	10.0747	11.2995	12.6745	14.1078
6.5	8.6048	9.5109	10.6041	11.8719	13.2508
7.0	8.2510	9.0439	10.0177	11.1797	12.4973
7.5	7.9608	8.6538	9.5203	10.5811	11.8295
8.0	7.7178	8.3252	9.0959	10.0619	11.2391
8.5	7.5132	8.0463	8.7317	9.6099	10.7165
9.0	7.3394	7.8077	8.4173	9.2149	10.2531
9.5	7.1906	7.6024	8.1444	8.8684	9.8413
10.0	7.0623	7.4244	7.9063	8.5632	9.4744

219 The dielectric constant of methanol shown in table 2 above showed that at
 220 temperature 10°C, the dielectric constant ϵ' is higher but decreases as the
 221 temperature increases beyond 10°C and within the frequency ranges of $0.05 \leq$
 222 $f \leq 1GHz$. However, at frequency 1.2GHz and beyond the dielectric constant
 223 increases as the temperature increased (see table 2 above).

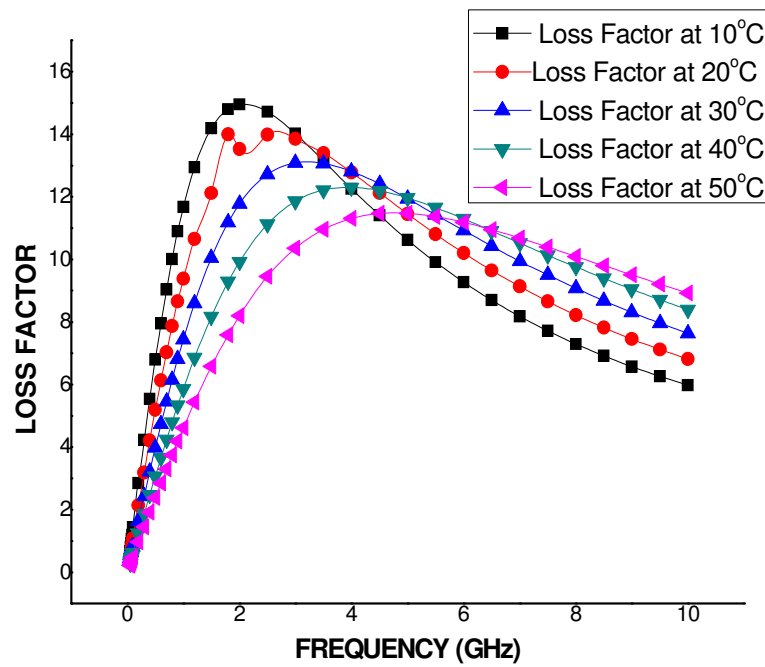
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226

227 Figure1: is graph of the dielectric constant of methanol against the frequency



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Figure2: is the 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.

DISCUSSIONS

The dielectric constant of methanol was fitted using the Debye relaxation method. The computation was done within the frequency range of 500MHz to 10GHz and temperature range of 10°C to 50°C. This variation in the frequency and temperature were made in order to ascertain which value of the frequency and temperature one can obtain the highest value of the dielectric constant. The results from our computation revealed that methanol has its highest value of the dielectric constant at frequency 0.05GHz and temperature 10°C. However, as the frequency increased 1.0GHz and temperature increases beyond 10°C the dielectric constant decreased. This decreased in the dielectric constant as both frequency and temperature increased was not the same at higher value of the frequency (i.e. 1.2GHz and beyond). This suggested that the dielectric constant is smaller at higher frequencies and increased as the temperature increases beyond 10°C.

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 decreased in the dielectric constant as the result of increased 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, suggesting 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 frequencies 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 possess 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 revealed 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.

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