

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

Winnipeg, Manitoba

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A B S T R A C T

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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T A B L E O F C O N T E N T S

<u>Chapter</u>		<u>Page</u>
1	INTRODUCTION	1
2	REVIEW OF PREVIOUS WORK	6
2.1	Optical Techniques for Studying Disturbances in Dielectric Liquids	6
2.1.1	The Kerr-Effect Method	7
2.1.2	The Doppler-Shift Method	12
2.2	Electric Field Distributions in Dielectric Systems	17
2.2.1	Electrical Field Distributions Between Parallel-Plane Electrodes	18
2.2.2	Electrical Field Distributions Along a Dielectric Solid	20
2.3	Disturbances in Electrically Stressed Dielectric Liquids	22
2.3.1	Electrohydrodynamic Motion	22
2.3.2	Prebreakdown Phenomena	25
2.4	Breakdown Processes	35
3	THE OPTICAL MEASURING SYSTEM	42
3.1	The Schlieren Optical Method	42
3.1.1	The Basic Principle of the Schlieren Optical Method	43
3.1.2	The Schlieren Optical System used for Measurements of Field Distributions and Other Disturbances	48
3.1.3	The Measurements of Temperature Gradients	55

<u>Chapter</u>	<u>Page</u>
3.2 The Shadowgraphic Method	61
3.2.1 The Basic Difference Between the Shadowgraphic Method and the Schlieren Method	61
3.2.2 The Shadowgraphic System used for the Studies of Prebreakdown Phenomena	64
4 THE SCHLIEREN IMAGES	66
4.1 Theory	66
4.2 Experimental Techniques	70
4.3 Experimental Results and Discussion	72
5 SCHLIEREN METHOD FOR THE DETERMINATION OF ELECTRIC FIELD DISTRIBUTIONS IN DIELECTRICS	91
5.1 Theory	92
I FIELD DISTRIBUTIONS BETWEEN SPHERE-SPHERE ELECTRODES	99
5.2 Experimental Techniques	99
5.3 Experimental Results and Discussion	101
II ELECTRIC FIELD DISTRIBUTIONS ALONG FLUID-SOLID DIELECTRIC INTERFACES	112
5.4 Experimental Techniques	113
5.5 Experimental Results and Discussion	116
6 PREBREAKDOWN PHENOMENA IN HIGH VISCOSITY DIELECTRIC LIQUIDS	134
6.1 Experimental Techniques	135
6.2 Experimental Results and Discussion	140
7 CONCLUSIONS	152
REFERENCES	153

L I S T O F T A B L E S

<u>Table</u>		<u>Page</u>
2.1	The Kerr's constant K_k and the characteristic electric field E_{k0} of some dielectric liquids	13
2.2	Pressure dependence of corona inception voltage in the dielectric oil	32
2.3	Comparison of the breakdown theory with experiment . . .	41
4.1	The summary of the results about the relative maximum change in δ_y and the time t required for such a change to reach a peak value under various conditions	83

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
2.1 The basic optical system based on the Kerr-effect. L.S: ligh source; L.E: light expander; Po: Polarizer; Co: Compensator; F: Focusing lens; A _n : Analyzer; S: screen.	8
2.2 A typical fringe pattern in nitrobenzene photographed (exposure time 0.3 μ s) at the peak of a 65.4 kV total- duration 10 μ s pulse. The fact that the field is uniform between the plates is demonstrated by the absence of interelectrode fringe. The side fringes are due to the fringing field along the length of the electrodes . . .	11
2.3 The Doppler shift method. v_w : velocity of a wave in medium; v_m : velocity of a medium; L_b : laser beam; v_d : velocity of an observer; V_s : velocity of a wave source; mi: mirror; sp: splitter; Fi: filter.	14
2.4 Electric field distortions introduced in a uniform field gap in nitrobenzene by various dielectric spacers bridging the gap	21
2.5(a) The photographs of propagation of prebreakdown disturbances produced by the impulse breakdown between point-plane electrodes in dielectric oil. These pictures were taken by Schlieren method, using a xenon flash lamp and a Beckman camera Applied voltage: 36 kV, 1 x 140 μ s, frame separation: 66.5 μ s, exposure time: 3.6 μ s; pressure: 0.5 mm Hg, gap length: 25.4 mm	26
2.5(b) The photographs of propagation of prebreakdown disturbances produced by the impulse breakdown between point-point electrodes in liquid notrogen. These pictures were taken by Schlieren method using a ring edge temperature -196°C, pressure 1 atm, gap length 6 mm, applied impulse voltage 58 V	27
2.6 Velocities of prebreakdown disturbances in white oil . . .	29
2.7 The effects of pressure on the streamer propagation . . .	32
2.8 The effects of additives on the propagation rates	33
2.9 The dependence of breakdown strength of some organic liquids upon applied hydrostatic pressure	37

<u>Figure</u>	<u>Page</u>
3.1 The basic Schlieren system. L.S: light source; C ₁ : condenser lens; H: pin-hole; C ₂ collimating lens; S: slit to control the size of the light beam entering the test region; F: Schlieren lens; F _S : Focal length of lens F	44
3.2 The Schlieren system. L.S: He-Ne laser (light source); D, diffusing lens; C, collimating lens; S, slit to control the size of the light beam entering the test region; F, Schlieren lens; M, magnifying lens	49
3.3 Typical variation of the image brightness on the screen with the knife edge position along the v-direction (with respect to an arbitrary reference position)	51
3.4 The detectable refracted angle ϕ_d as a function of the diameter of the parallel beam. A: f _S = 200 mm; B: f _S = 500 mm	53
3.5 Typical variation of the image brightness on the screen for the light passing through near the solid surface with the knife edge position along the y-direction (with respect to an arbitrary reference position)	54
3.6 δ_y as a function of temperature difference T ₁ - T ₂ for (A) benzene and (B) n-hexane (with respect to an arbitrary reference position)	58
3.7 Shadowgraphic system. L.S: light source; C ₁ : condenser lens; H: pin-hole; C ₂ : collimating lens; F: focusing lens; M: magnifying lens	62
3.8 Electro-optical system for the observation of prebreak-down phenomena. D: diffusing lens; C: collimating lens; F: focusing lens; M: magnifying lens	65
4.1 The electrode system for the study of the Schlieren images in electrically stressed dielectric liquids. A, stainless steel blade; B, 0.2 mm thick copper plate; C, Teflon electrode supporting frame; P ₁ and P ₂ , measuring points of temperature gradients	71

<u>Figure</u>	<u>Page</u>
<p>4.2 Illustrating the change of the original temperature gradient at $t = 0$, $(dT/dy)_0$, resulting from the liquid motion caused predominantly by the motion of ions. (A) $(dT/dy)_0 > 0$ at $t = 0$; $(dT/dy)_1 > \theta_1 > \theta_0$; and $(dT/dy)_2$, $\theta_2 < \theta_0$; electromechanical force in the direction opposite to the ionic motion. (B) $(dT/dy)_0 < 0$ at $t = 0$; $(dT/dy)_1 < (dT/dy)_0$, $(2\pi - \theta'_1) < (2\pi - \theta'_0)$; and $(dT/dy)_2 < (dT/dy)_0$, $(2\pi - \theta'_2) < (2\pi - \theta'_0)$; electromechanical force in the same direction as the ionic motion</p>	74
<p>4.3 Schlieren photographs for silicone oil after the application of + 7 kV to the blade at $t = 0$ showing the effect of the already-existing temperature gradient in the test region. (A) $(dT/dy)_0 > 0$ corresponding to the knife edge setting of $5\mu\text{m}$; a, $t = 0.5$ sec; b, $t = 1.0$ sec; c, $t = 8.0$ sec; (B) $(dT/dy)_0 < 0$ corresponding to the knife edge setting of $30\mu\text{m}$</p>	76
<p>4.4 The temperature gradient in terms of δ_y measured at point P_1 (0.7 mm above the plate) after the application of + 7 kV to the blade as a function of the initial temperature gradient $(dT/dy)_0$ in terms of setting of the knife edge at zero applied voltage</p>	79
<p>4.5 The temperature gradient in terms of δ_y measured at point P_1 (0.7 mm above the plate) after the application of - 7 kV to the blade as a function of the initial temperature gradient $(dT/dy)_0$ in terms of setting of the knife edge at zero applied voltage</p>	80
<p>4.6 The variation of δ_y with time measured at point P_1 (0.7 mm above the plate) after the application of 7 kV to the blade at $t = 0$ (witch on) and after the removal of the applied voltage at t of about 20 sec (switch off). (a) Applied voltage: + 7 kV; A: $(dT/dy)_0 > 0$ corresponding to the knife edge setting of $13.4\mu\text{m}$; B: $(dT/dy)_0 < 0$ corresponding to the knife edge setting of $25.5\mu\text{m}$; (b) Applied voltage: - 7 kV; A: $(dT/dy)_0 > 0$ corresponding to the knife edge setting of $10\mu\text{m}$; B: $(dT/dy)_0 < 0$ corresponding to the knife edge setting of $30\mu\text{m}$</p>	82

<u>Figure</u>	<u>Page</u>
4.7 The variation of δ_y with time measured at point P_1 (0.7 mm above the plate) and point P_2 (0.9 mm below the plate) after the application of ∓ 7 kV to the blade at $t = 0$. (A) $(dT/dy)_0 > 0$ corresponding to the knife edge setting of $6\mu\text{m}$; (B) $(dT/dy)_0 < 0$ corresponding to the knife edge setting of $31\mu\text{m}$. . .	85
4.8 The variation of δ_y with time measured at point P_1 (0.7 mm above the plate) and point P_2 (0.9 mm below the plate) after the application of -7 kV to the blade at $t = 0$. (A) $(dT/dy)_0 > 0$ corresponding to the knife edge setting of $3\mu\text{m}$; (B) $(dT/dy)_0 < 0$ corresponding to the knife edge setting of $25\mu\text{m}$	86
4.9 Current I and the percent change in δ_y (measured at a point 0.2 mm below the blade edge) as functions of voltage V applied to the blade for $(dT/dy)_0 >$ corresponding to the knife edge setting of $-2362\mu\text{m}$.	88
4.10 The variation of δ_y with the distance from the plate surface along the y direction. $\delta_y = 1$ unit corresponding to a relatively constant temperature gradient at the plate surface is used as the reference	90
5.1 (A) The electrode system. A and B - parallel copper plates, C - four glass tubes, D - two spherical electrodes. (B) The mesh diagram showing the positions of the points for electric field distribution measurements in the test region	100
5.2 Schlieren photographs for benzene showing the effect of applied voltages between two spherical electrodes on the temperature distribution in the test region .	103
5.3 Schlieren photographs for n-hexane showing the effect of applied voltages between two spherical electrodes on the temperature distribution in the test region .	104
5.4 The ratio \bar{A}/\bar{B} as a function of the square of the applied voltage for benzene. Dashed curves for the points near the negative electrode and solid curves for the points near the positive electrode. a: $x = 5, y = 10$; b: $x = 10, y = 10$; c: $x = 5, y = 6$; d: $x = 10, y = 6$; e: $y = 5, y = 4$; f: $x = 10, y = 4$.	106

<u>Figure</u>		<u>Page</u>
5.5	The ratio \bar{A}/\bar{B} as a function of the square of the applied voltage for n-hexane. Dashed curves for the points near the negative electrode and solid curves for the points near the positive electrode. a: x = 10.1, y = 10; b: x = 4.6, y = 10; c: x = 10.1, y = 6; d: x = 4.6, y = 6; e: x = 10.1, y = 4; f: x = x = 4.6, y = 4	107
5.6	The ratio \bar{A}/\bar{B} as a function of y at various applied voltages for benzene. Dashed curves for the points near the negative electrode at a fixed x = 5 and solid curves for the points near the positive electrode at a fixed x = 10. a and b: 20 kV; c and d: 18 kV; e and f: 16 kV; g and h: 14 kV; j: 12 kV; k: 10 kV . . .	109
5.7	The ratio \bar{A}/\bar{B} as a function of y at various applied voltages for n-hexane. Dashed curves for the points near the negative electrode at a fixed x = 4.6 and solid curves for the points near the positive electrode at a fixed x = 10.1. a and b: 20 kV; c and d: 16 kV; e and f: 12 kV; g and h: 8 kV . . .	110
5.8	The percent change in the ratio \bar{A}/\bar{B} as a function of x along the central line connecting the electrode centers at y = 10. Applied voltage: 16 kV. The values of \bar{A}/\bar{B} marked with arrows are used as references	111
5.9	Electrode system for measurement of electric field distributions along the liquid-solid dielectric interfaces. A, to high voltage source; B, to electrometer; C, teflon framework; D, glass plates; E, metallic rod contact; T, top aluminum electrode; H, aluminum block (bottom electrode)	114
5.10	Schlieren image photographs without applied fields. (A) initial temperature gradient $(dT/dy)_0 = 0$; (B) $(dT/dy)_0 = 0.7^\circ\text{C}/\text{cm}$	117
5.11	Schlieren image photographs with applied voltages. (A) V = + 5 kV, $(dT/dy)_0 = 0.7^\circ\text{C}/\text{cm}$; (B) V = - 5 kV, $(dT/dv)_0 = 0.7^\circ\text{C}/\text{cm}$; (C) V = + 10 kV, $(dT/dy)_0 = 0.7^\circ\text{C}/\text{cm}$; (D) V = - 10 kV, $(dT/dy)_0 = 0.7^\circ\text{C}/\text{cm}$	119

<u>Figure</u>	<u>Page</u>
5.12 Electric field distribution along the interface between n-hexane and a glass plate for negative (O) and positive (O) dc voltages applied to the top electrode. (A) - 2 kV, (B) + 2 kV, (C) - 4 kV, (D) + 4 kV, (E) - 6 kV, (F) + 7 kV, (G) - 8 kV, (H) + 8 kV .	121
5.13 Electric field distribution along the interface between n-hexane and a glass plate for 60 Hz ac voltages applied to the top electrode (A) 2 kV, (B) 4 kV, (C) 6 kV, (D) 7 kV	123
5.14 Electric field distribution along the interface between n-hexane and a glass plate for a specially cleaned glass plate surface. (A) 2 kV ac, (B) 4 kV ac, (E) 8 kV ac, (G) - 8 kV dc, (H) + 8 kV dc	125
5.15 The current through the interface between n-hexane and a $\text{Se}_{0.78}\text{Te}_{0.22}$ semiconductor film as a function of applied voltage. 0 - dc voltages, 0 + dc voltages. (A) Light intensity: 35 mW/cm ² , (B) 385 mW/cm ² , (C) 1660 mW/cm ²	127
5.16 Electric field distribution along the interface between n-hexane and a $\text{Se}_{0.78}\text{Te}_{0.22}$ semiconductor film for negative (O) and positive (O) dc voltages applied to the top electrode and under illumination with the light intensity of 385 mW/cm ² . (A) 4 kV, (B) 8 kV, (C) 10 kV, (D) 12 kV	128
5.17 Electric field distribution along the interface between n-hexane and a $\text{Se}_{0.78}\text{Te}_{0.22}$ semiconductor film for positive dc voltages applied to the top electrode and under illumination with the light intensity of 385 mW/cm ² . (A) 4 kV, (B) 8 kV, (C) 10 kV, (D) 12 kV.	130
5.18 Electric field distribution along the interface between n-hexane and a $\text{Se}_{0.78}\text{Te}_{0.22}$ semiconductor film for negative dc voltages applied to the top electrode and under illumination with the light intensity of 385 mW/cm ² . (A) - 4 kV, (B) - 8 kV, (C) - 10 kV, (D) - 12 kV	131

<u>Figure</u>	<u>Page</u>	
5.19	The peak electric field along the interface between n-hexane and a $\text{Se}_{0.78}\text{Te}_{0.22}$ semiconductor film as a function of voltage applied to the top electrode at various light intensities. (A) light intensity of 35 mW/cm^2 , positive dc voltage; (B) light intensity of 35 mW/cm^2 , negative dc voltages; (C) light intensity of 1660 mW/cm^2 , positive dc voltages; (D) light intensity of 1660 mW/cm^2 , negative dc voltages	133
6.1	The point-point electrode system for the observation of prebreakdown phenomena. A, copper plate connected to neutral ground; B, point-point electrode holder	136
6.2	Experimental arrangement for the measurement of the change of the refractive index in the disturbance reion	139
6.3	The photographs of the disturbances produced by the applied voltage of 48 kV between point-point electrodes with a gap length of 0.3 cm in epoxy fluid at temperature of -5.5°C	141
6.4	The photographs of the disturbances produced by the applied voltage of 34 kV between point-point electrodes with a gap length of 0.3 cm in epoxy fluid at temperature of $+5.6^\circ\text{C}$	142
6.5	The viscosity (A), the time required for the first appearance of the disturbance after the application of a step voltage of 48 kV (B), and the speed of the growth of the disturbance at the applied voltage of 48 kV (C) in epoxy fluid. Electrodes, point-point; gap length, 0.3 cm	143
6.6	Number of bursts of carriers injected from the point electrode per second as a function of temperature for epoxy fluid with a point-point electrode configuration of gap length of 0.3 cm. A, $f_p = 2.15 \times 10^6 \text{ V cm}^{-1}$ (negative point); B, $E_p = 2.15 \times 10^6 \text{ V cm}^{-1}$ (positive point); C, $E_p = 1.70 \times 10^6 \text{ V cm}^{-1}$ (negative point); D, $E_p = 1.70 \times 10^6 \text{ V cm}^{-1}$ (positive point)	146

<u>Figure</u>	<u>Page</u>
6.7 Average current as a function of temperature for epoxy fluid with a point-plane electrode configuration of gap length of 0.3 cm. A, $E_p = 2.15 \times 10^6 \text{ V cm}^{-1}$ (negative point); B, $E_p = 2.15 \times 10^6 \text{ V cm}^{-1}$ (positive point); C, $E_p = 1.70 \times 10^6 \text{ V cm}^{-1}$ (negative point); D, $E_p = 1.70 \times 10^6 \text{ V cm}^{-1}$ (positive point)	147
6.8 The reflected light intensity as a function of angle of incidence of light incident on the surface of the disturbance region	149

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_{k0}	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_0	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_0	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 pre-breakdown 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-