INVESTIGATIONS ON AC BREAKDOWN FIELD STRENGTH OF SYNTACTIC FOAM AT CRYOGENIC TEMPERATURE

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Abstract: Syntactic foam is a composite material consisting of a polymeric matrix material with embedded hollow microspheres. At ambient temperature it already substitutes several conventional insulation systems for high voltage applications like mineral oil or mineral-filled epoxy resin. In this paper the suitability of syntactic foam to serve as insulation system for high voltage superconducting applications to substitute liquid nitrogen as insulation is investigated. As microspheres feature lower density and costs compared to standard matrix materials, such hybrid insulation systems become lighter and less cost-intensive. The microspheres are also able to reduce shrinking during cooling process down to cryogenic temperature significantly. The present study deals with the investigation of various syntactic foam compositions with different filling degrees focussing on their short-term ac breakdown field strength at cryogenic temperature. To determine the influence of temperature comparison breakdown measurements at ambient temperature are carried out as well. As matrix materials epoxy resin and silicone are used. Coated, hollow, polymeric microspheres and hollow glass microspheres serve as filler.

1 INTRODUCTION

Since the discovery of high temperature superconductors (HTS) it is possible to use liquid nitrogen (LN_2) as cooling medium. Hence, LN_2 based insulation systems are commonly used in superconducting components for electrical power transmission. Especially in superconducting power cables the electrical insulation consists of LN_2 impregnated polypropylene laminated paper. Thus, LN_2 is not only cooling medium but also part of the insulation system at the same time. Routine tests of the cable performed immediately after production become worthless as the LN_2 is released for delivery and renewed during commissioning on-site. Therefore, a solid insulation system, which is able to keep its insulation ability in spite of LN_2 dumping, is desirable. Furthermore, a decrease of the dielectric strength of the insulation system as a consequence of bubble formation in LN_2 occurring due to heat losses during operation is eliminated, since the LN_2 is only needed as refrigerant medium.

One disadvantage of commonly used polymeric insulation materials such as cross-linked polyethylene (XLPE) or epoxy resin is their comparatively high volume shrinkage when cooled down to cryogenic temperatures. Fillers are able to reduce this volume shrinkage.

Syntactic foam is a composite material which consists of a polymer matrix and hollow microspheres. Such hollow microspheres have average diameters of some 10 µm. Figure 1 shows the inner structure of syntactic foam at a cutting area. As the filling degree could reach values of up to 50 Vol.-% the volume shrinkage due to cooling process can be reduced significantly. From this point of view, it is possible to use syntactic foam in superconducting applications.

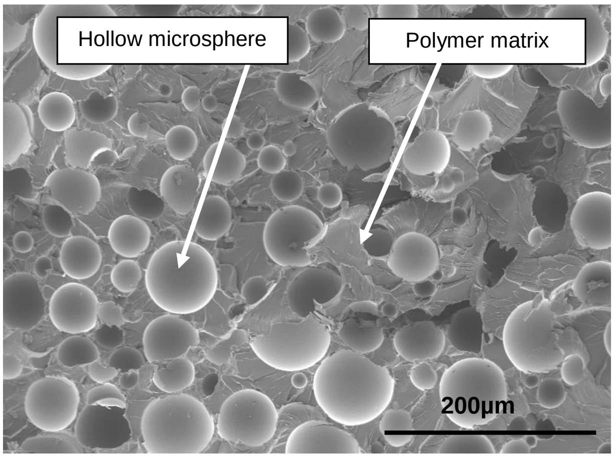

Figure 1: Scanning electron microscope picture of syntactic foam

2 INVESTIGATED MATERIALS

In this paper various syntactic foam compositions are investigated in respect of their electrical breakdown field strength. These foam compositions consist of different combinations of two matrix materials and two types of hollow microspheres with average diameters around 40 µm. As matrix materials epoxy resin and silicone are used. Polymeric hollow microspheres with $CaCO_3$ coating and hollow glass microspheres serve as fillers. Thus, four different foam formations can be composed. Each formation is investigated with filling degrees of 30, 40 and 50 Vol.-%, respectively. Table 1 gives an overview of all considered parameters.

Table 1: Parameters of syntactic foam compositions

Matrix material	Hollow microspheres (Ø=40µm)	Filling degree
Epoxy resin Silicone	Glass Coated Polymer	30 Vol.-% 40 Vol.-% 50 Vol.-%

3 TEST PROCEDURE

The following chapter describes the test specimens, the test setup and the test procedure of performed tests to determine the dielectric strength of syntactic foam.

3.1 Test specimens

To determine the short-term dielectric strengths of syntactic foams under consideration a specimen design with embedded spherical electrodes is used. The diameters of those electrodes are 12 mm and the sparking distance is 2 mm leading to a Schwaiger factor of 0.865. Thus, this specimen geometry generates a quasi-homogeneous electrical field.

3.2 Test setup

The AC test voltage is generated by a cascade of two 100 kV test transformers. To avoid surface discharges during testing at ambient temperature the specimen is placed in an oil vessel. The tests at cryogenic temperature are performed in LN_2, which is filled in an open box made of expanded polypropylene (EPP) for thermal insulation. Since the investigations are performed with ambient pressure LN_2 has got a temperature of 77 K.

3.3 Test procedure

During breakdown measurements the test objects are stressed with voltage steps illustrated in Figure 2.

The level of the start voltage is set to 70 % of the expected breakdown voltage. The holding time of each voltage step is t_h = 20 s and the step height is ΔU = 2 kV. To get the influence of cryogenic temperature on the breakdown field strength the tests are performed at both ambient and cryogenic temperature.

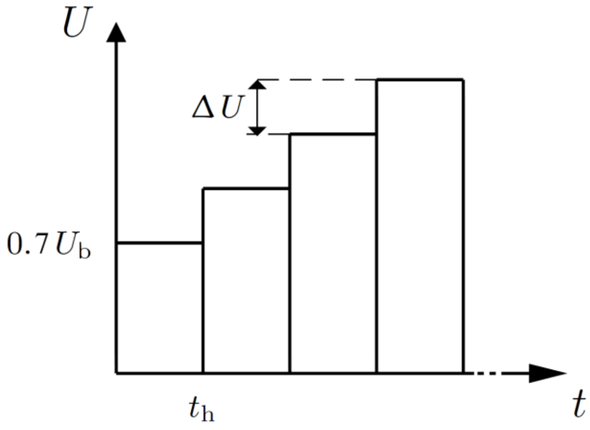

Figure 2: Development of test voltage for breakdown investigations of syntactic foam

4 RESULTS

The results of the investigations are separated in those of epoxy resin based syntactic foams and those of silicone based syntactic foams.

4.1 Breakdown field strength of syntactic foam based on epoxy resin

The results of breakdown field strength measurements of syntactic foam based on epoxy resin at ambient temperature including the 95 % confidence intervals are pictured in Figure 3. The lighter bars represent epoxy resin filled with hollow glass microspheres whereas the darker bars represent epoxy resin filled with polymeric hollow microspheres.

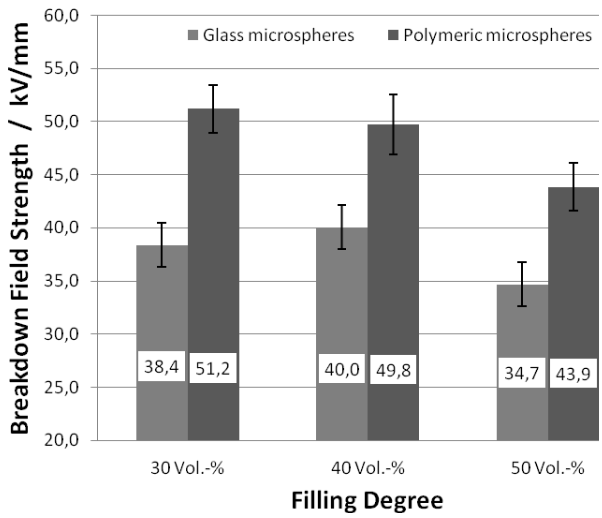

Figure 3: Breakdown field strength of epoxy resin based syntactic foam with different filling degrees of hollow microspheres at ambient temperature

It is found that the dielectric strength of epoxy filled with polymeric microspheres is about 25 % higher than the one for glass microspheres and decreases with increasing filling degree. For epoxy filled with glass microspheres no significant impact of the filling degree on the breakdown field strength is cognizable. This is attended by results in [1].

Investigations at cryogenic temperature in LN_2 shows the results illustrated in Figure 4. All breakdown field strengths, those of epoxy filled with hollow glass microspheres as well as those of epoxy filled with polymeric microspheres, are on similar level. This means that the effect of filling degree is negligible. In comparison to the results at ambient temperature shown in Figure 3 the breakdown field strengths of epoxy filled with glass microspheres are nearly unaffected by temperature whereas the dielectric strengths of epoxy filled with polymeric microspheres decreases by up to 20 %.

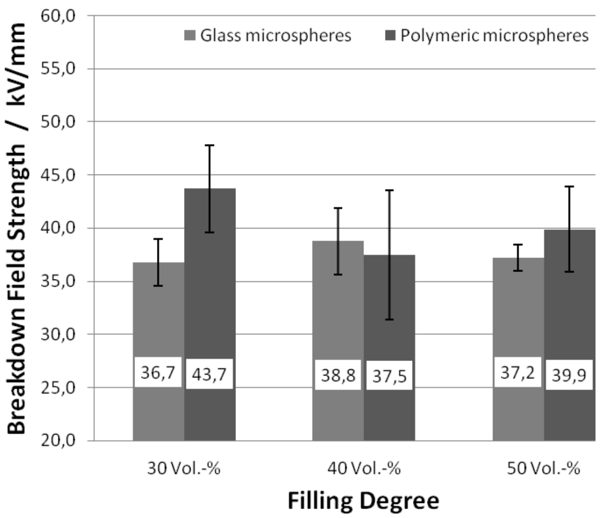

Figure 4: Breakdown field strength of syntactic foam based on epoxy resin with different filling degrees of hollow microspheres at cryogenic temperature

4.2 Breakdown field strength of syntactic foam based on silicone

Results of breakdown field strength measurements of syntactic foam based on silicone at ambient temperature including the 95 % confidence intervals are presented in Figure 5.

There is a slight increase of the breakdown field strength of silicone filled with polymeric microspheres with increasing filling degree. This is attended by results in [2]. Whereas the filling degree has no impact on the breakdown field strength of silicone filled with hollow glass microspheres. However, the dielectric strength is significantly lower than the one of polymeric filled silicone.

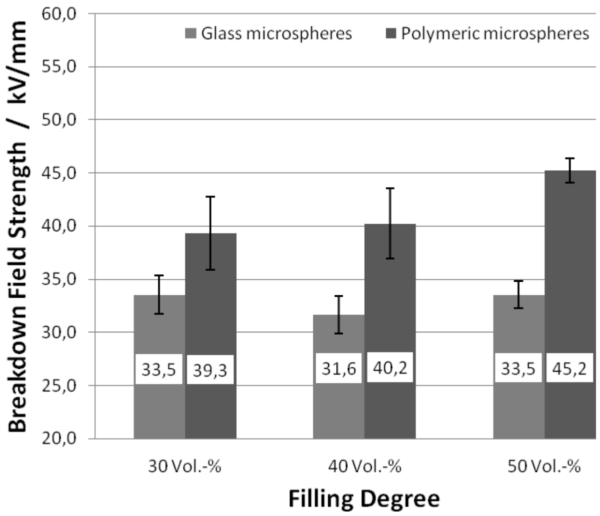

Figure 5: Breakdown field strength of syntactic foam based on silicone with different filling degrees of hollow microspheres at ambient temperature

Results of investigations performed at liquid nitrogen temperature are pictured in Figure 6. It can be figured out that breakdown field strength of syntactic foams based on silicone at cryogenic temperature is independent from filling degree but strongly depends on filler type as the dielectric strength of silicone filled with coated hollow polymeric microspheres is nearly 2.1 times the dielectric strength of silicone filled with hollow glass microspheres.

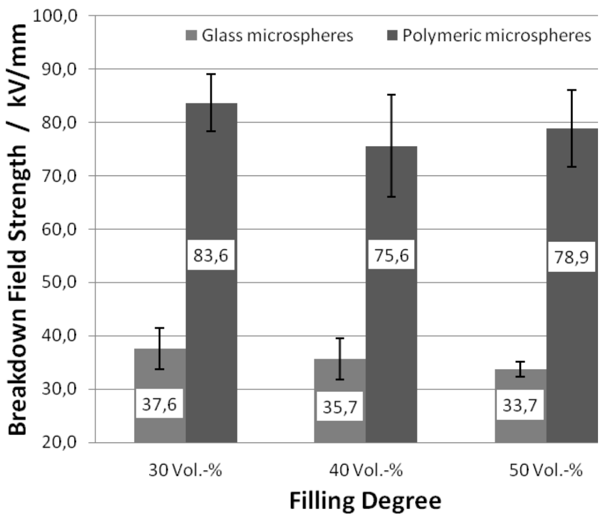

Figure 6: Breakdown field strength of syntactic foam based on silicone with different filling degrees of hollow microspheres at ambient temperature

5 DISCUSSION

The results of the investigations regarding the dielectric strength of syntactic foam at cryogenic temperature are discussed in the following chapter. It is differentiated between syntactic foams based on epoxy resin and silicone.

5.1 Syntactic foams based on epoxy resin

Investigations on the breakdown process in syntactic foams based on epoxy resin filled with hollow glass microspheres at ambient temperature are presented in [3]. In this work partial discharges are identified inside hollow microspheres serving as origin of the breakdown ignition. These partial discharges erodes the sphere wall first and afterwards the matrix material at this spot. An electrical tree starts growing till the electrodes are short circuited.

The results illustrated in Figure 3 show that there is no significant impact of the filling degree on breakdown field strength for both filler types. The same findings are presented in [1]. Numerical field simulations pointed out that same background field strength result in same maximum field strength inside hollow microspheres. Hence, the breakdown field strength is independent from filling degree.

In [2] hollow microspheres with $CaCO_3$ coating in a silicone gel matrix are examined. In comparison to syntactic foam based on silicone gel filled with uncoated microspheres a higher resistance against partial discharges can be reached by using coated microspheres as filler. The $CaCO_3$ coating serves as barrier leading to higher breakdown field strength. This conclusion is transmittable to syntactic foams based on epoxy resin as the dielectric strength of foams filled with coated polymeric hollow spheres is about 25 % higher than the dielectric strength of syntactic foams filled with glass microspheres.

Investigations at liquid nitrogen temperature show similar breakdown field strength levels for all foam constellations based on epoxy. Furthermore they are similar to that level of epoxy filled with glass sphere at ambient temperature. By cooling down the syntactic foam to 77 K the pressure inside the hollow microspheres decreases as a result of ideal gas law [4].

$$p\,V = n\,R\,T \tag{1}$$

where: p = Pressure in Pascal (Pa)
V = Volume in cubic meter (m³)
n = amount of substance
R = Gas constant (J/(K mol))
T = Temperature in Kelvin (K)

According equation (1) the pressure inside the microspheres is reduced at 77 K to 25 % in comparison to ambient temperature. With an average sphere diameter of 40 µm and the use of paschens' law, the discharge resistance of the gas inside the microspheres is expected to be higher than it is at ambient temperature. As shown in chapter 4.1 the breakdown field strength of epoxy filled with hollow glass microspheres is similar and the breakdown field strength of epoxy filled with hollow polymeric microspheres is even lower at cryogenic temperature compared to ambient temperature. Hence, microspheres cannot be a weak point in syntactic foam at cryogenic temperature unlike it is at ambient temperature.

The epoxy resin possibly gets mechanically pre-damaged by mechanically stress occurring during cooling process. This leads to microcracks which dominates the breakdown process and results in similar break down field strengths at cryogenic temperature independent from filler type.

5.2 Syntactic foams based on silicone

According to [2], the breakdown process of silicone based syntactic foams filled with coated polymeric hollow microspheres starts in the matrix, since its dielectric strength is exceeded due to field displacements inside the material. In the case of using microspheres coated with $CaCO_3$, this coating serves as barrier and the breakdown channel has to sidestep the sphere. Due to the higher number of barriers with increasing filling degree, the breakdown field strength is increasing as well. It is assumed that uncoated hollow microspheres form weaker barriers. Hence, the breakdown field strength is independent from filling degree and significantly lower in comparison to foams with coated microspheres.

By cooling specimens down to cryogenic temperature the breakdown field strength of hollow polymeric microspheres is about 2 times higher compared to investigations at ambient temperature. As silicone matrix at ambient temperature is pointed out as weak point of syntactic foam, silicone matrix gets obviously more field resistant at cryogenic temperature. Otherwise, the breakdown field strength of syntactic foam based on silicone and filled with polymeric microspheres would not increase but remains at the same level.

On the contrary, the syntactic foams with hollow glass microspheres remain at the same level of dielectric strength, independent from temperature. Since the silicone matrix is the weak point of the syntactic foam at ambient temperature, but features a higher dielectric strength by decreasing temperature, it is assumed, that the cooling process leads to delamination of microspheres and silicone matrix which dominate the breakdown process. This kind of delamination is implausible for coated microspheres as the coating serves as coupling agent. Hence, syntactic foams based on silicone using coated polymeric microspheres feature higher breakdown field strengths.

6 CONCLUSION AND OUTLOOK

6.1 Conclusion

In the presented study investigations were carried out to determine the short-term ac breakdown field strength of different syntactic foam compositions at cryogenic temperature. Therefore the matrix material, type of microspheres and filling degree were varied. To ascertain the influence of such low temperature on breakdown in syntactic foam, the results were compared with those performed at ambient temperature.

The results of epoxy resin based syntactic foams shows that their breakdown field strength at cryogenic temperature is independent from filling degree and type of microspheres. Because of a decreasing in breakdown field strength of epoxy resin filled with polymeric microspheres it was assumed, that microcracks inside the matrix induce the breakdown process.

Similar to the results of epoxy resin filled with hollow glass microspheres the breakdown field strength of silicone filled with glass microspheres remains unaffected in spite of temperature dropping. Silicone filled with hollow coated polymeric microspheres, however, becomes dielectrically stronger. Since the breakdown process of silicone based syntactic foam is not triggered by partial discharges, the matrix material seemes to be dielectrically improved by cooling it down to cryogenic temperature.

6.2 Outlook

During the measurements it was revealed, that syntactic foam, particularly those based on epoxy resin, becomes very brittle due to cooling down to cryogenic temperature. In high voltage applications an intact insulation system without any crack is essential. Hence, further investigations have to be carried out to determine the mechanically performance of syntactic foam at cryogenic temperature.

7 ACKNOWLEDGMENTS

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