SHORT
COMMUNICATIONS

Determination of the Hydrogen Diffusion Coefficient in Transformer Oil

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Abstract—The hydrogen diffusion coefficient in transformer oil is determined by optically monitoring the dynamics of the hydrogen bubble dissolution in pure degassed oil. The diffusion coefficient is found to be roughly two orders of magnitude smaller than those determined earlier. This result is of great importance for chromatographic analysis of gases dissolved in transformer oil, since it gives grounds to suspect that hydrogen is not so volatile as implicitly believed in a number of works. Accordingly, the reliability of diagnostic data for high-voltage oil-filled equipment improves.

Chromatographic analysis of oil-dissolved gases is a basic procedure for diagnostics of expensive high-voltage oil-filled electrical facilities. Gases migrate in oil by diffusion and due to flows. In addition, diffusion plays a major role in keeping gases in samplers and in extracting them for analysis. Hydrogen bears most information and, at the same time, is the most difficult to analyze, since it is generated in nearly any energy process carried out in electrical facilities. It is intuitively supposed that hydrogen, having very small atoms, is easy to escape from the oil sample at all stages of diagnostics. We think, however, that the coefficient of hydrogen diffusion in transformer oil has been determined incorrectly.

The hydrogen diffusion coefficient in oil was determined only in [1]. The gas was extracted from the liquid using a cylindrical vessel partially filled with oil. The oil layer was 8 cm thick. Prior to experiments, either air was evacuated from the upper part of the cylinder or hydrogen diffused into the air medium. In the former case, the gas almost completely evolved from the oil for about 0.5 h. In the latter, the hydrogen concentration in the gas phase after 0.5 h was even lower than 5%. Experimental data were processed under the assumption that diffusion is quasi-stationary.

However, there are circumstances that put in doubt the correctness of the diffusion coefficient determination. First, the diffusion coefficient is anomalously high, 10^{-7} m²/s. For comparison, the coefficient of self-diffusion of water in water equals 2.5×10^{-9} m²/s [2]. Since oil is viscous, the diffusion coefficient of any molecules is expected to be still lower. Second, diffusion into an evacuated space and into a gas-filled space must have the same rate, whereas these rates in [1] differ by almost two orders of magnitude (without using ultrasound). Third, in [1], the hydrogen distribution in

transformer oil is assumed to be quasi-steady (in this case, the flux is found by dividing the concentration by the dimension of the respective region). Actually, however, the situation is typical of a highly unsteady process.

In this work, we determined the gas diffusion coefficient by dissolving gas microbubbles in a liquid unsaturated with a gas [3]. This method is simple and comprehensible; in addition, attendant processes are similar to those observed in oil-filled electrical facilities. To obtain desired data, it is necessary to know gas solubility C and the dependence of microbubble radius R on time τ.

From the relationships given in [3] for the case of complete dissolution of a bubble near the wall, an approximate expression describing the dissolution dynamics of an ideally spherical bubble can be derived. Then, having solved the resulting quadratic equation, one easily obtains an equation for the diffusion coefficient,

$$\frac{dR}{dt} = CD\left(\frac{1}{R} - \frac{1}{(\pi D \tau)^{1/2}}\right). \tag{1}$$

We devised a special experimental cell in the form of vertical cylinder *1* (Fig. 1) with needle *2* built in the wall through which a gas to be diagnosed is delivered to the cell. The bottom and cover *4* of the cell were made of glass to observe the gas microbubble dissolution. The cell is filled with degassed transformer oil *6*, and the cover prevents air from being penetrated into the system. The oil-filled cell is placed under a microscope, and a bubble of a test gas is introduced into the oil through a gas supply tube and the needle. The bubble is held by grid *3*. The grid is a critical element of the system, since it "makes" the dissolving bubble quiescent and provides its sphericity. The dissolution
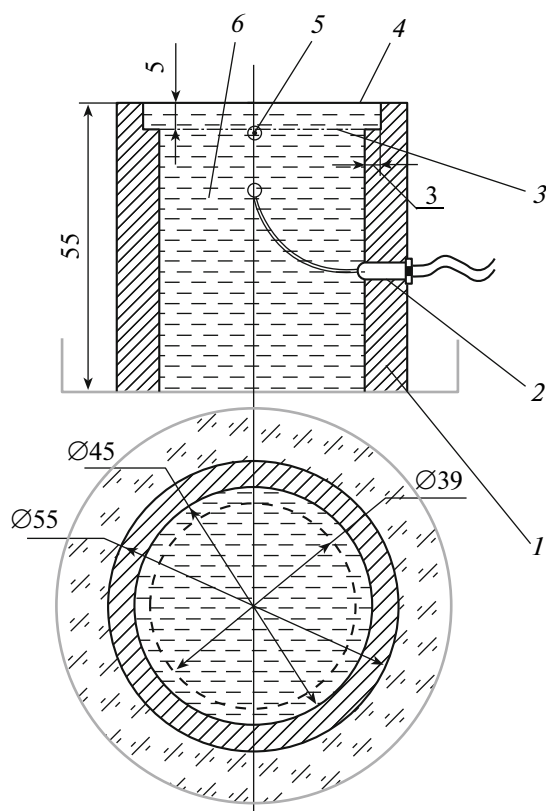
Fig. 1. Design of the experimental cell: (*1*) cell body, (*2*) needle, (*3*) grid, (*4*) cover, (*5*) gas microbubble, and (*6*) oil.

dynamics of the hydrogen microbubble was recorded with an ocular video camera connected to a PC.

Gas sampling and delivery were carried out using an Elchrom trier [4], which represents an all-glass syringe with a lap-fitted piston and a three-way vacuum cock. The first outlet is connected to the needle of the cell; the second, to the container with the test gas. The container was equipped with a fine-tune valve to avoid pressure surges in the system. The piston of the syringe was covered by a vacuum lubricant to avoid leakage of the gas and prevent air from being penetrated into the system. Immediately before the experiment, the gas path was blown out by the test gas to remove air.

After the dissolution of the microbubble had been recorded, the video image was decomposed into frames (Fig. 2). Framing allows one to take necessary measurements and plot R^2 versus time t (Fig. 3).

The scale was determined by measuring the diameters of the bubble and wire (of which the grid was made). The diameter of the wire was 0.11 ± 0.01 mm.

Taking into account the linear dependence of R on D and knowing hydrogen solubility C ($C = 0.05$ [5]) at 20°C, one can find the diffusion coefficient.

The hydrogen diffusion coefficient in transformer oil at 20°C determined by (1) equals 4×10^{-9} m^2/s,
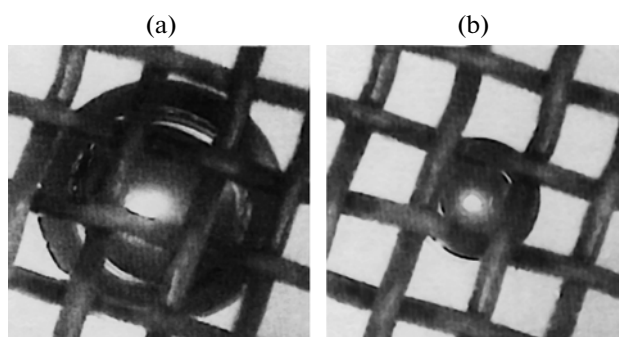

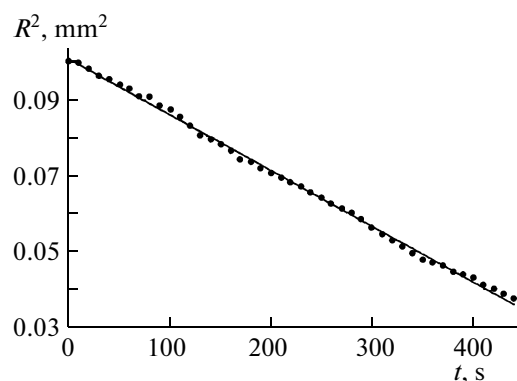**Fig. 2.** Hydrogen bubble at the (a) initial and (b) final instant of recording.

Fig. 3. Hydrogen microbubble dissolution diagram.

which is almost two orders of magnitude smaller than that determined earlier [1].

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