

A quantified analysis of the dielectric dispersion in a simple emulsion system

Robert M. Hill

Monymusk, Horsell Rise, Woking, Surrey GU21 4BD, UK

Received 30 January 2001; received in revised form 20 April 2001; accepted 21 April 2001

Abstract

The dielectric response of a simple, self emulsifying, system, based on a polysorbate and a medium chain length triglyceride, has been investigated as a function of the water content in the range 0 to 80% by weight. The low frequency capacitive dispersions have been characterised in terms of an electrode barrier layer dispersion, and the bulk conductance and capacitance have been quantified. It is shown that the barrier parameters are essentially insensitive to the water content, over concentrations from 2.5 to 75% by weight, and that the magnitude of the bulk emulsion conductance determines the form of the dispersions which can be observed. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Dielectric dispersion; Emulsion; Self emulsifying system

“All mathematical sciences are founded on relations between physical laws and laws of numbers, so that the aim of exact science is to reduce the problems of nature to the determination of quantities by operations with numbers”.

James Clerk Maxwell, ‘On Faraday’s Lines of Force’, 1856.

1. Introduction

Advances in measurement technology has placed an increased emphasis on the accurate quantitative analysis of high quality experimental data. In recent years there has been a significant advance in the quantity and the quality of low frequency, MHz to kHz, dielectric spectroscopy measurements which can be made over some ten decades in both frequency and electrical capacitance. Application of the technique to gels and emulsions gives not only the opportunity to characterise the bulk a.c. response of these structures but also the ability to quantify the specific features of the electrode barrier layers, which are common in such systems, and

E-mail address: robert.m.hill@ntlworld.com (R.M. Hill).

hence the interaction between the bulk properties of the emulsion and the barrier layers.

Data obtained from measurements made on a stable, self emulsifying, water based system (Pouton, 1985, Shah et al., 1994, Khoo et al., 1998), using the water concentration as the variable, are reported. This system has been found to be effective in increasing the oral absorption of water-insoluble drugs, Shah et al. (1994) and Khoo et al. (1998). Quantification of the observed dispersions, in terms of the Quasi-DC extension (Dissado and Hill, 1984) to the cluster model of relaxation (Dissado and Hill, 1983) has been carried out using a multi-variable curve-fit analysis program (Alison, 1991, 2000). From the numerical data a model structure for the electrical properties of the complete emulsion system, which makes use of a minimum number of dispersion elements, has been developed, and is reported for a range of water concentrations in order to determine whether there are significant differences in the emulsion in an aqueous environment, as would occur when a drug is taken orally.

2. Experimental

The emulsifier consisted of equal weight proportions of a polysorbate (Tween 80, NF, supplied by Honeywill Stein, Surrey, UK) and a medium chain triglyceride from a mixture of mono- and di-glycerides (supplied by Croda Oleochemicals, Goole, East Yorkshire and Surfachem Ltd., Leeds) of specific gravities 1.08 and 0.95 respectively, to which was added deionised water in known weight proportions to give a range of physically stable self emulsions. The a.c. dielectric properties of these samples were measured using a Solartron 1255 Frequency Response Analyser (Farnborough Hampshire) and a Chelsea Dielectric Interface (Dielectric Instrumentation, Holt Heath, Wiltshire), by inserting into samples of the emulsions (Hill et al., 1990) two parallel platinum electrodes, each of area $50 \times 10^{-6} \text{ m}^2$, and spaced 1 mm apart. An alternating potential, of magnitude 1.0 V in the frequency range from 10^{-4} Hz to 10^5 Hz, was applied, and the capacitance of the samples recorded as the real, $C'(\omega)$, and imagi-

nary, $C''(\omega)$, components of the complex capacitance $C(\omega)$. In the kHz to MHz frequency range the bulk, d.c. conductances, G , of the samples were of the order of 10^{-5} Siemens but the capacitive admittance, $i\omega.C(\omega)$, increased in magnitude with both increasing water content and a.c. frequency, sufficiently to overload the power supply and limit the upper frequency range that could be used. However, the dispersion due to the conductance in the same frequency region, $C''(\omega) = G(\omega)/\omega$, did not exhibit any significant variation from the classic inverse frequency form.

3. Analysis

Plots of the dispersions observed from two of the data sets, of 2.5 and 31 wt.% water, are presented in Fig. 1, and are typical of the responses recorded. Although the dispersions appear significantly different in form they contain equivalent information and both have been quantified by a curve-fit program using the series connected dispersion model indicated in Fig. 2, where the low frequency, electrode barrier layers are in series connection with the parallel connected, bulk conductance and capacitance, and of a Quasi-DC form. The frequency dependence of the Quasi-DC relaxation dispersion function is (Dissado and Hill, 1983)

$$C(\omega) = C_1(1 + i\omega/\omega_0)^{n-1} \times {}_2F_1\{1-n, 1-m; 2-n; (1 + i\omega/\omega_0)^{-1}\} \quad (1)$$

where C_1 is the magnitude of the response, $i = \sqrt{-1}$, ${}_2F_1(a, b; c; x)$ is the hypergeometric function (Abramowitz and Stegun, 1970) and ω_0 the relaxation frequency defined as the inverse of the relaxation time, τ , for the process. The essential difference from the loss peak dispersion process of the standard relaxation functions is that in the Quasi-DC case the numerical value of the low frequency dispersion exponent, m , is negative, resulting in an *increase* in magnitude, with *decreasing* frequency for both the real, $C'(\omega)$, and imaginary, $C''(\omega)$, components of the response (Dissado and Hill, 1984), whereas in the Cluster

model of relaxation the real component of the low frequency branch is constant in magnitude and the log gradient of the imaginary component is fractional and positive. In both forms the exponent n is the fractional efficiency of energy transfer between the polarisable elements within a grouping forming a localised cluster and the absolute value of m the equivalent fraction for energy transfer between these clusters. The negative exponent occurs when the clusters are extensive and the energy transfer leads to an imperfect charge transport process which dominates the low frequency response. The magnitude of the exponent m is the fractional efficiency with which charge transport takes place within the extended cluster. In emulsion systems the clusters are formed from local groupings of individual emulsion particles

which absorb a fraction, n , of the available energy from the local electric field by inducing polarisation in these structures.

Table 1 lists the parameters obtained using the curve-fit program for the nine samples investigated. Fig. 2 indicates the series connection between the Quasi-DC response of the barrier layer and the parallel connected responses of the conductance and capacitance from the bulk of the emulsion. The qualities of fit for both the real and imaginary components of the capacitance are reported in terms of the root mean square variation, RMSE, values of the logarithmic magnitudes of the data. This approach linearises the variations in the response, which covers some eight decades in absolute magnitude. The plot in Fig. 1(a) presents the measured data by symbols, and that in

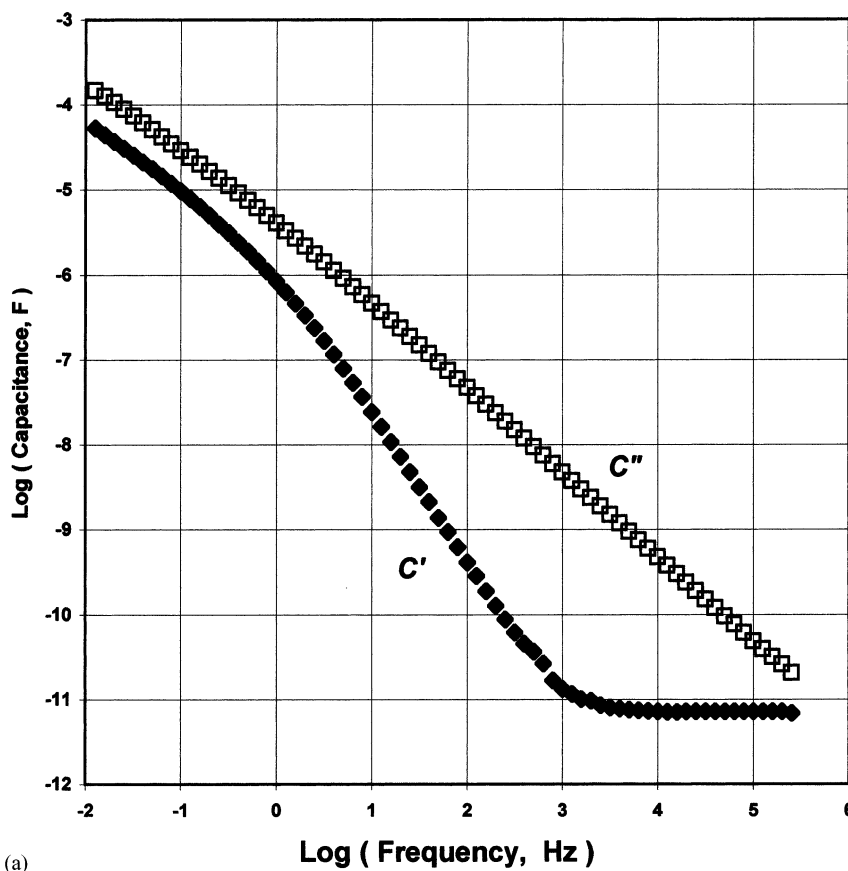


Fig. 1. Dielectric dispersions for two of the samples investigated. Figures (a) and (b) refer to the data for the samples containing 2.5% and 31% water content, respectively. In plot (b) the data has been superimposed with the best fit computed response.

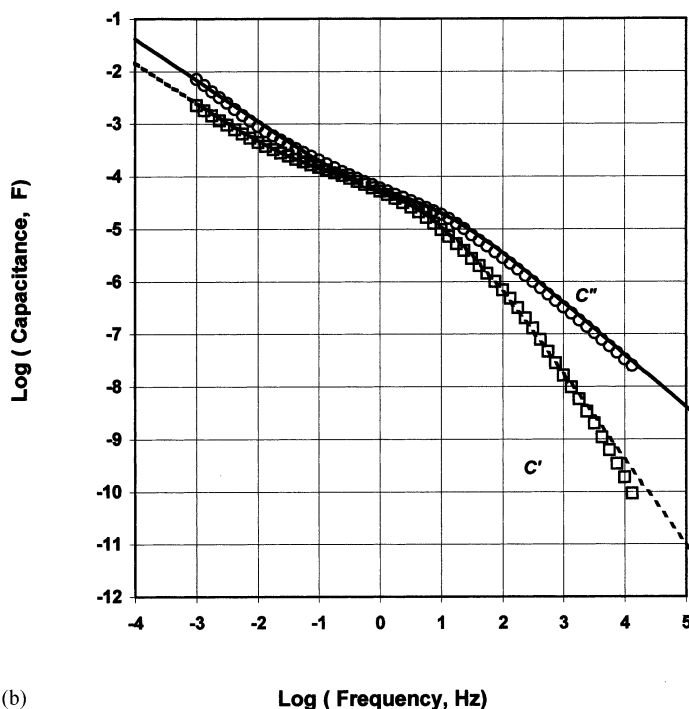


Fig. 1. (Continued)

Fig. 1(b) exhibits both the data and the 'best fit' computed plot by the imposed curves. The 'best fit' computed curves gave RMSE values for this sample of 7.5% and 4.3% for the real and imaginary components of the capacitive response, respectively, and 4.8% and 4.3%, respectively, for the sample with the smaller water concentration, Fig. 1(a). In both cases the higher frequency, imaginary component is dominated by the conductance, as shown by the inverse frequency dependence in this range.

The effect of random deviations in the measurements are always present and are particularly apparent when the exponents of the dispersion approach unity. Experimentally, the closest approach to unit loss tangent is when the ratio of the imaginary component, of the capacitance $C''(\omega)$ is large compared to the real component, $C'(\omega)$, as occurs in the frequency range from 200 to 700 Hz in Fig. 1(a) and for which the loss angle is 0.996 ± 0.002 radians. This particular data set is of a good quality and the observed variation in

the capacitive response is due to the measuring noise and of no particular significance in the broad pattern of the analysis for the complete dispersion.

It is emphasised that in a series connection, as indicated in Fig. 2, the observed response is the *inverse* of the sum of the *inverse* magnitudes of the individual responses, i.e. the smaller magnitude component dominates the observed response. The

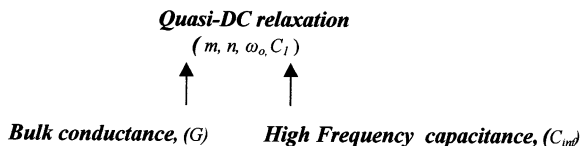


Fig. 2. A schematic diagram indicating that the bulk capacitance and conductance are electrically in parallel and this combination is electrically in series with the Quasi-DC barrier process. The background to the low frequency Quasi-DC process is given in Cooper and Hill (1996) and is characterised by the negative values for both the low frequency exponent, m , and the high frequency, exponent, $(n - 1)$. The magnitude of the Q-DC response, is C_1 , that of the conductance is G and of the capacitance C_{inf} .

Table 1
Characterisation of the dispersion data

% weight of water	m	n	ω_o	C_1	G	C_{inf}	RMSE	
			Hz	pF	Siemens	pF	C'	C''
0	−0.82	0.68	0.227	2.27e7	8.77e−6	4.79	0.048	0.034
2.5	−0.817	0.619	0.055	1.1e8	1.10e−4	5.31	0.043	0.077
5	−0.689	0.779	6.86	1.27e7	9.04e−5	8.04	0.021	0.026
8	−0.70	0.847	10.9	8.49e6	3.99e−5	7.48	0.064	0.057
20	−0.85	0.65	0.07	2.00e8	2.00e−4	#	*	*
31	−0.781	0.646	0.095	1.44e8	4.09e−4	#	0.075	0.043
54	−0.827	0.603	0.025	3.98e8	5.32e−4	#	0.065	0.44
77	−0.85	0.513	0.015	4.26e8	1.7e−4	#	0.575	0.054
88	−0.74	0.711	0.326	1.36e7	8.6e−6	4.59	0.554	0.053

Unstable due to current overload.

* Unstable during curvefitting.

principal difference between the plots in Fig. 1 is in the relative magnitudes of the bulk conductances, which are, in turn, directly dependent on the water content. However the magnitude of the bulk conductance increases only by a factor of four for a water concentration increase of about 12 times; this is an indication of the complexity of the water/emulsion interaction. Fig. 3 presents a schematic of the individual dispersions indicated in Fig. 1. The full Quasi-DC relaxation process is indicated by the symbols and exhibits both low and high frequency dispersions defined by the values of $(-m)$ and $(n-1)$ respectively. When the water concentration is low, the bulk conductance is low (plot $G(a)$) with the result that the intersection of the conductance and the Quasi-DC process takes place at a frequency *less* than that of the cross-over point of the Quasi-DC relaxation at 0.1 Hz, giving the smooth transitional response presented in Fig. 1(a). However when the conductance is high ($G(b)$), the intersection occurs with the high frequency branch of the Quasi-DC process in the region of 30 Hz, and the more complex dispersion of Fig. 1(b) is obtained.

At low concentrations of water the real components of the capacitance, in the kHz frequency range, exhibit no dispersion and are of a few picofarads in magnitude, as shown in Fig. 1(a). The inverse frequency dependence in the imaginary component at the same frequencies is due to the parallel conductance, $C = G/\omega$. However, at

lower frequencies the observed dispersion takes the form:

$$C(\omega) = C_o(i\omega\tau)^m \\ = C_o\{\omega\tau\}^m\{\cos(m\pi/2) - i \sin(m\pi/2)\} \quad (2)$$

with m negative and of magnitude approximately 0.8 across the range of samples investigated, Table 1.

Of direct significance in the analysis of the experimental data is the anomalous gradient of the real component of the capacitance in the frequency region which lies between the cross-over of the high frequency bulk capacitance and the low frequency dispersion considered above. It has been reported (Cooper and Hill, 1996) that when a conductance, of magnitude G , is set in series with a fractional power dispersion of the form:

$$C(\omega) = C(i\omega\tau)^{n-1} \\ = C_o(\omega\tau)^{n-1} \\ \times [\cos\{(n-1)\pi/2\} - i \sin\{(n-1)\pi/2\}] \quad (3)$$

with $0 < n < 1.0$, the resultant dispersion, in the frequency region greater than that of the intersection, takes, as the first order approximation, the form

$$C''(\omega\tau) = -G/\omega\tau \text{ but } C'(\omega\tau) = C(\omega\tau)^{-(1+n)} \quad (4)$$

The data presented here contains evidence of this anomalous dispersion in the real component of the complex capacitance. In practice the first approximation for the magnitude of n was obtained from the anomalous exponent defined in Eq. (4) and used as a starting value for the curve-fit program. We note that as $m \rightarrow +1.0$ and n to zero the limiting form of the Quasi-DC dispersion is of the Debye form, which is characteristic of a totally homogeneous dielectric sample (Debye, 1912).

4. Discussion

The data from the curve fit analysis, for the full range of samples, is listed in Table 1, together with the water concentrations by weight, the RMSE curve fit values and the magnitude of the characteristic capacitances and conductances. It is

noted that the observed high frequency capacitance values indicate that the observed bulk permittivity is not directly dependent on the water content, which indicates that the majority of the water in the emulsion is bound into the emulsion structure and not free to contribute directly to the background polarisation.

Fig. 4 presents plots of the observed values of the exponents n and m as functions of the water concentration. It is noticeable that the magnitudes of the individual exponents follow the same pattern and exhibit no significant variation over the range of stability of the emulsion, 10 to 80% water. The data emphasises the strength of the self-emulsifying property, characterised by the magnitudes of m and n , which define the form and nature of the observed dispersions. It is clear that there are no changes of phase or significant deviations from the simple model, characterised in Fig. 3, over the concentration range investigated. Only

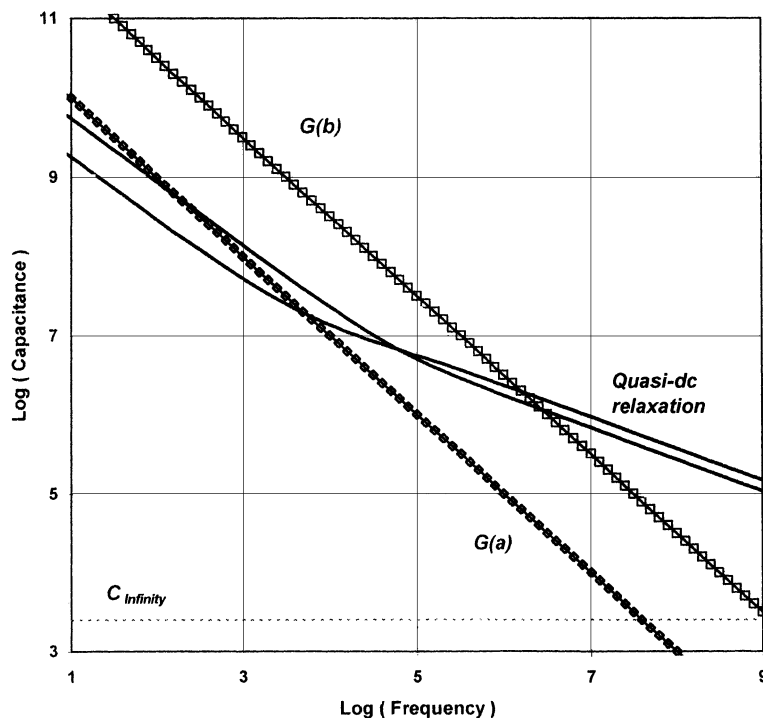


Fig. 3. The figure shows a Quasi-DC response which is overlaid with two series conductances. The high magnitude conductance, $G(a)$, interacts with the Quasi-DC process at a frequency that is sufficiently low that only the low frequency, m , branch of the barrier process is observed whereas the higher conductance, $G(b)$, intersects at a frequency greater than the characteristic value for the Q-DC process and hence the relevant cross-over part of the barrier process is revealed as a significant feature of the dispersion.

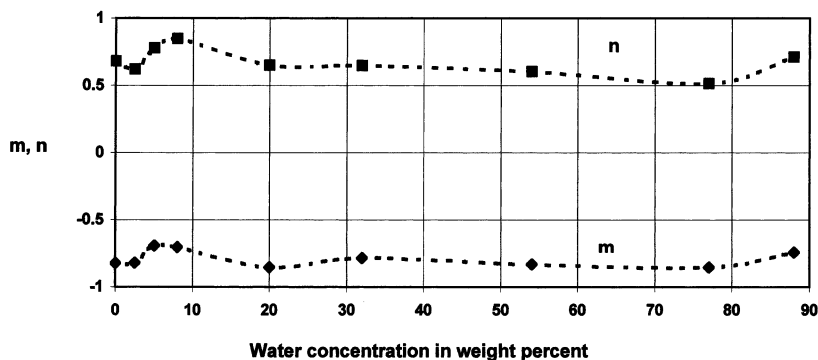


Fig. 4. Plots of the dispersion magnitudes m and n as functions of the water concentration. The range between zero and 10% is that in which the emulsion and its barrier layer develops a structure which remains constant up to more than 80% concentration, above which the emulsion is unstable. The dotted lines are only used to indicate the separate data sets here, and in the following figures.

at the lowest and highest values of water concentration is there any physical evidence for a change of structure and these were not characterised in the structure exponents of the Quasi-DC dispersion but in the general properties of the bulk emulsion, i.e. the conductance, G , the magnitude of the barrier capacitance, C_1 , and the Quasi-DC barrier relaxation frequency, ω_o . Having shown that an effect exists, further detailed examination of the concentration region from 2.5 to 25% water, by weight, is necessary in order determine precisely what is driving the observed anomaly in the bulk conductance and barrier capacitance. This detailed information is essential before, for example, a critical examination of the standard mixing laws could be carried out with any significance.

The effect of the water concentration on the rate of relaxation in the barrier is presented in Fig. 5(a), where the highest frequency observed for the barrier relaxation, 10.9 Hz, occurs in the same frequency region as an anomaly in both the capacitance and the conductance, Fig. 5(b). The relaxation frequency for free water lies in the GHz range, at room temperature, and hence the relaxation processes that we have observed have a stronger dependence on the interaction between water and the emulsifier rather than with the 'free' water. Indeed, the high frequency relative permittivities of the samples reported here are significantly less than 10, whereas pure water at these frequencies has a permittivity of 80, indicating

that there is, in practice, no 'free' water in the samples to contribute to the dispersion processes. The high relaxation rate for the barrier capacitance at 5% and 8% concentrations, when taken with the secondary peak in the conductance, implies weakly bound dipoles which may be due to the transfer of physical order from a looser structure at the electrode surfaces to that required within a well ordered barrier layer when excess water is present.

The measurable high frequency bulk conductances of the samples, G , in Table 1, as a function of the water content, is presented in Fig. 5(b). The plot indicates a maximum conductance in the region of 50% concentration. In simple systems this is commonly taken as evidence that the charged species moving in an electrical field has a simple A.B structural basis which leads to a parabolic dependence of the conductance on concentration, with the maximum at 50%, as broadly indicated in the figure. As the constituents here have similar specific gravities, but dissimilar molecular structures, the basis of the observation would be expected to be more complex than that of a simple one to one relationship.

The difference between the directly summable parallel response, and the computed series response c.f. the data in Fig. 3, is fundamental to the analysis of the data. The principal elements required to model the barrier response made use of a dispersion function which was obtained using a rigorous, quantum mechanical, derivation from

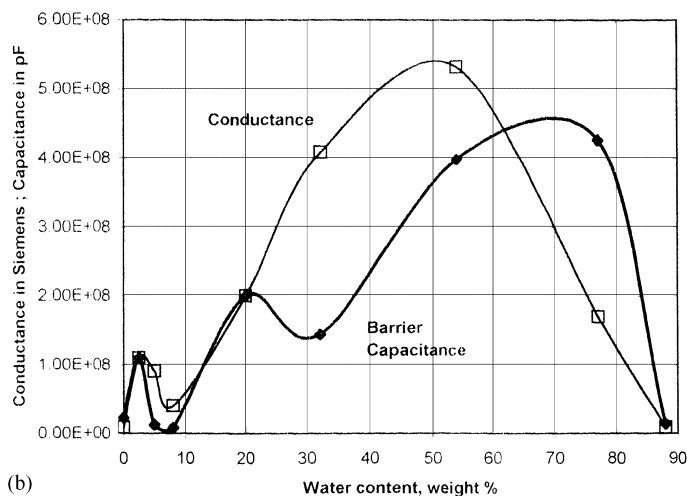
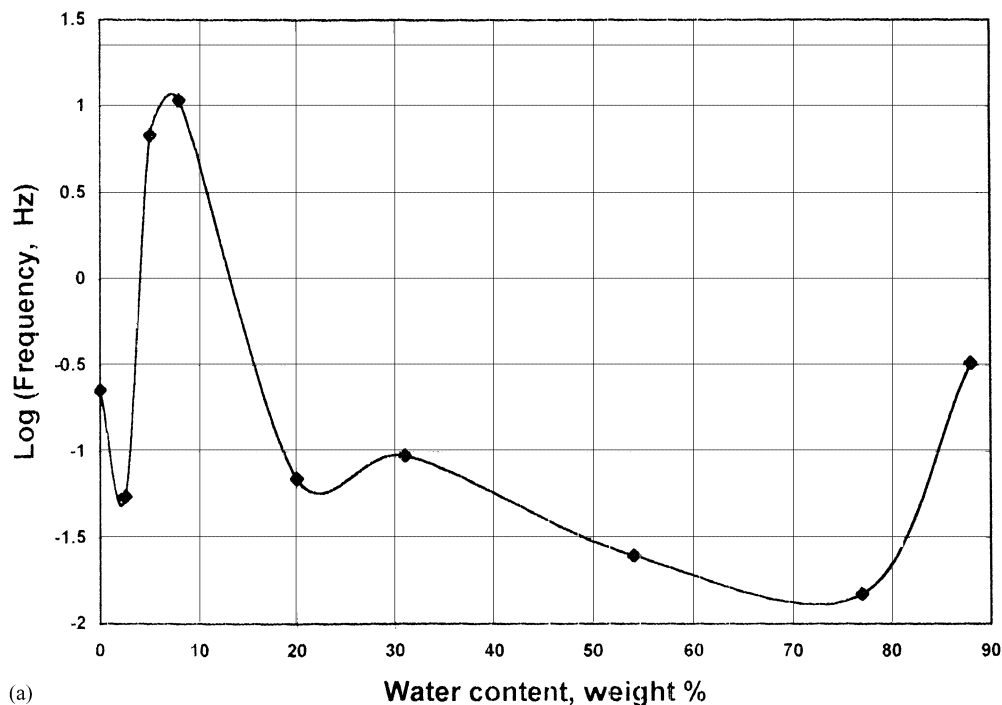


Fig. 5. The plot in (a) show the effect of the water concentration on the barrier layer relaxation frequency and that in (b) the dependence of the barrier layer capacitance and the bulk conductance on the water content. These are the only significant variations with water content that have been observed in the emulsion and indicates that the system is physically stable over the water concentration range from 20% to 80%, by weight. Below the 20% ratio there are weak maxima in the barrier capacitance and the bulk conductance accompanied by a minimum in the relaxation frequency which indicates the formation of a large scale disordered barrier. As the water content is added this breaks down to form a strong barrier to the high bulk conductance and a low relaxation frequency. These are indicative of a structurally well ordered barrier layer and a semi-porous structure in the bulk of the emulsion.

first principles. The data presented in the figures have been chosen not because they exhibit a low variation from the fitted function, but to show how the RMSE values are related to the nature of fit that has been achieved. Careful examination of Fig. 1(b) shows that the computed low frequency exponent, m , should be slightly greater than that reported, as, apparently, should be the low frequency exponent n . In the latter case, however, the real data is showing evidence of the high admittance condition considered earlier, and the lower value of the dispersion exponent has been retained as it fits the linear region of the response at the lower frequencies. We note that the transition region between the Quasi-DC dominated frequency range and the conductance dominated range, which is not trivial in form, is well characterised by the chosen parameters.

5. Conclusions

A set of simple, self-emulsifying, emulsions have been examined, and their dielectric responses have been measured over an extended frequency range. It has been determined, using a cooperative model to fit the observed responses of the high capacitance barrier layer, that the response is that of a Quasi-DC dispersion process which is connected in series with the 'bulk' response of the parallel connected 'bulk' capacitance and conductance. The capacitive component of the interaction is ameliorated by the dispersion exponent of the high frequency branch of the lower frequency process. Alison's multi-variable curve-fit program (Alison, 1991, 2000) has been used to quantify the specific features of the response and gave standard deviations in the logarithmic data values of better than 6% and 5% for the real and imaginary components, respectively, over approximately eight orders of magnitude in frequency and ten in capacitance with, typically, eight data values per decade of frequency. The system was chosen as likely to be stable and the data in Table 1 supports this view, but indicates that it is a dy-

namic stability with clear interactions between the bulk and the barrier properties. The evidence from this investigation is that the barrier layers at the electrodes and the bulk properties of the emulsion vary in magnitude and relaxation frequency with concentration, but not in their fundamental nature.

The single variable which drives the observed response of the system has been shown to be the relative magnitude of the bulk conductance, which controls the energy input to the system in the steady state, and the form of the frequency dispersion. We have observed that this parameter does not alter the fundamental properties of the internal responses, only the relative rates of relaxation. Hence it is deduced that the aqueous component of the emulsion would be effective as a drug host. We note that the maximum in the bulk conductance occurs for a water concentration of about 50%, by weight, which implies that at concentrations greater than this value there is less 'free water' in the system. This concentration does not correspond to a low barrier capacitance, that is the barrier can store a significant fraction of the energy in the sample.

Before the analysis technique presented here can be considered as providing directly applicable and useful information in the analysis of complex emulsion structures, it is essential that emulsion systems of a greater complexity should be investigated and reported. However, the data presented here has established a base from which comparisons with the equivalent responses from more complex systems can be developed in a logical and quantifiable manner. It is clear that Maxwell's comment is as valid now as when it was written in 1856.

Acknowledgements

The author gratefully acknowledges his debt to Professor M. Newton who, some twenty years ago, took the opportunity of a Fire Evacuation practice to discuss the application of the author's dielectric equipment to the analysis of emulsion systems and who has acted as a mentor since that time. The author also acknowl-

edges the assistance and support given to him over extended periods by Professor L.A. Dissado and by Dr J.M. Alison. To the former lies the credit for developing the Cluster model of relaxation, and the latter's computing skills and critical standpoint have been both a support and a challenge.

References

- Abramowitz, M., Stegun, I.A., 1970. Hypergeometric functions. In: *Handbook of Mathematical Functions*. Dover Press, New York pp. 555–565.
- Alison, J.M., 1991. The dielectric study of lossy materials over the frequency range 4–82 GHz. University of London, King's College, London Ph.D. Thesis.
- Alison, J.M., 2000. Dielectric dispersion analysis. Poster presentation, 31st Annual Conference of the Dielectrics Society, Canterbury.
- Cooper, J., Hill, R.M., 1996. Dielectric spectra of liquid lamellar phases. *J. Colloid Interface Sci.* 180, 27–35.
- Debye, P., 1912. Results of a kinetic theory of dielectrics. *Phys. Z.* 13, 976–1000.
- Dissado, L.A., Hill, R.M., 1983. A cluster approach to the structure of imperfect materials and their relaxation spectroscopy. *Proc. Roy. Soc. Lond.* A390, 131–180.
- Dissado, L.A., Hill, R.M., 1984. Anomalous low frequency dispersion. *Faraday Trans. 2. Chem. Soc.* 80, 291–319.
- Hill, R.M., Beckford, E.S., Rowe, R.C., Jones, C.B., Dissado, L.A., 1990. The characterisation of oil in water emulsions by a dielectric technique. *J. Colloid Interface Sci.* 138, 521–533.
- Khoo, S.M., Humbertstone, A.J., Porter, C.J.H., Edwards, G.A., Charman, W.N., 1998. Formulation design and bioavailability assessment of lipid self-emulsifying formulations of halofantrine. *Int. J. Pharm.* 167, 155–164.
- Pouton, C.W., 1985. Self-emulsifying drug delivery systems: assessment of their efficiency of emulsification. *Int. J. Pharm.* 106, 335–348.
- Shah, N.H., Carvajal, M.T., Patel, C.I., Imfield, M.H., Malik, A.W., 1994. Self-emulsifying drug systems (SEDDS) with polyglycolized glycerides for improving in vitro dissolution and oral absorption of lipophilic drugs. *Int. J. Pharm.* 106, 15–23.