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Investigation of the Dielectric Strength of Syntactic Foam at 77 K under DC Stress

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Abstract. Liquid nitrogen (LN_2) based electrical insulation systems for superconducting equipment of electrical power distribution networks are state of the art. Since LN_2 is a cryogenic liquid it has some disadvantages when used as insulation. This paper deals with syntactic foam as an alternative insulation system for superconducting apparatus. Syntactic foam is a composite material consisting of a polymeric matrix and embedded hollow microspheres with diameters of several 10 µm. As hollow microspheres are gas-filled, using those as filling material features significant reductions of the relative permittivity and of the thermal contraction due to cooling the material to liquid nitrogen temperature (LNT, T = 77 K). In this study both an epoxy resin (ER) and an unsaturated polyester resin (UPR) serve as matrix material. The hollow microspheres used in this investigation are made of untreated and silanized glass. The results of measurements of the dielectric DC strength show, that the dielectric strength of all investigated syntactic foam compositions are significantly higher at LNT compared to ambient temperature (AT). Furthermore, the effect of a higher dielectric strength of syntactic foam with silanized glass spheres at ambient temperature vanishes at LNT. Hence, the dielectric strength at LNT is unaffected by silanization of glass microspheres.

1. Introduction

LN_2-based insulation systems are commonly used in superconducting equipment of electrical power distribution networks. In this case, LN_2 takes cooling and insulating function simultaneously. Disadvantageously, nitrogen bubble formation due to heat losses leads to a reduction of the dielectric strength [1]. Furthermore, the routine tests after manufacturing of those utilities lose their significance, as the liquid nitrogen has to be emptied for delivery. An alternative to LN_2-based insulation systems are solid insulations. Using solids means that LN_2 henceforth has only cooling function and the disadvantages of LN_2 as electrical insulation are eliminated. To apply polymeric insulation systems for superconducting power apparatus it is necessary to use fillers to reduce the thermal contraction due to cooling the insulation down to liquid nitrogen temperature (LNT). Otherwise the insulation system will delaminate from metallic or superconducting electrodes, whose thermal contractions are much lower than those of pure polymers [2]. This paper deals with syntactic foam as an alternative solid insulation system. Syntactic foam consists of a polymeric matrix and embedded hollow microspheres (HMS) which serve as filler and providing a foam-like structure. Using a half-wave rectification different syntactic foam constellations are investigated concerning their dielectric DC strength at ambient and liquid nitrogen temperature. A scanning electron micrograph of syntactic foam is shown in figure 1.

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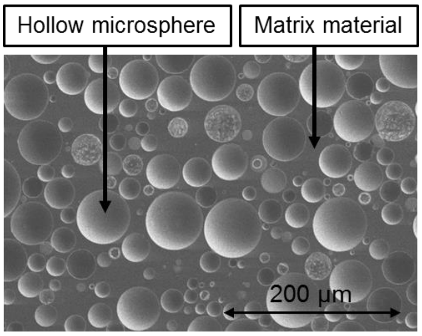

Figure 1. Scanning electron micrograph of syntactic foam.

2. Investigated Materials

2.1. Syntactic foam

To determine the influence of adhesion between the HMS and the matrix material on the dielectric DC strength, different constellations of syntactic foams are investigated. The matrix material is varied between epoxy resin (ER) and unsaturated polyester resin (UPR). Both matrix materials are hot cured polymers. The quality of adhesion is varied by using glass HMS which are on the one hand surface-modified by silanization and on the other hand untreated. The silanization results in an increase of bonding forces between the inorganic glass spheres and the organic matrix due to chemical bonding instead of physical bonding, as it occurs for untreated glass microspheres. The glass HMS have a mean diameter of 40 µm and a wall thickness of about 1 µm. Within these investigations filling degrees of 30 and 50 percentage of volume (vol. %) are examined to change the amount of boundary surfaces.

2.2. Test sample geometry

The dielectric DC strength of syntactic foam is determined with the aid of test samples with embedded spherical electrodes. The electrodes have diameters of 12 mm and the gap distance is 2 mm. This electrode configuration results in a field efficiency factor η of 0.865 which features a quasi homogeneous electrical field between the electrodes after voltage applying.

3. Experiments and Simulations

The DC test voltage is induced by a half-wave rectification. The rectified AC voltage is generated by a transformer cascade with a maximum output of 200 kV rms. To avoid surface discharges during the measurements at ambient temperature the test samples are placed in an oil vessel. The measurements at LNT are performed in LN_2, which is filled in a basin made of expanded polypropylene (EPP) for thermal insulation. To ensure a test sample temperature of 77 K and to avoid material cracking due to high temperature gradients the samples are cooled stepwise over a time period of one hour.

According to [3] the test voltage is applied stepwise. Starting with a voltage U_s, which is 40 % of the prospective breakdown voltage U_b, the voltage is increased every $t_h = 20$ s by $\Delta U = 2$ kV until breakdown occurs. By means of the breakdown voltage U_b, the dielectric strength E_b is given by

$$E_\mathrm{b} = \frac{U_\mathrm{b}}{\eta s} \tag{1}$$

with the field efficiency factor η and the gap distance between the sample electrodes s [4]. For each syntactic foam composition five samples are investigated.

Furthermore, simulations are carried out to obtain the electrical DC field distribution inside syntactic foam. Therefore, three HMS are arranged in parallel to a background field strength $E_0 = 45$ kV/mm, which is determined by the dielectric strength of ER respectively UPR filled with 50 vol. % silanized glass HMS at AT. The conductivities of the syntactic foams' components used in this simulations are set to $\lambda_{ER} = 10^{-15}$ S/m, $\lambda_{UPR} = 10^{-15}$ S/m, $\lambda_{glass} = 10^{-12}$ S/m and $\lambda_{gas} = 10^{-18}$ S/m.

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4. Results
The results of the dielectric DC strength measurements are presented in figure 2 including the 95% confidence interval. The testing temperature differs between ambient temperature and liquid nitrogen temperature (LNT). The matrix materials are ER and UPR filled with untreated or silanized glass HMS. The filling degree varies between 30 vol. % and 50 vol. %.

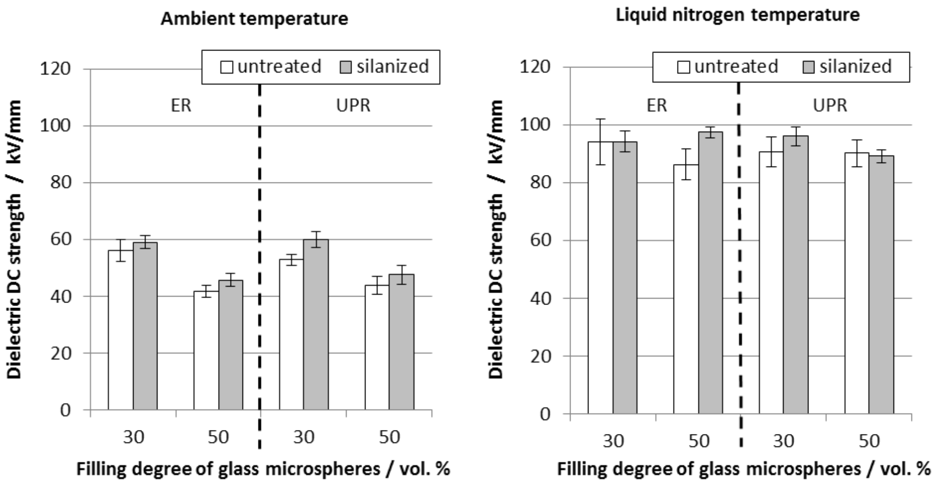

Figure 2. Dielectric DC strengths of different syntactic foam compositions with untreated and silanized HMS at ambient and liquid nitrogen temperature.

It can be observed that the choice of the matrix material between ER and UPR has no significant impact on the dielectric DC strength of syntactic foams. Furthermore, the dielectric strengths of all investigated syntactic foams increase significantly by decreasing the test temperature to LNT. Focussing on the impact of the filler material of syntactic foams, the dielectric strength at ambient temperature decreases significantly with increasing filling degree and increases with silanization of the glass HMS by trend for both matrix materials. Comparing the results at LNT, only a slight trend of decreasing dielectric strength with increasing filling degree is recognized. However, the silanization of the HMS does not show a significant impact on the dielectric strength at LNT.

Figure 3 shows the simulation results. It is found that the field distribution depends on the matrix material. The electrical field inside the HMS embedded in UPR is enhanced (Figure 3 left). It is assumed that discharges within the spheres will occur by increasing background field strength and that will lead to an enhancement of the field between the spheres like it is the case of HMS embedded in ER. There the field inside the HMS is reduced and the field between spheres is enhanced (Figure 3 right).

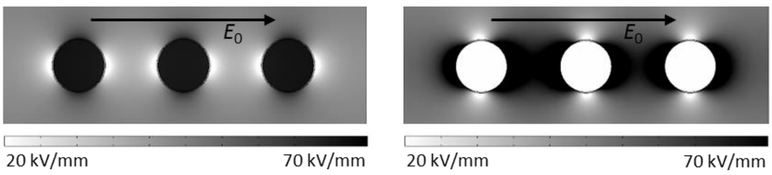

Figure 3. Electrical DC field distribution of three glass HMS in UPR (left) and ER (right) at ambient temperature.

5. Discussion
Due to higher adhesion of silanized HMS to the matrix materials there are no gaps between spheres and matrix. Those gaps could reduce the dielectric DC strength of syntactic foam at ambient

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temperature and could occur within the curing process of syntactic foam. Because of the much higher conductivity of glass compared to the conductivities of the filling gas of the HMS and ER, the field stress on the parts between two spheres is enhanced for higher filling degrees. It is assumed that the same field distribution would be found, if spheres embedded in UPR discharge due to enhanced field stress of the spheres interior. Thus, independent of the matrix material the breakdown starts at lower background field stresses for higher filling degrees [5]. When lowering the test temperature to LNT the matrix material begins to shrink so that the gaps between untreated HMS and the matrix seam to vanish and the dielectric DC strength of syntactic foam becomes unaffected of the silanization process. The decrease of dielectric DC strength with increasing filling degree is damped and can only be recognized by trend. In general, the dielectric DC strength increases significantly at LNT. Assumed that the electrical field distribution within syntactic foam at LNT is similar to that at ambient temperature the electrical field displacement leads to a similar enhancement of the field stress in the matrix material between the HMS. Thus, the higher dielectric strength of syntactic foam at LNT must arise from an increase in dielectric strength of the matrix material at LNT as it is found for some epoxy resins in [6].

6. Conclusion

In this paper syntactic foam is investigated regarding its dielectric DC strength under ambient and liquid nitrogen temperature. It was observed that the dielectric DC strength decreases with increasing filling degree of HMS. This results from a higher field stress of the matrix material between HMS since the electrical field is displaced out of the hollow spheres at DC stress. A silanization of HMS leads to higher dielectric strengths at ambient temperature but not at LNT. However, thermal contraction of syntactic foam leads to vanishing gaps at LNT between untreated HMS and the matrix which can occur during the material curing. Hence, the impact of silanization becomes negligible. At last, the dielectric strengths of syntactic foam increases significantly by lowering the test temperature to LNT. This effect seems to be affected by increasing dielectric strength of the matrix materials providing an electrical field displacement similar to that at ambient temperature.

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References

[1] Sauers I, James DR, Ellis AR, Tuncer E, Polizos G, Pace MO. Breakdown in liquid nitrogen in the presence of thermally generated bubbles for different electrode geometries. Annual Report Conference on Electrical Insulation and Dielectric Phenomena, October 2009, Virginia Beach, USA, 2009.

[2] Ekin JW. Experimental techniques for low-temperature measurements. Boulder, CO, Oxford University Press, 2006.

[3] IEC 60243-2, “Electric strength of insulating materials (IEC 60243-2:2001); German version”, VDE-Verlag, 2001.

[4] Kuffel E, Zaengel WS, Kuffel J. High voltage engineering: Fundamentals. Butterworth-Heinemann, Oxford, 2000.

[5] Strauchs A, Schnettler A. Enhancements of epoxy resin based syntactic foam by inner interface and matrix modifications. Annual Report Conference on Electrical Insulation and Dielectric Phenomena, October 2011, Cancun, Mexico, 2011.

[6] James DR; Sauers I; Pace MO; Ellis AR. High voltage breakdown of solid epoxies at room temperature and in liquid nitrogen. Annual Report Conference on Electrical Insulation and Dielectric Phenomena, October 2002, Cancun, Mexico, 2002.