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A technique for rapid diagnostics of dielectric liquids basing on their high-voltage conductivity

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ABSTRACT

The electrical conductivity of a liquid dielectric is one of its most important properties; however, it is typically measured in the low-voltage range whereas the features of the current passage processes under the effect of strong electric field remain poorly investigated. The paper presents an experimental technique for rapid measurement of the high-voltage conductivity. The current–voltage characteristics obtained with the voltage modulation by a saw-tooth signal underlie the proposed technique. Some examples are given to demonstrate the importance of its application. The experimental data were complemented with the computer simulation of the corresponding processes.

1. Introduction

The electric conductivity is one of the most important characteristics of a dielectric liquid. Despite a long history of its investigation and a number of fundamental works devoted to it (e.g., [1,2]), measuring and understanding the current passage processes is still a topical question, with the corresponding issue being discussed in a number of recent papers [3–6]. On the one hand, the conductivity is an important property that is widely used to calculate the leakage current in high voltage insulation systems and to monitor the health of equipment as changes in conductivity can indicate the presence of one or another process taking place in the bulk, in particular, partial discharges. On the other hand, the understanding the conductivity per se is still a complicated issue since it is a property of the whole system, including electrode material, operating conditions, electric field distribution, etc. [7,8], rather than the intrinsic property of an insulating liquid. Moreover, different techniques for measurement of the electrical conductivity even yield diverse results, which is discussed among specialists in the field of electrophysics of liquids [5,7,9].

Usually, only the value of the so-called low-voltage conductivity measured in a cell with plane-parallel electrodes at low electric field strength is generally used for diagnostics of liquid dielectrics. However, the present work is devoted to a perspective technique for the rapid measurement of the high-voltage conductivity (i.e., the effective conductivity of liquid in the case when strong electric field (>10^7 V/m) is applied to the latter, with injection processes and emergence of electrohydrodynamic (EHD) flows being enabled) of a liquid basing on the current–voltage characteristic obtained with the voltage sawtooth modulation. Its application to the investigation of high-voltage conductivity of dielectric liquids was suggested in the experimental work [10], where the corresponding data sets were called the dynamical current–voltage characteristics or DCVCs. Later, a similar approach was realized in investigation of the conductivity and relative permittivity of conducting liquids [11], with the corresponding technique being titled triangular waveform voltage one. Also, a similar technique was suggested in Ref. [12] where some experimental data were presented for the needle-plane electrode system with AC voltage being used.

Though the idea was suggested and the first experimental results were obtained many years ago, there has been actually no use of the DCVC until recently due to complexities in the interpretation of experimental data. In particular, one of the main issues of the data analysis is caused by the presence of the capacitive current that has high value in comparison to conduction current owing to high modulation rate (about several kilovolts per second) and low conductivity of the medium. However, presently all issues are resolved: a method for measuring and subtracting the capacitive

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electric current is suggested, and a computer model is developed for the description of the high-voltage current passage through low-conducting liquid without disregarding the injection and dissociation mechanisms of charge formation as well as migration and convection charge transport [13–15].

2. Pros and cons of the high-voltage conductivity

The high-voltage current passage through a liquid dielectric presents a complicated issue with the Ohm's law being poorly applicable to describing the conduction processes. The total electric current passing through a cell increases under the effect of a strong electric field due to the emergence of high-voltage charge formation (i.e., the injection and field-enhanced dissociation [16]) and the convective mechanism of charge transport, i.e., an EHD flow. Thus, the actual conductivity of a dielectric liquid is a function (or even a tensor) rather than a constant, especially in the case when the emerging EHD flow causes ion streamlines to differ from electric field lines [17]. However, using such a description in practice is a complicated approach and hereinafter the simplified understanding of the conductivity as a ratio of the voltage and current will be implied.

The control of the high-voltage conductivity proper is of great interest and appears to be the most perspective and sensitive method for the examination of the state of a dielectric liquid. This is so for the following reasons. Firstly, it is the conductivity that governs the actual value of the electric current in high-voltage equipment. Secondly, the measurement of its value represents an easier task due to higher values of the signal. Thirdly, the appearance of even a small amount of an impurity in a liquid can be indicated by a change of its value. Besides, the technique for diagnostics of the dielectric-liquid state on the base of the measurement of high-voltage conductivity has several advantages over others (e.g., measurement of the breakdown strength [18] or dissolved-gas analysis [19,20]), since it is a nondestructive one and there is no need to use complicated special-purpose equipment. Moreover, a special interest to the high-voltage conductivity is provided by its relation to emergence of the electroconvection. Earlier [10], it was stated on the basis of the experimental data analysis that the increase of conductivity begins immediately after the onset threshold of EHD flows and continues as their intensity increases. Thus, the change in the intensity of electroconvection can be revealed by measuring the high-voltage conductivity without necessity to use the particle image velocimetry technique [21].

Despite a number of advantages, the measurement of high-voltage conductivity is still of very infrequent use for diagnostics of a dielectric-liquid state. First and foremost, it is caused by difficulty of getting stable and reproducible data even in a comparably simple electrode system [5,22]. Further, an electrical breakdown of the interelectrode gap can take place during the corresponding measurements, since most (currently available standard) test cells exhibit low dielectric strength [7]. To reduce the probability of the breakdown but heighten the intensity of high-voltage charge formation, systems with highly non-uniform electric field distribution are generally utilized [6,23,24]. In turn, the latter leads to creation of favorable conditions for the emergence of intensive EHD flows that cause the appearance of electroconvective mechanism of the conductivity and complicate the analysis of the results. Besides, until recently, there has actually been no complete computer model that enables treating various high-voltage phenomena concurrently.

3. Experimental technique and some simulation results

Schematic diagram of the experimental set-up is presented in Fig. 1. The set-up consists of high-voltage source *VIDN–30*, high-frequency generator *AKIP–3405* (for voltage modulation), two analog-to-digital converters *L–Card E14–140*, CCD camera *EVS-746-USB*, and a transparent test cell that is filled up with the liquid under study. Blade–plane (mainly) and wire-plane electrode systems with highly non-uniform electric field distribution were dealt with. In the present study, a blade (with 10 ± 1 μm curvature radius and 6 cm length) and wire (with 50 ± 2 μm radius and 6 cm length) were used as the high-voltage electrode, whereas isooctane, engine oil and olive oil served as working liquids, the interelectrode gap being 11 mm long. The voltage and current were measured with the help of two separate high-speed analog-to-digital converters. A CCD camera recorded the images of interelectrode gap illuminated by laser to control the presence (or absence) of mechanical impurities in the vicinity of the electrode tip during the measurement.

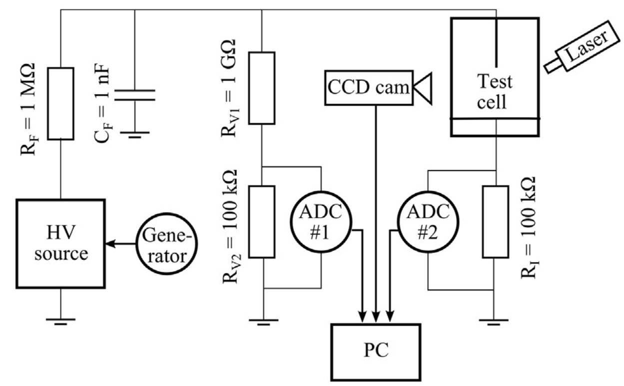

Fig. 1. Schematic diagram of the experimental set-up.

Blade–plane electrode system was chosen for the following reasons. Firstly, it features highly non-uniform electric field distribution, which provides the conditions for activation of high-voltage charge formation mechanisms without producing the electrical breakdown of liquid in contrast to standard test cells [7]. Secondly, the system provides intensive and stable EHD flow that helps to mix the liquid and shorten the steadying process. Otherwise, e.g. when the standard cell with plane electrodes is used, an EHD flow either emerges and disturbs stability of the electric current [22] (since the flow has a non-regular structure) or fails to do so but the steadying process lasts for a long time [9]. Thirdly, the use of blade–plane system enables simulating charge transport processes in the 2D approach, which is of great importance since the complete set of EHD equations (i.e., resource-intensive task) is to be calculated. Fourthly, such a geometry allows experimental investigation of the EHD flow and hence electroconvective charge transport. The corresponding study was conducted for the olive oil using the particle image velocimetry technique, and the results are presented below. At last, the blade–plane electrode configuration appears to be a more appropriate system as compared with the needle-plane one since the latter exhibits instable EHD flows (especially in the case of the strong injection) [25], which, in turn, can lead to electric current fluctuations [13] and distort experimental data [12].

In the case of low-conducting liquids, the capacitive current can affect the shape of the characteristics. As opposed to approach described in Ref. [12], a method for subtracting the capacitive current from the total one was implemented in the developed technique. The capacitance is measured experimentally, the electrodes being fed with a short voltage pulse with sufficiently low magnitude and steep rising edge. Then, the electric current passing at the first instant of time consists of the capacitive component only. After computing the capacitance, the capacitive current is evaluated by the observed time dependence of the voltage: