Intensification of electrohydrodynamic flows using carbon nano-tubes

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Abstract. Study of behaviour of floating up bubbles in the mixture of transformer oil with carbon nanotubes under the action of high electric field was carried out. The possibility of using carbon nanotubes to create hydrodynamic flows in a liquid dielectric at a very low concentration of nanotubes is shown. It is assumed that the mechanism of the formation of flows is the injection of charge from the surface of nanotubes.

1. Introduction

The study of partial discharges (PDs) in liquid dielectrics has quite a long history. Despite this it remains a very important field of physics of electrical phenomena in dielectrics. There are two basic factors determining practical significance of these studies. All possible PDs events in dielectric liquids are divided into two primary types. The uncompleted streamers that can form both from the electrode surfaces and in the bulk of a dielectric \cite{1} belong to the first type. The second type includes the local electrical discharges in bubbles that always exist in a liquid. Both types of PDs lead to aging of insulation in high voltage electrical equipment that increases the probability of the electrical breakdown of insulation and accident that causes the equipment failure. This is the first factor. The second factor is that the probability of breakdown of the insulating gap is proportional to the intensity of PDs in isolation that is their repetition rate and the total electric charge flowing through the external circuit due to PDs. Therefore, the registration of the PDs activity is one the promising methods for assessing the state of insulation in operating high-voltage devices.

The probability of the PD initiation in helium bubbles in transformer oil under the conditions of lowered natural radiation was studied in the works \cite{2,3}. The bubbles were floating up between the flat electrodes that allowed the authors to expose them to the high electric field for shot time intervals. It was stated that the probability of initiating a discharge in helium bubbles in transformer oil is radically reduced and strongly depends on the strength of the applied electric field. This effect was explained by the small number or even the absence of initial free charges in the gas that can initiate an electric discharge in the bubble. To test this assumption, similar measurements were performed in \cite{2–4}, in which floating up bubbles were exposed to short periodic pulses of X-ray radiation. It was shown that X-rays initiate PD in the bubbles. The probability of a bubble breakdown increases tenfold, which confirms the role of primary electrons in initiating PDs in the bubbles.
In this paper we investigate the dynamics of the floating up bubbles under the assumption that there is another way to ensure the appearance of initiating electrons. We added carbon nanotubes (CNT) to transformer oil before the application of high electric field. We expected that CNT can play a significant role in PD inception because of two reasons. First, CNT produce very high electric field at their ends. Second, it is well-known that CNT in vacuum serve as very good sources of free electrons due to injection from their surface [5]. It can be assumed that they are also a source of free electrons in transformer oil. In addition to initiating PDs in bubbles, it was found that the CNT additives lead to the development of intense hydrodynamic flows in the electric field, which may be significant for practical applications. This work studies the possibility of development of the electrohydrodynamic flows in the transformer oil with added CNT under the action of the high electric field. The other effect will be described elsewhere.

2. Preparation of mixtures and experimental setup

The experiments with transformer oil were performed, which was cleaned, dried, and degassed thoroughly before the use. Then, the mixtures of transformer oil with carbon nanotubes were prepared. It is well known that the dry carbon nanotubes easily stick together forming agglomerates looking like flakes. They are not suitable for preparing any homogeneous mixture with a dielectric liquid. Therefore, we used a ready-made mixture produced by the company "OCSIAL" [7], containing 0.2 percent single-wall carbon nanotubes (SWCNT) in a mixture of 0.4 percent polyvinylbuteral in isopropyl alcohol, in which the nanotubes are distributed fairly uniformly. This mixture with nanotubes was added to transformer oil and then thoroughly mixed with the oil using a magnetic stirrer and 600 W ultrasonic stirrer. The mixtures with different concentrations of CNT were prepared and tested. The diameter and the length of nanotubes were 1.6 nm and 5 μm, respectively.

Then, the mixture of transformer oil with CNT was poured into the experimental cell. The sketch of the cell is shown in figure 1. The plexiglass cell had the shape of a cube with the length of the inner edge equal to 10 cm. The flat electrodes with round edges were mounted vertically at a distance of 10 mm between them (see figure 1).

![Figure 1](image-url)

**Figure 1.** The cell for registering the processes in the gap with the mixture of transformer oil with CNT. 1 – cubic cell of plexiglass, 2 – optical window, 3 – transformer oil, 4 – electrodes, 5 – helium bubble, 6 – supply system of helium bubbles, 7 – video camera.

Two transparent windows were used for optical registration of the processes in the gap between the electrodes. A video camera focused on the center of the gap allowed recording the events in the gap at a rate of 1200 frames per second. Additional lightning was used. The helium bubbles were blown out
using a needle mounted in the bottom of the cell. The size of the bubbles varied only slightly and was about 2 mm. The bubbles floated up between the electrodes along the central line in the gap with the approximately constant speed.

The AC voltage of the frequency of 50 Hz was set manually by adjusting the input voltage on a laboratory transformer in the range from 11 V to 17 V. Then this voltage was transformed to the values from about 8 kV to 12.5 kV and applied to the cell. The electrical scheme was described in details in [6].

Previously, experiments were performed with a mixture of oil and isopropyl alcohol, which excluded the influence of isopropyl alcohol on the initiation of discharge in the bubbles.

3. Experiments
Several experimental series with floating up helium bubbles were performed. First, the bubbles were ensured to flow up strongly vertically along the straight line that passes through the center of the gap. It was shown earlier in [4,6] in the experiments with pure transformer oil that two effects can be observed after PD in a bubble. One of them is that the bubble elongated during PD and then oscillated for some time. Nevertheless, its trajectory remained the same straight line. Another one is that the bubble could break up into two (sometimes three) smaller bubbles that continued moving along their own linear vertical trajectories after several oscillations. We suggested that the movement of bubbles serves a good indicator of hydrodynamic flows.

Second, the experiments were carried out inside the room that was carefully screened from external sources of radiation. At these conditions, electrical discharges in bubbles at the voltage corresponding to the Pashen’s law were not observed in pure transformer oil [2,3]. This absence of PDs was explained by the lack of primary electrons that could initiate the electrical discharge in gas. This idea was confirmed by the experiments with pulse X-rays source.

Two effects were observed after we had added carbon nanotubes to transformer oil. Highly dispersed mixture of nanotubes caused the initiation of PDs in floating up bubbles at the amplitude of applied voltage corresponding to the Pashen voltage for helium bubble and higher.

At relatively high concentrations, the formation of agglomerates of carbon nanotubes was observed. In the electric field, these agglomerates had the shape of filaments oriented along the electric force lines. These filaments can be seen in figure 2 as short dark horizontal strokes. At the relative CNT mass concentration of $3.3 \times 10^{-8}$, these agglomerates became visible in the gap during $\sim 1$ ms after voltage application.

![Figure 2. Partial discharge in helium bubble. $V_{app} = 8.8$ kV.](image)

The typical PD in a single bubble is shown in figure 2. The entire process in the figure took about 70 ms or 7 half-periods of voltage. After breaking the bubble into two child bubbles the child bubbles carried opposite electric charges that forced them to make three oscillations about the line of the movement of the parent bubble. Then the child bubbles continued to move straight along parallel
vertical lines. The bubble movement was supposedly governed by electrical forces that disappeared after the charges in the bubbles relaxed (i.e. during collision of the bubbles).

Figure 3 shows the frames of movement of bubbles between the electrodes at the amplitude of the applied voltage $V_{\text{app}} = 9.5 \text{ kV}$. Two large agglomerates (filaments) of nanotubes are seen clearly along with many small agglomerates.

![Figure 3](image)

**Figure 3.** Change of the trajectory and the shape of bubbles near the tip of CNT agglomerate. $V_{\text{app}} = 9.5 \text{ kV}.$

These large agglomerates seemed to be in contact with the left electrode from time to time. Namely, we observed small movements of the large agglomerates along electric force lines (in the direction perpendicular to the electrode surface). The agglomerates approached the electrode and bounced back off its surface at the distance of about 0.5 mm after some time. Then they returned. When the bubble approached the tip of the lower CNT filament it declined from its straight pathway to the right (in figure 3). The bubble deformation under the action of AC voltage is regular and periodic [8]. In contrast, the bubble deformation in figure 3 began with its elongation toward the right electrode that can be due to the increased value of electric field near the filament tip. However, then the bubble shape began to change irregularly. Different parts of the bubble were deformed to different extent as the bubble migrated to the right. We think that the bubble was carried away by the flow of liquid. The bubble continued to move upright after it had reached the right electrode. Probably it went away of the horizontal flow. Similar dynamics were observed for the bubble below and many subsequent ones. This effect disappeared after some time ($\sim 1.58 \text{ s}$). This happened after the oil layer of the thickness of $\sim 1 \text{ mm}$ appeared between the filament and the electrode. The bubbles passed by the tip of the filament moving along the straight line. Nevertheless, during this period the shapes of the bubbles were changing significantly when the bubbles entered the spatial region near the carbon filament tip. This period lasted $1.3 \text{ s}$. Then, the carbon agglomerate contacted the electrode again and we observed another period with developed flow (bubbles declined significantly from their initial pathway). This behavior repeated with other agglomerates.

Figure 4 shows the frames from video record of bubble dynamics at the voltage amplitude $V_{\text{app}} = 10.2 \text{ kV}$. The middle bubble in the group of three bubbles (left upper frame) approaches a group of nanotubes located very close the left electrode. In the next frames, we see that the bubble is moving and elongating to the right which indicates the presence of fluid flow. Then, the PD takes place in the bubble. The discharge not only destroys the bubble but leads to the formation of the spatial structure similar to a streamer in liquid. This structure decays very quickly ($\sim 4.5 \text{ ms}$) into the cluster of small bubbles. These bubbles are carried away by the flow of liquid to the right electrode. When approaching the right electrode this cluster disintegrates into two groups. One of them moves up and another one moves down probably because the stream of the fluid spreads over the electrode surface. The next bubble (the lower one on the first slide) also enters the flow, which can be seen by the change in its trajectory and characteristic deformations. In contrast to the middle bubble, there is
therefore, it is carried away to the right electrode with the flow and then moves straight up.

**Figure 4.** PD in bubble, “streamer”, formation of gas cluster in the microflow of transformer oil, originated from CNT filaments. $V_{\text{app}} = 10.2$ kV.

Thus, we may conclude that the moving bubbles can not create noticeable hydrodynamic flows while the presence of CNT agglomerates can produce them.

4. **Discussion**

We observed the behavior of the bubbles, indicating possible existence of the hydrodynamic flows near the CNT filaments. The initiation of PDs in floating up bubbles also indicates the presence of free electric charges in transformer oil or at the oil-gas interface.

The estimations of the sizes of the CNT filaments give its length from 3 mm to 3.5 mm and thickness of about $250 \, \mu\text{m}$. This filament is at least of the order of magnitude thinner at its tip than in the middle part. If we assume that the very tip of the filament is one nanotube, then we can evaluate the electric field at the tip as $10^9 \, \text{V/cm}$. This is enough for electron injection from the nanotube tip. The real fields have to be significantly lower. Nevertheless, the values of the real fields are assumingly sufficient for the field electron emission in accordance with the Fowler–Nordheim equation. There are many devices that use nanotubes as the emitters of electrons [9].

It is well known that there are two mechanisms of injection of electric charges that are responsible for the initiation and the development of the electrohydrodynamic flows. These are injection from the electrode surface and dissociation in volume. For low conductive liquids, the mechanism of injection is prevalent [10].

Thus, at very small concentrations, the CNT additives do not initiate the electric breakdown even in rather thin layers of dielectric liquids under the action of the moderate electric fields. Based on our
experiments, we can say that the carbon nanotubes as additives can be a reason for generation of microflows in liquid dielectrics.

**Conclusions**

Thus, at an extremely low concentration of nanotubes and with their good dispersion, the movement of the bubbles remained regular (vertical in an almost straight line). At higher concentrations of nanotubes, CNT agglomerates appeared having the shape of filaments oriented along the electric field. Near these filaments, intense hydrodynamic flows between the electrodes developed, as evidenced by the complex trajectory of each of the bubbles that fell into the flow area. These flows were observed both with partial discharges and in their absence. Thus, quite low electric field can produce electrical flows in dielectric liquids if small amounts of highly dispersed carbon nanotubes are added. This effect can be used for intensification of hydrodynamic flows in dielectric liquids in engineering devices.

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