The Tony Davies High Voltage Laboratory

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School of Electronics and Computer Science

Electrode Polarization of Mineral Oil

Yuan Zhou
George Chen
Electronic and Electrical Engineering
University of Southampton
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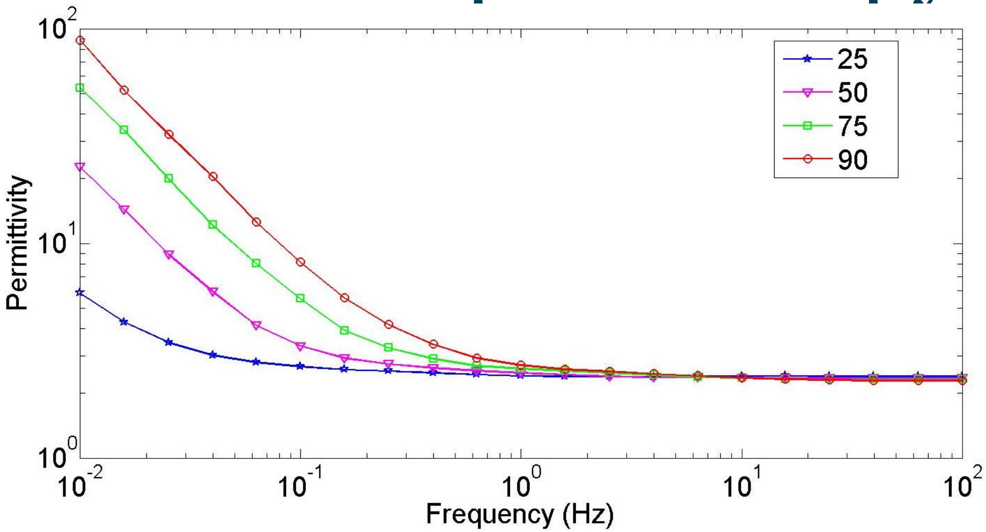
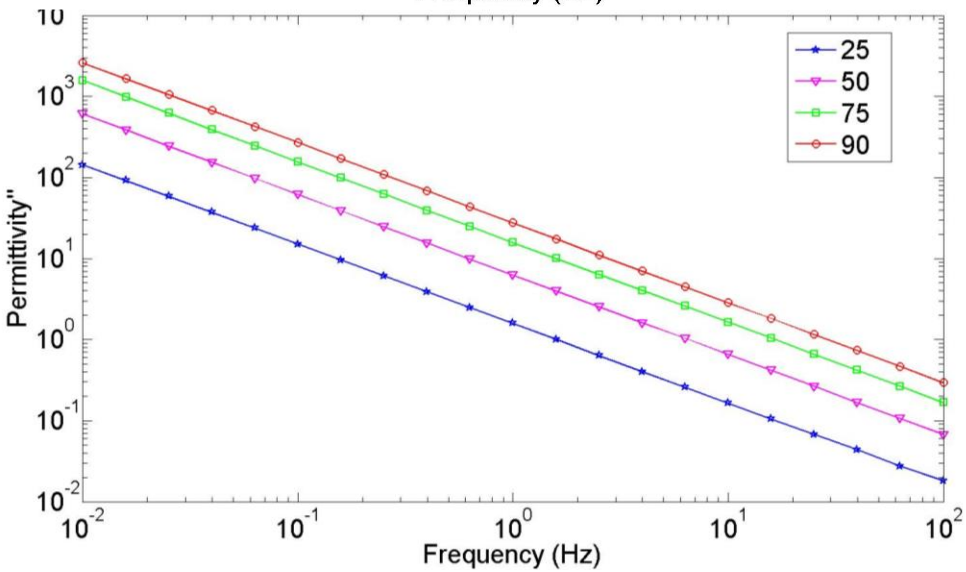
Dielectric Spectroscopy Measurement





As observed from loads of experimental result, the frequency response of mineral oil share the same character.

Real part of permittivity is constant at medium frequency(1Hz-100Hz), and increase at low frequency.

Imaginary part of permittivity have an approximately linear relationship with frequency.

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Details of Measurement

There are three different types of oil going to be tested.

- Shell Diala S3 ZX-I (fresh oil)
- Terna (aging time over 50 years)
- Hydro Quebec (aging time around 10 years)

Frequency range: 0.01Hz-100Hz

Temperature: 25°C, 50°C, 75°C, 90°C

Electric potential: 1V

Distance between two electrodes: 0.5mm

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Electrode Polarization

Since the charge around the electrode can attract opposite charge in the electrode by electrical force, the permittivity and conductivity of mineral oil will be affected by this extra current. As the frequency goes low, more charge carriers will accumulate in that area and result in a serious field distortion in the vicinity of the electrode. This parasite polarization can result in extremely high values of real part of the complex permittivity, therefore, if the real part of permittivity increases strongly with the decrease of frequency, this is a clear sign of electrode effect.

Drift of Ions in Low Frequency Range

The Since the electric field changes with the time under AC field, it would be necessary to analyse the movement of charge carriers in an alternative field. The electrical force due to the electric field can be written as

$$F(t) = qE\sin(\omega t)$$

According to Stokes' law, the friction force cause by the viscosity can be described as:

$$F'(t) = 6\pi\eta rv$$

a drift equation under AC field can be obtained as

$$F(t) - F'(t) = m\frac{dv}{dt}$$

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Drift of Ions in Low Frequency Range

With a boundary condition that v=0 at t=0, the velocity of ions with respect to time can be solved as

$$v(t)=\frac{k_1k_2\sin(\omega t)}{k_1^2+\omega^2}-\frac{k_2\omega\cos(\omega t)}{k_1^2+\omega^2}+\frac{k_2\omega}{k_1^2+\omega^2}e^{-k_1t}$$

with

$$\begin{cases} k_1=6\pi\eta r/m \\ k_2=Eq/m \end{cases}$$

when frequency is below 100Hz, the above equation can be simplified as

$$v=\frac{Eq}{6\pi\eta r}\sin\left(\omega t\right)$$

Basic Theory

This frequency-domain problem can be simplified by being restricted to one dimensional case with the transportation of charge carriers in x direction.

The internal electric field is governed by Poisson equation:

$$\nabla \bullet E = \frac{\rho}{\varepsilon_0 \varepsilon_r}$$

The drift and diffusion of charge carriers can be denoted as:

$$\begin{cases} J_+(x,t) = q\mu_+ n_+(x,t)E(x,t) - qD_+ \dfrac{dn_+(x,t)}{dx} \\ J_-(x,t) = q\mu_- n_-(x,t)E(x,t) - qD_- \dfrac{dn_-(x,t)}{dx} \end{cases}$$

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Basic Theory

Since mineral oil can be treated as weak electrolyte, ionic dissociation and recombination should also be taken into consideration:

$$\begin{cases} \dfrac{dn_+(x,t)}{dx} = K_R n^2 - K_R n_+(x,t) \times n\_(x,t) \\ \dfrac{dn\_(x,t)}{dx} = K_R n^2 - K_R n_+(x,t) \times n\_(x,t) \end{cases}$$

The charge induced in x=0 can be written as:

$$Q(t) = \frac{q}{d} \int_0^d x\left[(n_+(x,t) - n\_(x,t)\right] dx$$

Basic Theory

When the external voltage applied to the electrodes is a sine voltage, the relative complex permittivity can be denoted as:

$$\begin{cases} \varepsilon''(\omega) = \dfrac{2I_{real}}{\varepsilon_0 \omega E S} \\ \varepsilon'(\omega) = \dfrac{2I_{imag}}{\varepsilon_0 \omega E S} \end{cases}$$

with

$$\begin{cases} I_{real} = \dfrac{1}{T}\displaystyle\int_0^T \dfrac{dQ(t)}{dt} S \sin(\omega t)dt \\ I_{imag} = \dfrac{1}{T}\displaystyle\int_0^T \dfrac{dQ(t)}{dt} S \cos(\omega t)dt \end{cases}$$

Two Types of Charge Carrier

There are many different types of charge carriers in mineral oil. We will assume there are two main types of charge carrier, one moves slow and can be blocked by the electrode and the other one moves fast and can get through the electrode. Here, the ratio of the slow charge carriers contributes to the total conductivity can be defined as:

$$\alpha = \frac{\sigma_s}{\sigma} \qquad (\sigma_s + \sigma_f = \sigma)$$

If the conductivity is constant and there are only one type of charge carrier in mineral oil, a higher mobility will result in a smaller quantity. For simplicity, we assume the field distortion are mainly caused by the slow charge carriers.

Modified Theory

With the above two assumption, the classical drift and diffusion theory can be simply modified.

$n_+(x,t)$ and $n_-(x,t)$ stand for the density of positive and negative of the slow charge carriers in space and time.

Since the fast charge carriers do not affect the field distribution notably, the current caused by these ions has a linear relationship with the electric potential, then the equation of complex permittivity can be rewritten as:

$$\begin{cases} \varepsilon''(\omega) = \dfrac{2I_{real}}{\varepsilon_0 \omega E S} + (1-\alpha)\dfrac{\sigma}{\omega \varepsilon_0} \\ \varepsilon'(\omega) = \dfrac{2I_{imag}}{\varepsilon_0 \omega E S} + \varepsilon_{100Hz} \end{cases}$$

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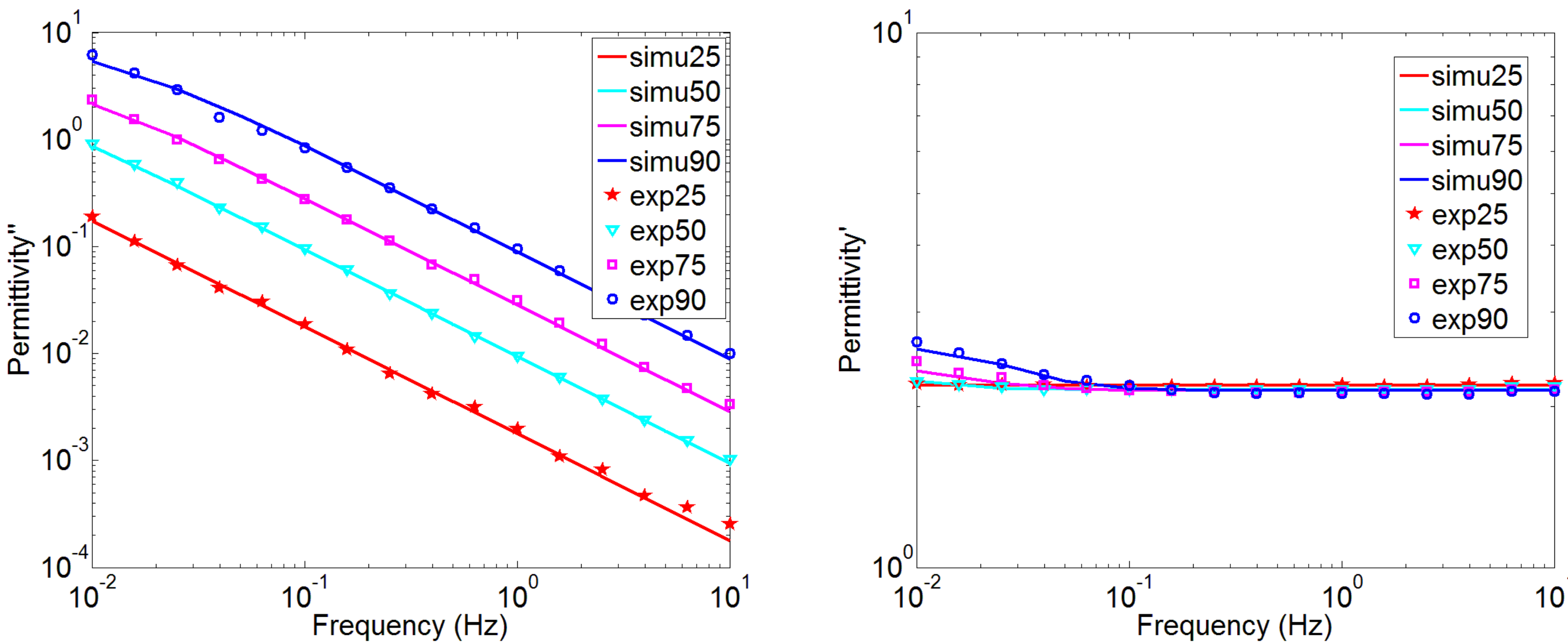
Simulation Result of Shell ZX-I Oil



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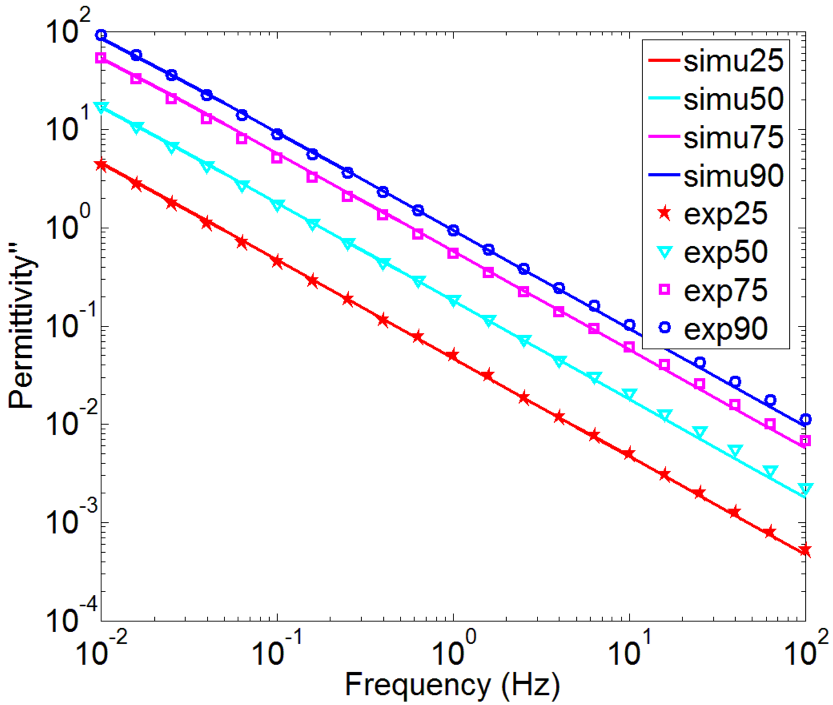
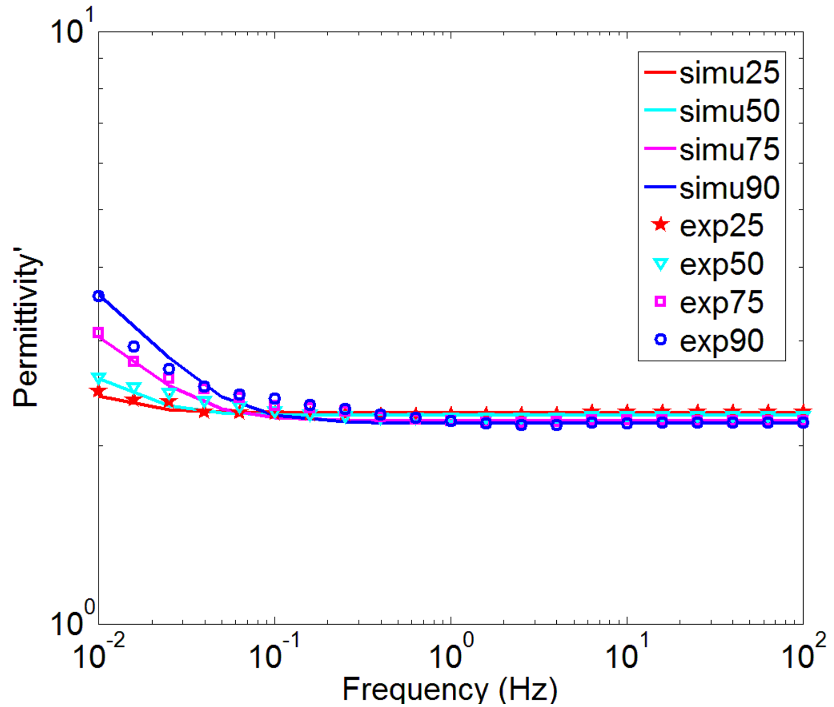
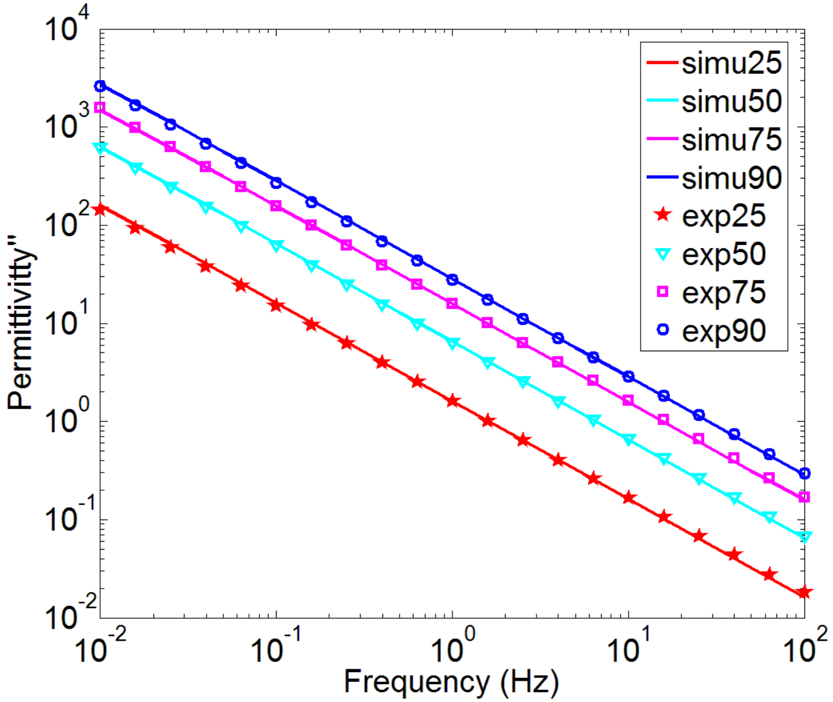
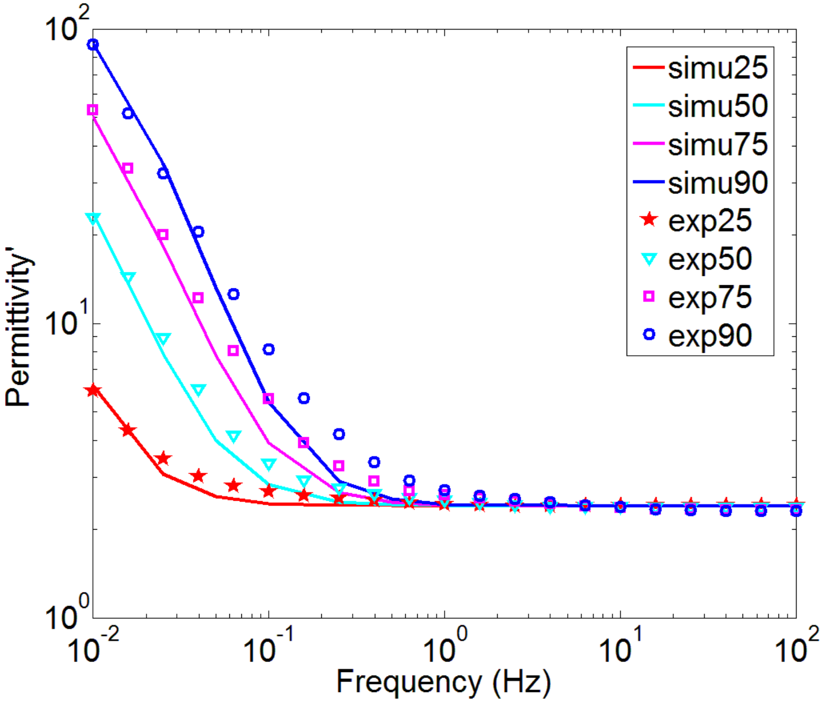
Simulation Result of Hydro Quebec Oil





Simulation Result of Terna Oil





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Simulation Result

As seen from the above simulation result, this modified model can fit the experimental data quite good. However, the feature of the fast charge carrier is still unknown, thus, this model can not provide a perfect fit. More research is still needed.

Observed from the table, the ratio for the blocked charge carriers also change with the aging time and temperature.

	25℃	50℃	75℃	90℃
Shell ZX-I	≈1	≈1	≈1	≈1
Hydro Quebec	0.65	0.28	0.20	0.21
Terna	0.16	0.12	0.10	0.10

α For different types of mineral oil

Conclusion

- There are at least two types of charge carriers in the mineral oil. One can be blocked by the electrode, while the other one can pass the electrode.
- Ionic drift and diffusion theory can be used to modelling the frequency response of mineral oil.
- The ratio of charge carriers that can be blocked by the electrode varies with the aging time of mineral oil and temperature.

Thanks