Time Resolved Measurement of Electric Field Distribution in a Liquid Dielectric

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Abstract - Measurement technique of three dimensional electric field distribution in liquid dielectrics have been studied. Kerr effect and computed tomography(CT) method have been used. Measuring time has been shortened by the use of multi-optical systems to less than several milliseconds. Near future, electric field distribution in front of a streamer tip of breakdown would be measured.

1. Introduction

Measurements of electric field in liquid dielectrics is important to clarify electric breakdown mechanism and to analyze real problems. However, direct electric field measurement by any sensor is difficult, because the sensor inserted could disturb original field distribution. Optical measurement becomes useful by development of laser with stable out put intensity and electronic equipments.

Since 1980, several trials to measure electric field intensity and field distribution in liquids were published. Field distribution between sphere-plane electrode in nitrobenzene was carried out using interference pattern [1]. The interference method was also used for parallel plane and sphere-sphere electrodes [2]-[6]. These are measurements for uniform field or simple field distribution. An electronic method has been developed which could obtain light intensity in terms of electric signal [7]. These allowed high speed measurement of electric field and field distribution. Early studies have been limited to measure uniform field. However, Takada et al have developed electric field vector in two dimensional plane [8], which have conducted three dimensional measurements of electric field in liquids. Field vector in three dimension could be measured by the two dimensional technique [10] and theoretical finding [9]. Then three dimensional field distribution cloud be successfully measured using three dimensional vector measurement combined with computed tomography method [11].

Our final goal of this study is to measure electric field at a tip of positive or negative streamer which would move at very high speed of about some thousand km per second. We try to measure electric field distribution in three dimension at some ms range.

When linear polarized light goes into liquid subjected by a D.C. electric field, it separates into two waves, ordinary and extraordinary, the former speed being independent of field intensity and the latter decreased with increasing field strength. The two waves are in two planes perpendicular to light travelling direction and perpendicular to each other. Since the extraordinary wave loses in speed, its phase is changed by Γ as the light passes a distance L in the liquid. The two waves will be added at the exit of the cell, being an ellipse of which component could be measured to obtain field intensity.

Kerr effect shows that difference of refractive indexes, n_0 and n_e, for ordinary and extraordinary waves is proportional to the square of applied field E as follows:

$$n_e - n_0 = \lambda KE^2 \tag{1}$$

where λ is wave length of the light and K the Kerr constant.

After travelling a distance L, the phase difference of the two waves becomes

$$\Delta\theta = 2\pi LKE^2 \tag{2}$$

In an electric field, a liquid behaves as an uni-axial crystal in which polarized wave separates into two waves with velocity of ν_1 and ν_2 as following relations:

$$\nu_1^2 = \nu_0^2 \tag{3}$$

$$\nu_2^2 = \nu_0^2 \cos^2\alpha + \nu_e^2 \sin^2\alpha \tag{4}$$

where α is the angle between applied electric field vector and light travelling direction, ν_0 and ve the velocity of ordinary and extraodinary wave for $\alpha = 0$.

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Received October 11, 2002 ; Accepted November 28, 2002.

Combining eqs. (1)-(4), one obtains for the phase difference 'of two beams,

$$\Gamma = 2\pi \int l(\frac{1}{\nu_2} - \frac{1}{\nu_1})$$
$$= \frac{2\pi n_0 l}{\lambda} \left(\frac{1}{\sqrt{\cos^2\alpha + \frac{n_0^2}{\lambda B E^2}\sin^2\alpha}} - 1 \right)$$
$$= 2\pi L K E^2 \sin^2\alpha = 2\pi L K (E \sin\alpha)^2 \qquad (5)$$

The term Esin' is appearing in eq.(5) instead of E in eq.(4). Fig. 1 shows that Esin' is a projection of E on the plane perpendicular to light direction, which means that polarized light is modulated by two dimensional electric vector Ex-z instead of E. Eq.(5) is proved experimentally [9]: A rotated parallel plane electrode was used to make various α. At any α and an applied field, measured field strength calculated using eq.(5) was independent of ' but those calculated by eq.(4) decreased with decreasing α.

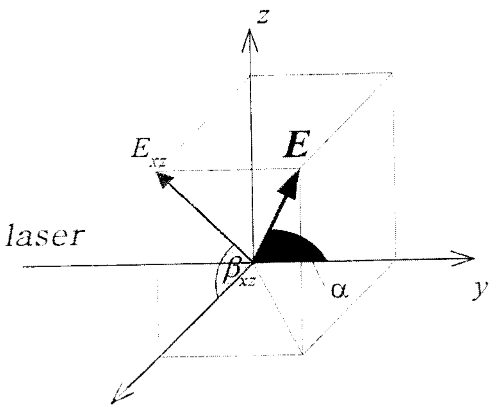

Fig. 1 Relation of electric field and light travelling diretion

This implies that even if polarized light passes through a train of three dimensional vector, it's speed can be changed by a train of two dimensional vector of which directions are in the plane perpendicular to the light travelling direction as shown in Fig. 2 It should be again stated that polarized light is affected by two dimensional vector train. Then, intensity distribution of electric field can easily be reconstructed by a computed tomography method [10].

Using these technique, electric field distributions have been measured in sphere-sphere and sphere-plane electrodes in nitrobenzene with the highest Kerr constant in liquids [11]. These are axial symmetric, but non-symmetric fields can also be measured [12].

The technique of field measurement is really surprising but has some weak points: one of them was very long period of time at early stage of this study in which laser

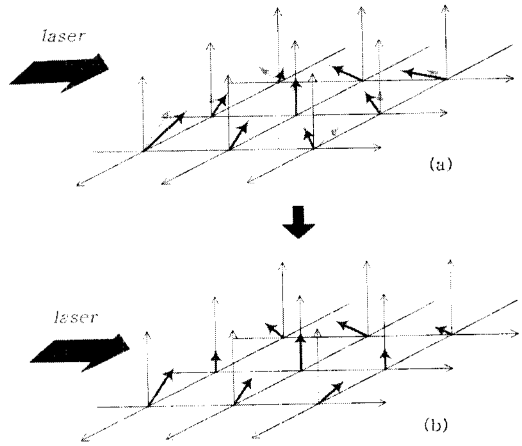

Fig. 2 Three dimensional vector train

beam with thin diameter of about 0.1mm should be scanned at a measured plane and be rotated several directions around the center axis of the electrode tested, which needed several hours for measurement. Then, the laser beam was expanded by optical lenses as a plane beam with 3-5mm width. Moreover, a beam splitter was used to measure two components of polarized light simultaneously. Finally, the improved light system was developed, which was consisted of three sets of optical system and allowed us to measure an electric field distribution in three dimension by only one voltage pulse application and resulted in measuring period of less than some hundreds of milliseconds.

2. Experimental Procedures

Fig. 3 shows the experimental setup for single beam experiments. The polarized light come from the He-Ne laser of 10mW goes into a quarter wave plate, a paralyzer, an electrode cell and an analyzer before arriving at a linear optical sensor of which out put supplies a personal computer to calculate and to reconstruct a field distribution. Two steel sphere electrodes of 7 mmΦ make a gap of 20mm. Two spheres for upper electrode and one sphere for lower electrode make an axial non-symmetric field. Rectangular voltages

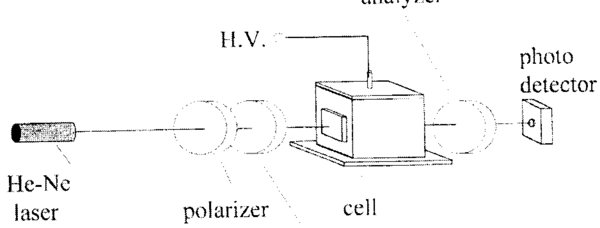

Fig. 3 Schematic diagram of one beam measurement

of 5kV and 10kV are applied to the upper electrode.

Fig. 4 shows the schematic diagram of three optical systems for instantaneous measurement of electric field distribution, being inserted by a beam splitter before the analyzer. Two steel sphere electrodes of diameter of 7mm are used for a gap of 10mm. The measured plane is 3.5mm below the sphere electrode, as in Fig. 5 Six sheets of optical glass are used for the windows of the cell filled with nitrobenzene. A rectangular voltage pulse of 100ms width is applied to the upper electrode. To synchronize all systems, an electric trigger pulse is applied to the personal computer. The light intensity I0 is measured before the electric pulse and after the voltage reaches plateau, light intensity It was measured by 1 ms step. $I_t - I_0$ is the intensity change due to the applied field at time t, 1 to 4ms, as in Fig. 6.

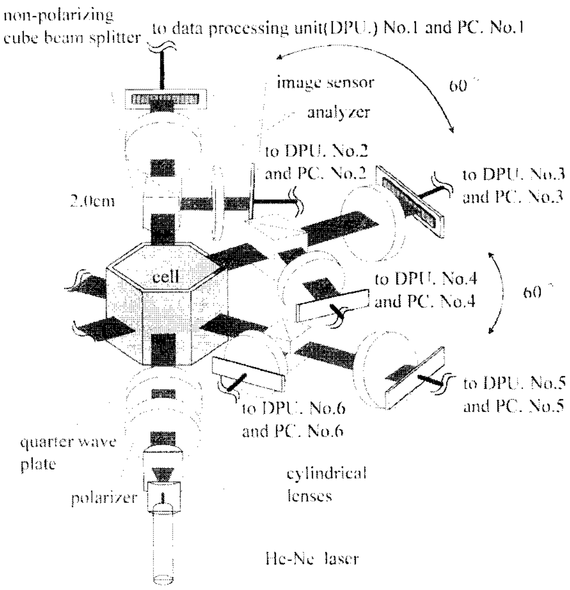

Fig. 4 Schematic diagram of three beam experiments

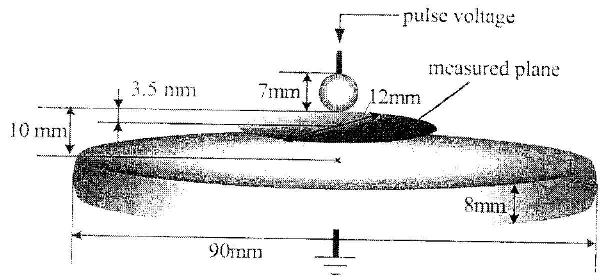

Fig. 5 Sphere-plane electrode

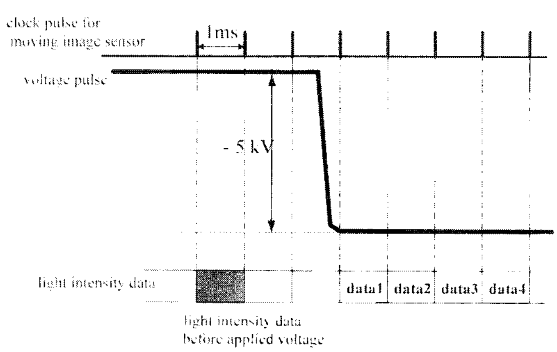

Fig. 6 Measuring time

3. Results and Discussions

On a plane perpendicular to the center axis of sphere-sphere electrode, field distribution is measured as shown in Fig. 7. The lower map shows the projection of field distribution on the measured plane and the upper one is a side view of the field vectors at the line a-b. The difference between measured and calculated field vectors is not recognized, which allow us to apply the other than axial symmetric distributions.

The upper sphere is replaced by two spheres sustained by the same potential as shown in Fig. 8(a) Obtained field map is shown in Fig. 8(b) Three circles in the lower

Fig. 7 Sphere-sphere electrode and field map between them[14]

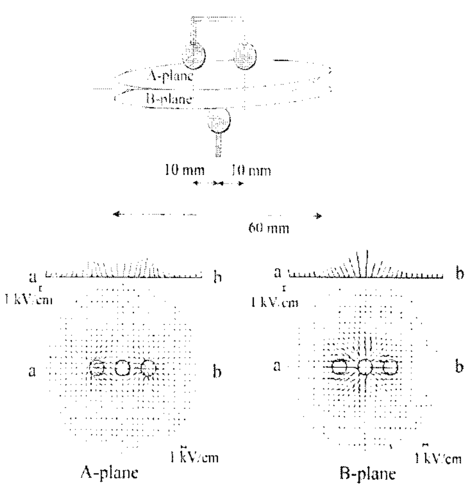

Fig. 8 Two spheres- one sphere electrode system and its field map

map indicate the positions of sphere electrodes. Near the upper spheres vectors are directed towards the sphere in A-plane and those focussed the lower sphere in B-plane. It is clear that non-symmetric distribution of field should be measured by this technique.

To reduce measuring time, three optical systems as in Fig.4 are used. A voltage pulse of 5 kV and 100 ms width is applied to the sphere-plane electrodes of 20mm gap. Fig. 9 (a) shows the field distribution at 0-1 ms. The upper map designates vector distribution on the measured plane and the lower two maps are side view of A-B and C-D lines. Figs 9(b), 9(c), 9(d) are those at 1-2 ms, 2-3 ms, 3-4 ms, being small changes in strength and direction. At the center O coincide with center axis of sphere electrodes, the projection of field vector on the y-z plane shows no change, but indicates random rotation on the x-y plane, as shown in Fig. 10(a). At P 1.13mm from

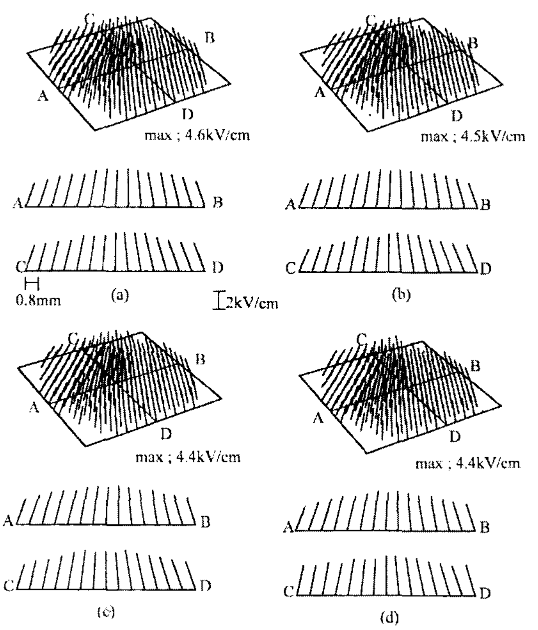

Fig. 9 Field map measured by three optical systems

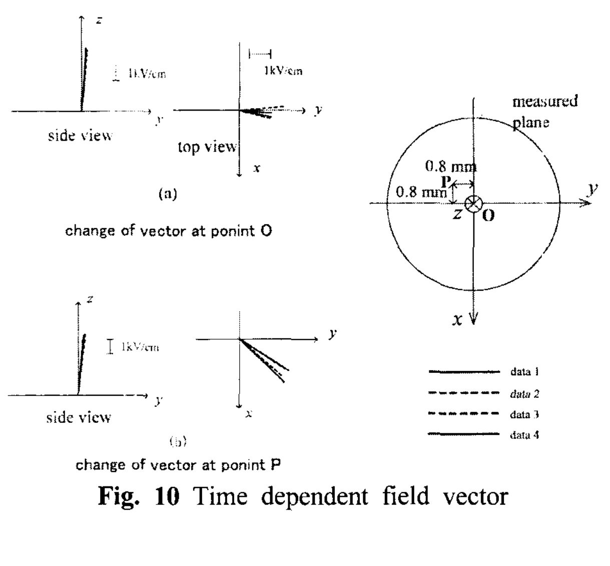

Fig. 10 Time dependent field vector

the point O, similar tendency is observed as in Fig. 10(b).

The rotation may be caused by liquid flow. When a liquid in parallel plane electrodes is subjected by a D.C. field, oil flow would be occurred [13]. The criterion of the flow is next equations,

$$M^2R \geq 161 \qquad (6)$$

$$M^2C^2R \geq 22077 \qquad (7)$$

where $C=(q_0 d^2/\varepsilon V)$, $R=\mu\rho v/\eta$ and $M=(\varepsilon/\rho)^{\frac{1}{2}}/\mu$

q_0 is carrier number, d the gap distance, ε the dielectric permittivity, V the applied voltage [kV], ρ the density, η the viscosity, μ the carrier mobility. Since carrier number q_0 is not known, eq.(6) should be used for the criterion.

For nitrobenzene, $\mu \fallingdotseq 10^{-7}[m^2/Vs]$, $\varepsilon=2.99\times10^{-11}$ $[F/m]$, $V=5.0[kv]$, $\rho=117[kg/m^3]$, $\eta=2.01\times10^{-3}$ $[Ns/m^2]$ give the number of M^2R equal to 746 much larger than 161. Liquid flow in nitorobenzene would be generated in uniform field for given condition. Generally speaking, since liquid flow occurs easily occurred in nonuniform field than in uniform field, the criterion of eq.(6) is also applicable to the sphere-sphere electrode.

Although the literature does not state build up time of the flow, it begins less than 1ms in this case. It is not discussed that the effect of liquid flow on liquid breakdown is not clear, because time to breakdown is much less than 10-6 s. In the near future, discussion of the effect of liquid flow on the conduction and breakdown mechanism by development of this study would be under taken.

It would be possible to discuss breakdown streamer development in liquids, if field strength at or near streamer tip is measured. The strength allows us to calculate potential drop and also carrier number in the streamer stem. Moreover, it should become clear whether the stem is in liquid or gaseous state. If field map near the streamer tip will be depicted, direction of next streamer development from the tip would be discussed which is a dream for breakdown mechanism itself.

Now, we have a ticket for the travel to the final goal.

4. Conclusions

Three dimensional electric field distribution can be measured by this method. Non-symmetric distribution can also be measured. This method results in time dependent measurements down to several milliseconds. Liquid flow may begin at least 1 ms after the voltage applied.

There are some problems, such as large error at fringe of distribution, improvement of reconstruction algorithm and speed of optical sensor.

This method has a possibility of field measurement at or near streamer tip, if sensitivity of light sensor would be improved. These would allow us to discuss mechanisms of breakdown development in liquid dielectrics.

Acknowledgments

The authors thanks to Prof. Kitani for helpful discussion, Mr. Nishimoto for maiking experimental set up and students who contributed the experiments.

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