



The Dielectric Study of Ethylene Glycol as a Coolant Using Davidson- Cole Relaxation Model

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Authors' contributions

This work was carried out in collaboration between all authors. Author TJI designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Author FG and SA managed the analyses of the study. Author SAO managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

In this work, the dielectric properties of ethylene glycol as an additive to heat transfer fluid is studied. To do this, the Davidson-Cole relaxation equations were derived from Debye equation. The static permittivity (ϵ_s), complex permittivity (ϵ_ω) and the relaxation time (τ) of ethylene glycol were substituted in the derived equations. The dielectric constant (ϵ') and loss factor (ϵ'') of ethylene glycol were computed using Microsoft Excel. The result showed that the dielectric constant is higher at lower frequencies (i.e. 44.30 at 0.01 GHz and 10°C) but decreases as the temperature increases. However, at high frequency, the dielectric constant increases as the temperature increases. The loss factor also decreases as temperature increases but increases to its maximum value as the frequency increases. It then decreases steadily after attaining its maximum value at further increase in the frequency. The decrease in the loss factor as the temperature increases showed that ethylene glycol does not generate so much heat when subjected to an applied field. The higher dielectric constant at lower frequencies, on the other hand, suggest that ethylene glycol as a coolant can perform optimally at those frequencies.

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1. INTRODUCTION

Heat transfer fluids (HTFs) are gases or liquids specifically manufactured for the purpose of transmitting heat from one system to another. These fluids also called thermal fluids offer thermal stability at elevated temperatures. The most common examples are water, brine, alcohol, oil, propylene glycol, ethylene glycol etc. Water has been the most common one used by motorists because it is inexpensive and provides the best heat transfer properties. However, it is limited by its temperature range and that is why a mixture of water and ethylene glycol which has an efficient freezing point dispersant and a high boiling point is required.

Ethylene glycol also called ethanediol lowers the freezing point of water, and this protects the car block engine from cracking caused by the expansion of freezing water in the car's cooling system. In most cars, adding water only to the radiator will only prevent the car from overheating (assuming the rest of the cooling system is operating properly). However, when ethylene glycol is mixed with water, it will actually raise the boiling point of water to above 212°F or 100°C [1]. The use of pure ethylene glycol in the car can also serve as anti-corrosion additive (that is, it can help keep the radiator, water pump, heater core etc. from corroding as quickly as they would without the anti-corrosion components) [1].

Ethylene glycol, apart from providing boil-over and freeze protection, it controls, the corrosive action of water on commonly used radiator and engine metals, including aluminium and prevents loss of coolant and cooling efficiency due to foam and boil-over. Diethylene glycol and propylene glycol can also be used as antifreeze/coolants but they are more likely to be mixed with ethylene glycol. Their addition is usually restricted to a small percentage of the total glycol content.

Marine diesel engine specialists observed that the most frequent source of premature engine failure is the cooling system [1]. Improper coolants and inadequate cooling system maintenance can result not only in the catastrophic of overheating but also in corrosion damage and even vessel flooding. This is because most of the cooling system is inside the engine and difficult to observe. Damage can

occur gradually over time, essentially rotting the core of an otherwise hearty diesel [1].

Recognizing these properties associated with ethylene glycol, many authors have devoted their time to study the dielectric properties of the mixtures of this substance with other polar molecules under varying compositions because it helps in formulating adequate models of liquid relaxation and also obtaining information about the relaxation process in the mixture [2-4]. These dielectric relaxation studies confirmed that the relaxation time of the system had a linear behaviour with the mole fractions of water in the mixture. It was also concluded that ethylene glycol (EG) molecules and surrounding water molecules formed EG-water clusters via hydrogen bonds and the nature of homogeneous and heterogeneous clusters changed with the water concentration in the binary mixture.

Several attempts are made to study the dielectric behaviour of various homologous series of alcohol mixtures with water and other polar solvents [5-7]. At room temperature, only one relaxation peak is observed for alcohol-water mixtures in the frequency range from 10 MHz to 20 GHz. The dielectric relaxation process of these systems is described by a sum of the Debye equation [8] and the Cole-Cole equation [9,10,11]. Though alcohol is the most popular material employed to study the hydrogen-bonding molecular liquids, it has been investigated systematically for only a few different alcohols. Experimental results of these binary systems are interpreted on the basis of a model of three kinds of cooperative domains coexisting.

The temperature dependent dielectric relaxation mixture of ethylene glycol and water has been investigated [12] and their results for the mixtures showed a Debye-type behaviour while that of pure ethylene glycol described the Cole-Cole. In this work, the behaviour of pure ethylene glycol at different temperatures and frequencies is studied using Davidson-Cole relaxation model.

2. MATHEMATICAL DERIVATION OF DEBYE EQUATIONS

Let us consider a capacitor that consists of two plane parallel electrodes in a vacuum having an applied alternating voltage as:

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

Let us also assume that the current passing through the capacitor is given by:

$$i_1 = I_m (\cos \omega t + \frac{\pi}{2}) \quad (2)$$

In an ideal dielectric the current leads the voltage by 90° and if a material of dielectric constant ϵ' is placed between the plates the capacitance increases to $\epsilon_0 \epsilon'$ and the current is given by:

$$i_2 = I_m \left[\cos \omega t + \left(\frac{\pi}{2} \right) - \gamma \right] \quad (3)$$

The dielectric constant is a complex quantity and it is represented by:

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

2.1 Polarization Build Up

When a dc voltage is applied to a polar dielectric, then, the polarization builds from zero to the final value. Referring to the exponential law, we can write our polarization as a function of time as:

$$P(t) = P_\infty (1 - e^{-t/\tau}) \quad (5)$$

Differentiating equation (5) with respect to time t using the product rule, we obtain:

$$\frac{dP(t)}{dt} = -\frac{1}{\tau} P_\infty = \frac{P_\infty e^{-t/\tau}}{\tau} \quad (6)$$

Expanding the right-hand side of equation (5) gives

$$P_\infty e^{-t/\tau} = P_\infty - P(t) \quad (7)$$

Dividing both sides of (7) by P_∞ , we have

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

Substituting equation (8) into equation (6), we obtain

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

We can now express our total polarization as:

$$P_T(t) = P_a(t) + P_e \quad (10)$$

The final value attained by the total polarization is given by:

$$P_T(t) = \epsilon_0 (\epsilon_s - 1) E \quad (11)$$

$$P_e(t) = \epsilon_0 (\epsilon_\infty - 1) E \quad (12)$$

Where ϵ_0 and ϵ_∞ are the dielectric constant under direct voltage and at infinity frequency respectively

ϵ_∞ is defined in Maxwell's relation as:

$$\epsilon_\infty = n^2 \quad (13)$$

Substituting equations (11) and (12) into (10), we have

$$P_a(t) = \epsilon_0 \epsilon_s E - \epsilon_0 \epsilon_\infty E = \epsilon_0 (\epsilon_s - \epsilon_\infty) E \quad (14)$$

Representing the alternating electric field as:

$$E = E_{max} e^{j\omega t} \quad (15)$$

Substituting equation (14) into equation (9) we obtain

$$\frac{dP(t)}{dt} = \frac{1}{\tau} [E (\epsilon_s - \epsilon_\infty) \epsilon_0 - P(t)] \quad (16)$$

Again substituting equation (15) into equation (16), we have

$$\frac{dP(t)}{dt} = \frac{1}{\tau} [E_{max} e^{j\omega t} (\epsilon_s - \epsilon_\infty) \epsilon_0 - P(t)] \quad (17)$$

Adding on both sides of the expression $\frac{1}{\tau} P(t)$ and solving the resulting equation, we obtained

$$(\epsilon' - j\epsilon'') = 1 + \left[\epsilon_\infty - 1 + \frac{(\epsilon_s - \epsilon_\infty)}{(1 + j\omega\tau)} \right] \quad (18)$$

Equation (18) can be written into the real and the imaginary parts of the Debye equations as follows:

$$\epsilon' = \epsilon_\infty + \frac{(\epsilon_s - \epsilon_\infty)}{(1 + \omega^2 \tau^2)} \quad (19)$$

And

$$\epsilon'' = \frac{(\epsilon_s - \epsilon_\infty) \omega \tau}{(1 + \omega^2 \tau^2)} \quad (20)$$

Details of the above derivations are shown in [11-12]

3. DAVIDSON-COLE RELAXATION EQUATIONS

The Davidson-Cole relaxation equation is derived from Debye equation i.e.

$$j\epsilon'' = \epsilon' - \epsilon_\infty - \frac{(\epsilon_s - \epsilon_\infty)}{(1 + j\omega\tau)} \quad (21)$$

The relaxation time, τ in equation (21) has been replaced with Davidson-Cole relaxation parameter, τ_{d-c} and equation (21) can be express as follows:

$$j\varepsilon'' = \varepsilon' - \varepsilon_\infty - \frac{(\varepsilon_s - \varepsilon_\infty)}{(1 + j\omega\tau_{d-c})} \quad (22)$$

Or

$$-\varepsilon' + j\varepsilon'' = -\varepsilon_\infty - \frac{(\varepsilon_s - \varepsilon_\infty)}{(1 + j\omega\tau_{d-c})} \quad (23)$$

So that

$$\varepsilon' + j\varepsilon'' = \varepsilon_\infty + \frac{(\varepsilon_s - \varepsilon_\infty)}{(1 + j\omega\tau_{d-c})} \quad (24)$$

Now, left-hand side of (24) can be written in term of complex quantity as $\varepsilon^* = \varepsilon' + j\varepsilon''$, so that equation (24) reduces to

$$\varepsilon^* = \varepsilon_\infty + \frac{(\varepsilon_s - \varepsilon_\infty)}{(1 + j\omega\tau_{d-c})} \quad (25)$$

The empirical equation for the complex dielectric constant of Davidson-Cole is written as thus:

$$\varepsilon^* = \varepsilon_\infty + \frac{(\varepsilon_s - \varepsilon_\infty)}{(1 + j\omega\tau_{d-c})^\beta} \quad (26)$$

Therefore, equation (26) is the Davidson-Cole relaxation equation, where, β is a constant characteristic of the material and takes the value from, $0 \leq \beta \leq 1$.

Thus, equation (26) is the Davidson-Cole relaxation equation. The real and imaginary parts are the above equation can, therefore, be expressed respectively as:

$$\varepsilon' = \varepsilon_\infty + (\varepsilon_s - \varepsilon_\infty)(\cos\phi)^\beta \cos\phi\beta \quad (27)$$

And

$$\varepsilon'' = (\varepsilon_s - \varepsilon_\infty)(\cos\phi)^\beta \sin\phi\beta \quad (28)$$

The Davidson-Cole parameters of ethylene glycol were adapted in National Physical Laboratory (MAT-23) [13] and a Microsoft Excel was used to generate results for dielectric constant ε' and loss factor ε'' . The results obtained using equations (27) and (28) are shown in the Tables below:

Table 1. The dielectric constant and loss factor of ethanediol at temperatures 10°C and 20°C

F (GHz)	10°C		20°C	
	ε'	ε''	ε'	ε''
0.01	44.30	0.55	41.89	0.33
0.02	44.28	1.10	41.88	0.52
0.03	44.23	1.66	41.89	0.70
0.04	44.18	2.20	41.83	1.04
0.05	44.10	2.75	41.80	1.39
0.06	44.01	3.29	41.76	1.74
0.07	43.90	3.82	41.72	2.08
0.08	43.78	4.36	41.67	2.42
0.09	43.64	4.88	41.61	2.77
0.1	43.49	5.40	41.54	3.11
0.2	41.24	10.09	40.53	3.45
0.4	34.63	16.06	37.07	6.68
0.6	28.16	18.14	32.74	11.92
0.8	23.13	18.13	28.51	15.21
1	19.47	17.29	24.83	16.81
1.2	16.81	16.20	21.80	17.30
1.4	14.85	15.10	19.36	17.14
1.6	13.38	14.07	17.40	16.63
1.8	12.24	13.14	15.82	15.97
2	11.34	12.30	14.53	15.24
2.5	9.77	10.60	12.21	14.52
3	8.77	9.31	10.70	12.86
3.5	8.09	8.31	9.66	11.47
4	7.60	7.51	8.91	10.32
4.5	7.22	6.86	8.35	9.38
5	6.93	6.31	7.92	8.59

The dielectric constant ε' and the loss factor ε'' for temperatures 10°C and 20°C is presented in the Table 1. The above table showed that the dielectric constant ε' is higher at low frequency (i.e. 44.30 at 0.01GHz and 10°C) and the loss factor ε'' is small at the same frequency and temperature (i.e. 0.55). The dielectric constant decreases as both frequency and temperature increases within the frequency range of 0.01GHz to 0.2GHz. However, at higher frequency range of 0.4GHz to 5.0GHz the dielectric constant increase as temperature increases

Table 2. The dielectric constant and loss factor of ethanediol at temperatures 30°C, 40°C and 50°C

F(GHz)	30°C		40°C		50°C	
	ϵ'	ϵ''	ϵ'	ϵ''	ϵ'	ϵ''
0.01	39.66	0.21	37.63	0.14	35.71	0.09
0.02	39.65	0.42	37.63	0.27	35.71	0.19
0.03	39.65	0.62	37.62	0.41	35.71	0.28
0.04	39.64	0.83	37.62	0.55	35.71	0.37
0.05	39.63	1.04	37.61	0.68	35.70	0.47
0.06	39.61	1.25	37.61	0.82	35.70	0.56
0.07	39.59	1.46	37.60	0.96	35.70	0.66
0.08	39.57	1.66	37.59	1.09	35.69	0.75
0.09	39.55	1.87	37.58	1.23	35.69	0.84
0.1	39.53	2.07	37.57	1.37	35.68	0.94
0.2	39.13	4.10	37.39	2.72	35.59	1.87
0.4	37.66	7.81	36.68	5.30	35.23	3.68
0.6	35.49	10.86	35.58	7.66	34.66	5.41
0.8	32.95	13.15	34.18	9.70	33.90	7.02
1	30.32	14.72	32.58	11.39	32.98	8.47
1.2	27.77	15.69	30.86	12.74	31.94	9.75
1.4	25.42	16.19	29.12	13.77	30.82	10.86
1.6	23.31	16.36	27.42	14.51	29.65	11.80
1.8	21.45	16.28	25.78	15.01	28.46	12.58
2	19.83	16.05	24.25	15.31	27.27	13.20
2.5	16.63	15.12	20.90	15.44	24.43	14.19
3	14.36	14.03	18.24	15.04	21.89	14.57
3.5	12.71	12.97	16.16	14.40	19.70	14.55
4	11.49	12.00	14.52	13.67	17.85	14.29
4.5	10.55	11.14	13.22	12.94	16.30	13.88
5	9.82	10.39	12.18	12.24	15.00	13.41

The dielectric constant ϵ' and the loss factor ϵ'' for temperatures 30°C, 40°C and 50°C is presented in the Table2 above. The above table showed that the dielectric constant ϵ' is higher at low frequency (i.e. 39.66 at 0.01GHz and 50°C) and the loss factor ϵ'' is small at the same frequency and temperature (i.e. 0.21). The dielectric constant decreases as both frequency and temperature increases within the frequency range of 0.01GHz to 0.6 GHz. However, at higher frequency range of 0.8 GHz to 5.0 GHz the dielectric constant increase as temperature increases

4. DISCUSSION

The behaviour of the dielectric constant ϵ' and the loss factor ϵ'' of ethylene glycol are discussed below in term of changes in frequency and temperature as shown in the Figs. 1,2.

The behaviour of ethylene glycol in an alternating field has been studied using Davidson-Cole relaxation model. The results revealed that the dielectric constant of ethylene glycol is higher at low frequencies and temperatures. The dielectric constant, however, decreases as both frequency and temperature increases see Fig. 1. The higher dielectric constant at low frequencies and temperatures is due to the contribution from the four types of polarizations (i.e. orientation, electronic, ionic and space charge) to the ethylene glycol that makes it a good anti-corrosion. The decrease in the dielectric constant of ethylene glycol as the frequency increase is

due to the fact that at higher frequencies only ionic and electronic polarizations contribute [14]. The decrease in the dielectric constant when the temperature increase may be due to the fact that the orientation polarization varies inversely proportional to the temperature [15] or because of 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 temperatures [16].

The loss factor, on the other hand, has a small value at low frequency and increases to reach its maximum value as the frequency increases. It then continues to decrease after attaining the maximum value (see Fig. 2). This behaviour exhibited by the loss factor may be due to the contribution from all the four types of polarization [17-19].

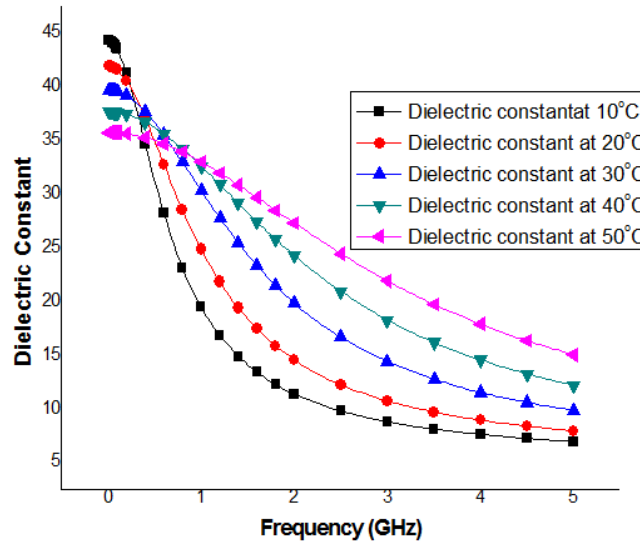


Fig. 1. The dielectric constant at different temperatures against the frequency

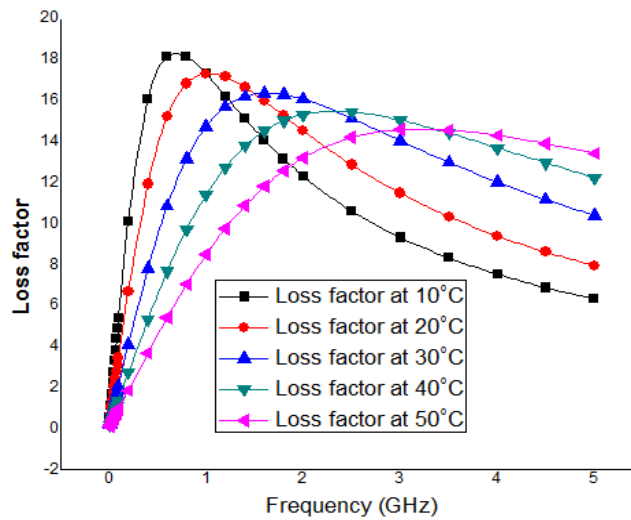


Fig. 2. The loss factor of ethylene glycol at different temperatures against the frequency

5. CONCLUSION

The dielectric constant and loss factor of ethylene glycol has been computed using Davidson-Cole relaxation model. The result from our computation showed that ethylene glycol has higher dielectric constant and small loss factor at low frequencies and temperatures. This higher dielectric constant at low frequencies and temperatures may be the reason why ethylene glycol is a good anti-corrosion. The small value of the loss factor at those frequencies and temperatures as shown in Fig. 2 simply mean ethylene glycol does not generate too much heat when subjected to the alternating field.

In Fig. 2 above, it can be concluded that the loss factor decreases continuously after attaining its maximum value. This behaviour exhibited by ethylene glycol showed that even as the frequency and temperature become very high ethylene glycol does not produce too much heat. This may be the reason why ethylene glycol increased the boiling point of water when mixed.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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