Evaluation of the Electrical Insulating Properties of Paraffin

C. Dotterweich, S. Harrer, M. H. Zink
University of Applied Sciences Würzburg-Schweinfurt
Schweinfurt, Germany
Christian.Dotterweich@fhws.de

***Abstract*—The insulation system of high voltage applications is often highly thermally stressed. To improve the thermal behavior of high voltage applications phase change materials (PCM) are one promising group of materials, due to their ability to store heat during a phase change while keeping the temperature constant. In this paper paraffin is investigated with respect to its electrical insulating properties, i.e. the breakdown voltage and electrical conductivity were determined. For determination of the breakdown voltage a suitable test cell was developed which allows measurements at temperatures up to 120 °C. The electrical conductivity measurements were carried out by means of the PDC method. The breakdown voltage measurements show that the electrical strength in the liquid phase is comparable to that of mineral oil. The PDC measurements of liquid paraffin show a temperature- and field-dependent conductivity. Hence, an ion transport, known from mineral oil, is assumed to be the dominating charge transport mechanism.**

Keywords - phase change materials; paraffin; breakdown voltage; electrical conductivity

I. Introduction

In high voltage equipment, the maximum operating temperature of the insulating materials is often the limiting factor for the transmission of electrical energy. To avoid a damage of the electrical insulation the temperature has to be limited by cooling or by limitation of the rated current. Another possible solution is to stabilize the temperature during periods of high loads by using materials with a high heat storage capacity.

In this paper, paraffins that provide a large heat storage capacity are investigated with respect to their electrical insulating properties. Thus, the electrical conductivity and the temperature-dependent breakdown voltage are determined and compared to mineral oil.

In the subsequent chapter II the chemical and thermal properties of paraffins are described. Chapter III deals with the development of a test cell for determination of the breakdown voltage and in chapter IV a method to evaluate the electrical conductivity is described. Finally, chapter V shows the results and discussion of the measurements.

II. Paraffin

Phase change materials (PCM) are able to store heat during a phase change from solid to liquid while they remain at a constant temperature [1]. Paraffins are one promising group of PCM for thermal optimization of electrical components due to their high heat storage capacity and availability in a large temperature range. Moreover, they provide a very similar chemical structure compared to mineral oil which is commonly used in high voltage insulation. Paraffins are organic materials consisting mostly of long-chain hydrocarbons with the general chemical formula C_nH_{2n+2}, where n indicates the number of carbon atoms [2].

The melting point of paraffin increases with the number of carbon atoms. Therefore, it is possible to select a paraffin whose melting point is suitable to the designated application. Paraffins are already used in various technical applications, e.g. for thermal storage in buildings [1].

Beside the thermal properties, it is important to investigate the electrical properties in order to qualify the material for the use in high voltage applications. Thus, the electrical conductivity and the breakdown voltage in the solid and liquid state were determined. To perform temperature-dependent breakdown voltage tests, a suitable test cell, described in the following chapter, was developed.

III. Test cell for measurement of electrical breakdown

To determine the breakdown voltage of paraffin in the solid and liquid state a new test cell was developed. It allows breakdown tests at temperatures up to 120 °C which is necessary to ensure a complete melting of paraffins with a high melting point. The test cell was designed by following the standard IEC 60156 for the determination of the breakdown voltage of insulating liquids [3].

According to the standard, the material of the test cell has to be nonconductive, transparent and chemically inert towards the liquid sample. To fulfill these requirements and to allow measurements at temperatures up to 120 °C it was decided to use Makrolon® (polycarbonate) provided by Bayer AG as material for the test cell. To obtain more values of breakdown voltage at a single material sample, the test cell was built with four similar chambers. Each chamber includes a pair of electrodes and can be filled with the specimen.

For the high voltage connection, a cylinder (Fig. 1) was designed to ensure a sufficient electrical insulation. The cylinder is made of polytetrafluorethylene (PTFE) due to its excellent dielectric, mechanical and chemical properties. Inside the PTFE cylinder there is an aluminum cylinder for shielding the bare high voltage conductor at the end of the cable. To avoid discharges at the top of the aluminum cylinder a toroidal shaped electrode is placed at the PTFE cylinder. Hence, the toroidal shaped electrodes are connected to the inner aluminum cylinder.

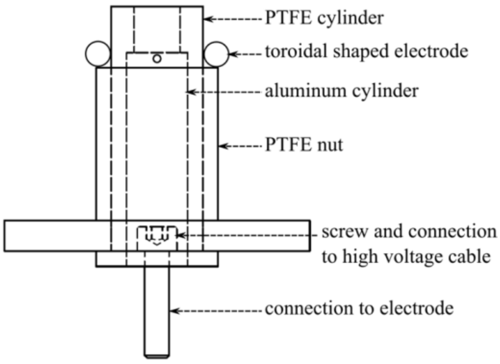

Figure 1. Scheme of the PTFE cylinder for high voltage connection

The high voltage electrodes used inside are designed according to IEC 60156. The electrodes are connected to screws which are fixed at the PTFE cylinder and which guarantee the correct electrode distance.

IV. ELECTRICAL CONDUCTIVITY MEASUREMENT

To determine the electrical conductivity of paraffin, the polarization and depolarization current (PDC) method was used [4]. This method is widely used to investigate the electrical insulating properties of a material because it takes both into account, the AC displacement field and the DC conduction field. The measured current I thereby is given within an area A as a function of the applied field E by,

$$I = \int_A \varepsilon_0 \cdot \varepsilon_r \cdot \frac{\partial \vec{E}}{\partial t} \mathrm{d}\vec{A} + \int_A \sigma \cdot \vec{E} \mathrm{d}\vec{A} \tag{1}$$

where the first term indicates the AC displacement field with the permittivity $\varepsilon_0 \cdot \varepsilon_r$ and the second the DC steady-state conduction field with the electrical conductivity σ. During a PDC measurement both, the transient and steady-state DC current response are measured. The PDC method is a step response measurement in time domain. The measurement is divided into three parts: First, the sample is short-circuited to guarantee a thermodynamic equilibrium in the specimen. Second, a voltage step is applied to the specimen and a time-dependent polarization current is measured. Third, the specimen is short-circuited again and a time-dependent depolarization current is measured. The electrical conductivity $\sigma(t)$ then is calculated taking into account the applied voltage U, the electrode area A, the sample thickness d and the measured time-dependent current $i(t)$:

$$\sigma(t) = \frac{i(t)}{U} \cdot \frac{d}{A} \tag{2}$$

If the steady-state is not reached at the end of the polarization phase, the electrical conductivity is calculated out of time-dependent currents and therefore called time-dependent electrical conductivity.

In Fig. 2, the test cell for the determination of the electrical conductivity of liquid samples is depicted. The test cell consists of a three-electrode arrangement including a measuring electrode, high-voltage electrode and a guard-ring to achieve a uniform electrical field. The measuring electrode is connected to a *PDC-Analyzer* [5] which can measure currents in the range of picoampere. The material sample (here: liquid paraffin) is placed between the measuring electrode and high voltage electrode. In case of a liquid material sample, spacers define the sample thickness d. For temperature-dependent measurements the test cell is placed inside a temperature-controlled oven.

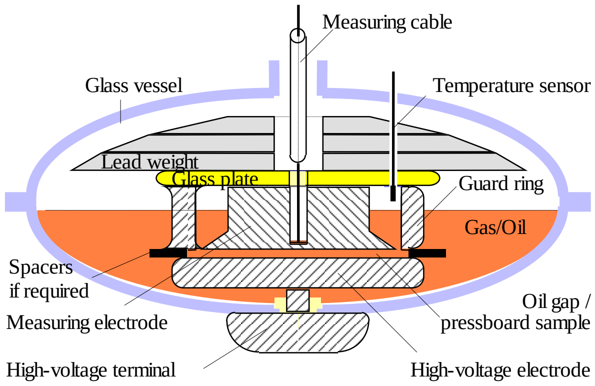

Figure 2. Test cell for determination of the electrical conductivity [4]

V. INVESTIGATION OF ELECTRICAL INSULATING PROPERTIES OF PARAFFIN

To evaluate the electrical insulating properties of paraffin a technical-grade, high purity paraffin (PARAFOL® 18-97, n-Octadecane, nOD) provided by Sasol Germany GmbH was chosen. The melting point of nOD is at 26.9 °C [6]. For sample preparation, nOD was molten at a temperature of 40 °C in a temperature-controlled oven for both, electrical conductivity and breakdown voltage measurements. Afterwards the liquid paraffin was filled in the pre-heated test cells.

A. Breakdown in the liquid state

The breakdown voltage of paraffin in the liquid state was determined at an electrode distance of 1 mm and at a temperature of 40 °C. The applied AC voltage (50 Hz) was increased by 1 kV/s until breakdown occurred. The test procedure was divided into several measurement cycles. Therefore, each chamber was stressed with six breakdowns in a row. At each measurement, one electrode was set to high voltage potential and the other seven electrodes were grounded. According to IEC 60156 the time between each breakdown was 2 min. This time delay allows the specimen to recover from the previous breakdown. With this procedure 24 values were obtained per measurement cycle. Between two measurement cycles there was a time delay of 30 min. Overall 120 values of breakdown voltage were obtained at a single material sample.

Fig. 3 shows the results of the breakdown voltage tests on liquid nOD. Every measurement cycle includes 24 values of measured breakdown voltages. Every dot indicates the mean value out of 6 breakdown voltages. The dashed-dotted line shows the averaged breakdown voltage of 41.44 kV ± 3.9 kV calculated out of all measured values. To compare the results of nOD, tests with a dried and degassed mineral oil (Shell Diala S3 ZX-IG) were performed using a commercially available breakdown voltage tester provided by BAUR GmbH. The measurements were carried out with an electrode distance of 1 mm and an AC voltage ramp of 1 kV/s.

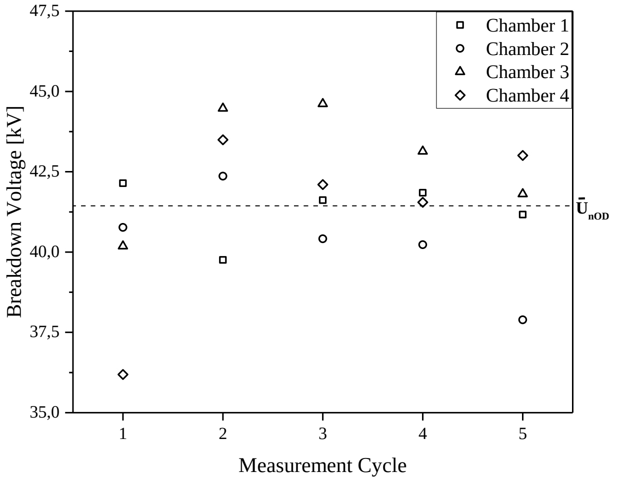

Figure 3. Determined breakdown voltages at an electrode distance of 1 mm and a temperature of 40 °C. The dashed-dotted line shows the mean value of breakdown voltages of nOD.

The results show a breakdown voltage of 45.3 kV ± 3.9 kV. Compared to the results of nOD it can be stated that paraffin in the liquid state shows a high breakdown strength comparable to that of mineral oil.

B. Breakdown in the solid state

For the breakdown voltage tests in solid state, the sample was filled in the pre-heated test cell at a temperature of 40 °C. Afterwards the test cell was cooled down to 20 °C to ensure complete solidification. Then, the breakdown voltage was determined at an electrode distance of 1 mm and at 20 °C. The determined breakdown voltages were between 5 kV and 9 kV. Compared to the results in the liquid state of nOD the breakdown voltage in the solid state is remarkably lower. This can be explained by the macroscopic structure of the sample in the solid state. Due to defects and voids within the specimen, the electrical breakdown strength is significantly lowered by field migration into these defects. Further investigations showed, that solid nOD shows a high crystallinity and therefore the formation of defects is enhanced. To improve the dielectric strength in the solid state, a paraffin with a more amorphous structure needs to be used [7].

C. Electrical conductivity in the liquid state

For determination of the electrical conductivity of nOD in the liquid state, the sample was filled in the pre-heated test cell (Fig. 2) at 40 °C. The PDC measurements were done at two temperatures (40 °C; 70 °C) and two electrical field strengths (0.1 kV/mm; 1 kV/mm) to investigate temperature-dependent and field-dependent electrical conductivity of liquid nOD. As described in chapter II paraffins have a similar chemical structure compared to mineral oil. Therefore, the electrical conductivity is assumed to be caused primarily by ionic charge transport processes. Thus, positive and negative ions move to the counter electrodes under the influence of the applied electric field.

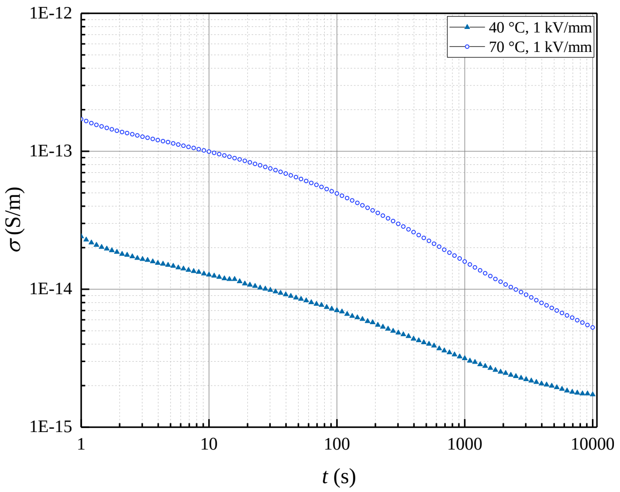

Figure 4. Electrical conductivity at 40 °C and 70 °C, 1 kV/mm

Fig. 4 shows the electrical conductivity versus time for two temperatures (40 °C; 70 °C) and at a field strength of 1 kV/mm. The initial conductivities at different temperatures are $2.41 \cdot 10^{-14}$ S/m (40 °C) and $1.71 \cdot 10^{-13}$ S/m (70 °C). Then, the electrical conductivities decrease with time of energization. According to (1) the initial conductivity is mainly caused by the transient field stress. For $t = \infty$ the electrical conductivity is time-independent since the time-dependent term in (1) becomes zero. Though, in Fig. 4 the steady-state conductivity is not reached for both measurements. Due to long time constants as known for mineral oil the steady-state conductivity is often not reached even after many hours of energyzation. Moreover, it is seen that the electrical conductivity σ increases with temperature. This behavior is well-known for mineral oil [8] and is due to an increasing ion mobility μ following *Walden's rule* (3).

$$\mu \cdot \eta = \text{const.} \tag{3}$$

Equation (3) means that if the viscosity η of an insulating material decreases (e.g. due to an increase in temperature) the ion mobility μ increases.

In Fig. 5 the electrical conductivities at 70 °C and two field strengths (0.1 kV/mm and 1 kV/mm) are plotted. Like mineral oil, nOD in the liquid state shows a field-dependent conductivity. The conductivity of mineral oil at different field strength follows a bath tub curve [9]. I.e. at first the electrical conductivity decreases with increasing field strength until a minimum conductivity is reached and before it starts to increase again. This can be explained by means of the amount of intrinsic charge carriers. At low field strengths (i.e. 1 kV/mm to 2 kV/mm for mineral oil) [9] there is only a negligible injection of charge carriers into the liquid. The intrinsic charge carriers drift to the counter electrodes under the influence of the electric field and form a *hetero charge* layer [10]. Between 1 kV/mm…2 kV/mm a conduction minimum is reached. At higher field strengths, injection processes and hence the generation of new charge carriers leads to an increase in conductivity again.

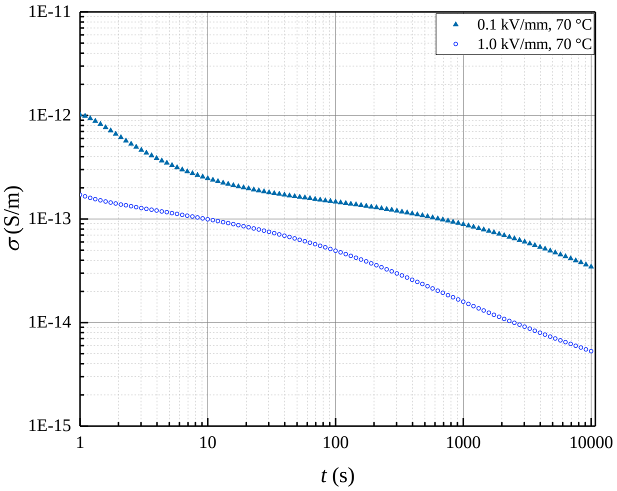

Figure 5. Electrical conductivity at 0.1 kV/mm and 1.0 kV/mm

As can be seen in Fig. 5, the electrical conductivity of liquid nOD increases with lower field strengths. Consequently, due to this field-dependent conductivity it is reasonable to also assume an ion transport for liquid paraffin as the dominating charge transport mechanism.

VI. Conclusion

The maximum operating temperature of insulating materials in high voltage applications is often the limiting factor when it comes to the transmission of electric energy. Due to their ability to store heat during a phase change paraffins are one promising group of PCM to limit the temperature of high voltage equipment. In this contribution, the electrical insulating properties of paraffins were determined. To investigate the breakdown voltage in the liquid and the solid state a suitable test cell was developed following the standard IEC 60156. The test cell consists of four chambers to obtain more breakdown voltage values at single material sample. Moreover, the test cell allows measurement temperatures up to 120 °C to ensure complete melting of the material sample.

The breakdown voltage of liquid nOD was determined to be 41.4 kV at an electrode distance of 1 mm. Therefore, the breakdown voltage of liquid nOD is comparable to that of mineral oil. The breakdown strength of paraffins can be optimized by using a material with a more amorphous structure. In the solid state nOD shows a high crystallinity and therefore the breakdown voltage is significantly lowered due to defects and air bubbles in the specimen.

The electrical conductivity measurements were carried out by using the PDC method. To investigate temperature- or field dependent conductivity of liquid nOD, the measurements were done at two temperatures (40 °C, 70 °C) and two field strengths (0.1 kV/mm, 1 kV/mm). The electrical conductivity of liquid nOD was determined to be between $1.72 \cdot 10^{-15}$ S/m and $3.46 \cdot 10^{-14}$ S/m and is in the range of mineral oil [8]. Moreover, it was shown that liquid nOD shows a temperature- and field-dependent conductivity. It can be assumed that like mineral oil the electrical conductivity is primarily caused by ion transport mechanism.

Further investigations have to prove the electrical insulating capability of paraffin in the solid state. Therefore, a paraffin with a more amorphous structure will be used and solid material samples will be prepared to carry out electrical conductivity measurements. Also tests for thermal qualification of the PCM in mock-ups have to be carried out.

References

[1] Zalba, B., Marín, J. M., Cabeza, L. F., and Mehling, H., “Review on thermal energy storage with phase change: Materials, heat transfer analysis and applications,” Applied Thermal Engineering, vol. 23, no. 3, pp. 251–283, 2003.

[2] Kousksou, T., Jamil, A., Rhafiki, T. E., and Zeraouli, Y., “Paraffin wax mixtures as phase change materials,” Solar Energy Materials and Solar Cells, vol. 94, no. 12, pp. 2158–2165, 2010.

[3] Insulating liquids - Determination of the breakdown voltage at power frequency - Test method, IEC 60156:1995, 1995.

[4] Schober, F., Harrer, S., Kuchler, A., Berger, F., Exner, W., and Krause, C., “Transient and steady-state dc behavior of oil-impregnated pressboard,” IEEE Electr. Insul. Mag., vol. 32, no. 4, pp. 8–14, 2016.

[5] Alff, J.-J.; Der Houhanessian, V.; Zaengl, W. S.; Kachler, A. J.: A novel, compact instrument for the measurement and evaluation of relaxation currents conceived for on-site diagnosis of electric power apparatus: Conference record of the 2000 IEEE International Symposium on Electrical Insulation. Disneyland Hotel, Anaheim, California, April 2 - 5, 2000. Piscataway, NJ 2000.

[6] Sasol, Technical Bulletin: PARAFOL Single Cut Paraffins.

[7] S. Harrer, C. Dotterweich, J. Hartmann, M.H. Zink, F. Hemberger, H.-P. Ebert, T. Schnitzler, “Phase Change Materials for Use in Thermally and Electrically Stressed Insulation for High Voltage Applications,” IEEE Electrical Insulation Conference, Montreal, Québec, Canada, pp. 605–608, 2016.

[8] Judendorfer, T.; Pirker, A.; Muhr, M.: Conductivity measurements of electrical insulating oils: 2011 IEEE 17th International Conference on Dielectric Liquids (ICDL).

[9] B. Gänger, G. M.: Widerstandsverhalten von Isolieröl im Gleichspannungsfeld. BBC Mitteilungen (1969), S. 525–33.

[10] Liebschner, M., Küchler, A., Krause, Ch., Heinrich, B., Berger, F.: Interaction of Oil Ducts and Solid Insulation in HVDC Barrier Systems. In: 16th International Symposium on High Voltage Engineering, Cape Town, South Africa, 2009.