THE UNIVERSITY OF MANITOBA

OPTICAL TECHNIQUES FOR THE DETERMINATION OF ELECTRIC FIELD DISTRIBUTIONS AND FOR THE STUDY OF PREBREAKDOWN PHENOMENA IN DIELECTRIC LIQUIDS

by

HACHIRO SUEDA

A Thesis

submitted to the Faculty of Graduate Studies

in partial fulfillment of the requirements for the

Degree of Doctor of Philosophy

Department of Electrical Engineering

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ABSTRACT

The work being presented in this thesis consists of three parts. The first part deals with the Schlieren images, observed in electrically stressed dielectric liquids. The second part deals with the new method for the determination of electric field distributions in dielectrics and along the interface between a dielectric liquid and a dielectric solid. The third part deals with the prebreakdown phenomena in high viscosity materials.

In the first part, experimental results for the Schlieren images observed in silicone oil are presented. The Schlieren images related to the liquid motion normally observed in electrically stressed dielectric liquids are discussed. The liquid motion is mainly caused by two mechanisms: (a) the Coulombic force due to the interaction of the space charge with the field, and (b) the electromechanical force created by the field resulting from the spatial variation of the dielectric constant due to the variation of temperature from domain to domain and from time to time in the liquid. The direction of such a liquid motion depends on which of these two mechanisms is dominant. The Schlieren images show mainly the change of the already-existing temperature gradients in the liquids, and this change is due to the liquid motion caused by either mechanisms (a) or (b) or both. It is concluded that the Schlieren images are directly governed by the temperature distribution in the liquid, and have no direct bearing on the formation and distribution of space charges.

In the second part, a new method for the determination of electric field distributions in dielectrics using a Schlieren optical system and

the applications are presented. This method is based on the principle that the spatial distribution of the refractive index produced by a small applied temperature difference is changed due to an electro-mechanical force created by the field resulting from the spatial variation of the dielectric constant. Some experimental results for benzene and n-hexane between two spherical electrodes obtained with this method show the essential features predicted from the space charge effects. This method has also been used for the measurements of the field distribution along the interface between a dielectric fluid and a dielectric solid. Some experimental results for the interfaces between n-hexane and a glass plate surface, and between n-hexane and a semiconducting layer surface obtained with this method, show that the space charge is the dominant factor controlling the field distributions. The other factors such as the dielectric constants and resistivities of the two materials forming the interface would play an important role in determining the field distributions if and only if the space charge effect is negligibly small or can be ignored. This method can be used to study electric field and space charge distributions along fluid-solid dielectric interfaces for practical insulation systems under both steady-state and transient conditions.

In the last part, experimental results for the effects of viscosity and applied field on the prebreakdown phenomena in high viscosity Epoxy are presented. The shadowgraphic image reflects only a region of disturbance occurring in a dielectric liquid, which differs in refractive index from its surroundings. The time required for the onset of a pre-

breakdown disturbance after the application of a step-voltage, and the rate of growth of the disturbance depend strongly on the viscosity (or the temperature) of the liquid. The refractive index inside the disturbance region is smaller than that outside it. The variation of the external current is consistent with the temporal change of the disturbance. It is proposed that the formation of a disturbance region is due to the Coulombic repulsion of local homocharges which in turn causes a decrease in local density and hence a decrease in refractive index. At high fields the anode injects holes to form positive ions and the cathode injects electrons, and the electric conduction is filamentary. The electric breakdown in condensed materials (liquids and solids) involves double injection and the creation of low density regions to enable the charge-carrier multiplication processes to take place. Thus the breakdown strength is governed by the parameters which control the conditions for such prebreakdown phenomena to arise.

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LIST OF MOST USED SYMBOLS

E	Electric field
E_b	Breakdown field strength
E_k	Electric field for transmitted light minima in a Kerr-effect system
E_{ko}	Characteristic electric field of a Kerr cell
F	Force for electrohydrodynamic motion
f	Electromechanical force
f_s	Focal length of the lens
g	Gravitational acceleration
I	Current
K_k	Kerr's constant
K_n	Temperature coefficient of the refractive index of the medium
K_ε	Temperature coefficient of the dielectric constant of the medium
K_ρ	Temperature coefficient of the density of the medium
N	Density of ions
n	Refractive index
n_a	Refractive index of the medium outside a test region
n_o	Average refractive index of the medium
q	Electron charge
R	Radius of the lens
T	Temperature
T_o	Average temperature
T_R	Temperature at a reference point

δ	Deflecting distance
δ_x	Deflecting distance for x-direction
δ_y	Deflecting distance for y-direction
ε	Dielectric constant
ε_o	Dielectric constant of the medium corresponding to the average temperature of the system
θ	Refracted angle inside the test region
θ_x	Refracted angle in the x-z plane
θ_y	Refracted angle in the y-z plane
λ	Wavelength of the light
ρ	Density of the medium
ρ_o	Density of the medium corresponding to the average temperature of the system
ϕ	Refracted angle outside the test region
ϕ_d	Detectable refracted angle

CHAPTER 1

INTRODUCTION

High-field electric conduction and breakdown phenomena in dielectric liquids have been extensively studied by many investigators for more than fifty years. However, from both the experimental results and the many theoretical approaches published in the literature, it is shown that there is no one unified theory which can explain beyond doubt all the experimental results. The slow progress of this field can be considered as due at least partly to the discrepancy among the experimental results reported by different investigators which may be mainly caused by different experimental conditions used by them. Thus, in the past two decades, investigators have given much attention to sample purity and electrode preparation, and have improved techniques to control their experimental conditions in order to obtain reproducible results. They have also developed new experimental techniques to study the prebreakdown phenomena from different angles. These efforts have shed some light upon the understanding of this field. Prior to breakdown, there are always some disturbances created by high electric fields. Such disturbances have been studied by means of Schlieren, shadowgraphic, Kerr-effect and other optical methods, such as disturbances related to electrohydrodynamic motion [Gray and Lewis 1969, Hewish and Bringmell 1975, Usuda and Sakamoto 1977], to particle migration [Poulter and Snaddon 1978], to electrostriction [Hakim and Higham 1962] to electric field distribution

[Cherney and Cross 1973, Cassidy et al. 1974] and to prebreakdown and breakdown phenomena [Farazmand 1961, Morikawa 1972, Heiman et al. 1976, Chiu 1976].

Since an optical image of a phenomenon shows only a region which has a different refractive index, it, in general, does not provide any information about the mechanisms responsible for its occurrence, though the conditions for its occurrence may be known. We have had to search for the mechanisms from the relations between the images and other experimental results. The difficulty is mainly due to the lack of other data to help the analysis of the optical observations. Therefore, to study any disturbance it is important to observe the phenomenon optically and to measure simultaneously the other properties which are related to this phenomenon.

The Schlieren optical method can detect only the difference in refractive index in a domain of interest. If this method is employed for studying the physical processes responsible for any disturbance in an electrically stressed dielectric liquid, the first question to be asked is: what are the factors resulting in a change of the refractive index? The answer to this question not only would give some hints to the mechanisms responsible for the occurrence of a disturbance, but also would lead to further development of this method. Therefore, at first, we have to clarify the interpretation of the Schlieren images normally observed in electrically stressed dielectric liquids.

For studying the charge transport and breakdown processes in dielectrics, the measurements of field distributions are extremely important. Up to now the field distributions, in general, are measured by means of a probe or the Kerr-effect. However, the probe may disturb the potential distributions and the Kerr-effect can be applied only to those materials, the anisotropy of whose refractive index is field dependent. In fact the Kerr-effect can be observed significantly only for a few materials such as nitrobenzene and chlorobiphenyls. We have therefore developed a new technique for the determination of field distributions. This technique is non-destructive and non-disturbing, and it can be applied to any dielectric systems. We have used this method for studying the field distributions in liquid and along the liquid-solid interfaces.

Electric breakdown is generally preceded by the growth of a disturbance whose refractive index is different from that of its surroundings [Sharbaugh _et al._ 1978]. In the past, the study of such a prebreakdown disturbance has been concentrated on low viscosity dielectric liquids or almost infinite viscosity dielectric solids with applied fields very close to their breakdown strength. However, the information so far gathered has not been sufficient to indicate with certainty the origins and the nature of prebreakdown disturbances. One of the difficulties of the studies of the prebreakdown phenomena is that the propagation velocity of the disturbances in low viscosity dielectric liquids is very fast and it is necessary to have a high speed camera or recording system to record them. Recently, several investigators have developed an ultra-high speed electro-optical system with a time resolution of the order of 10^{-8} sec, and they have observed the pre-