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Suitability of LN_2 impregnated Open-Cell Foam as Electric Insulant for Superconducting Power Equipment

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Abstract. The suitability of an open-cell foam is investigated for the application as electric insulant in superconducting power equipment. The tested foam is made from melamine resin, a thermoset plastic from the aminoplastics group; it is a mechanical very flexible material with excellence compatibility to high and low temperature.
The aim of these investigations was to test the aptitude of the liquid nitrogen impregnated open-cell foam with respect to the dielectric properties and the electric strength under different conditions. In this paper the results of permittivity measurements and ramp voltage tests are discussed and an outlook for future applications is given. The tests showed excellence mechanical and thermal characteristics for the application in LN_2 vessels. The ACBV of the LN_2 impregnated foam was 50 % less than the ACBV of pure LN_2.

1. Introduction

The idea of this research project was to investigate the combination of fully LN_2 saturated solid medium and its behaviour under electrical stress [1]. Beside the electrical properties also the mechanical properties have to fulfil special requirements. For the application as electric insulation medium no gas bubbles should occur. From the mechanical point of view the foam should not become brittle under LN_2 impregnation. It should resist to compressive and shear forces. For this reason several kind of foams were tested for its application according to the technical specification. Only one type of open-cell foam was found which showed the mechanical flexibility at LN_2 temperature without breaking. This type of foam is shown in figure 1. The foam made of melamine resin is produced with a three-dimensional filigree network structure formed from slender and hence readily thermo formable filaments. The impregnation with liquid nitrogen enables the application as electric insulating material. The main advantage of impregnated insulants is the very high life exponent, the self healing effect and the low relative permittivity, which has a positive effect on the load capacitance to reduce dielectric losses.

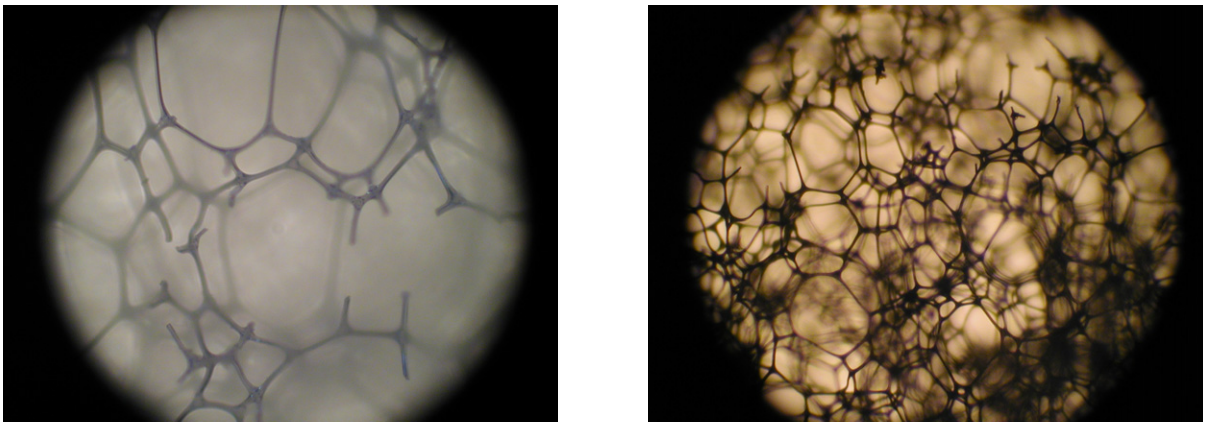

Figure 1: Open-cell foam from melamine resin (1:100 left, 1:40 right)

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Under the microscope the open-cell structure can be seen very well. When impregnating this foam with LN_2 full penetration is expected. In the first test series the test objects were disks to find out the electric insulating behaviour, the breakdown strength and the relative permittivity. On rotational symmetry insulation models the application for the insulation of a power cable is demonstrated.

2. Electric Tests on Disks of Open-Cell Foam

Several electric tests were done to find out if the impregnated material is applicable under LN_2 conditions. For this reason the breakdown strength and relative permittivity was investigated. The special interest of breakdown measurements was the change of dielectric strength of pure LN_2 and the combination of the LN_2 impregnated foam. The permittivity measurements should show the influence to the ε_r when the open-cell foam is brought into the cryogenic test vessel.

2.1 *Breakdown Strength*

To test the electrical breakdown strength of this foam a test vessel was constructed with an electrode configuration of 3 mm gap and plane parallel surface. The foam was cut to slices of 3 mm thickness. After impregnation with LN_2 gas bubbles appeared, for this reason it was necessary to cool down the LN_2 to approximately 65K. This procedure was done with undercooling the whole test vessel in a vacuum chamber to 266 mbar.

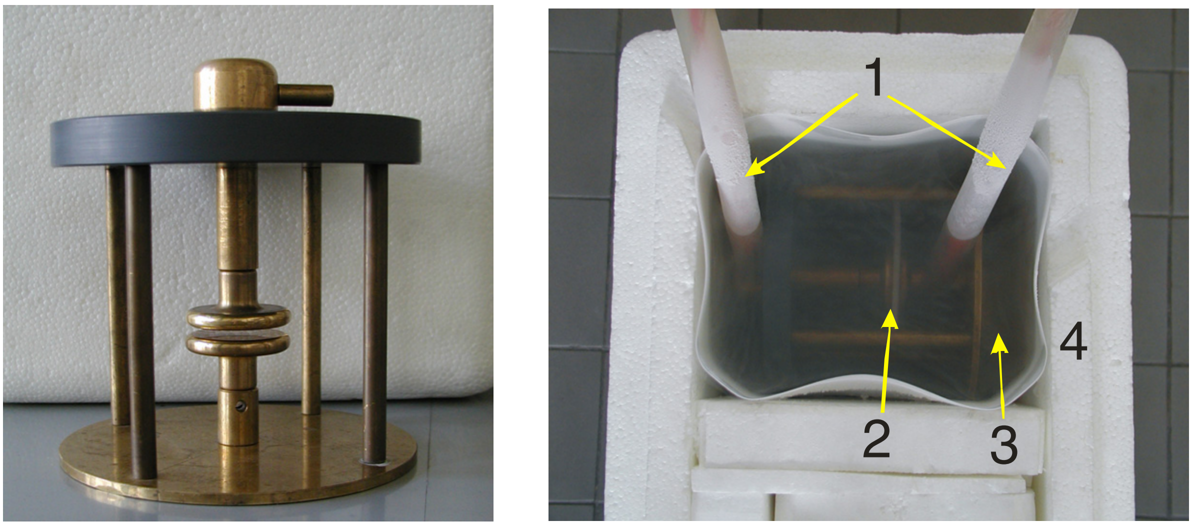

Figure 2: Test electrodes (left) and test vessel (right) for electric breakdown tests

1… Current Leads
2… Test Object: impregnated open-cell foam
3… LN_2
4… Cryostat

For the breakdown tests an AC ramp voltage with 2 kV/s was applied. After each breakdown a new test sample was placed between the electrodes and to prevent of gas bubbles the temperature was kept constant at 65K. The ACBV of 60 samples was reported automatically by the test instrument. The results were evaluated by applying the two-parametric Weibull distribution because this distribution gives the best results for electric strength tests. The 63 % quantiles of ACBV @ 65 K was 35 kV. As reference the ACBV of LN_2 without foam @ 65 K was measured and the 63 % quantile was calculated with 72 kV. Earlier investigations showed [2] that the breakdown voltage of LN_2 according to IEC 60156 with a gap between electrodes of 2.5 mm is 65 kV and higher, this means that the achieved test results were satisfactory. The reason of the lower breakdown voltage of the impregnated foam can be found in conduction mechanism in the tested material. The test results were plotted in a Weibull distribution, see figure 3.

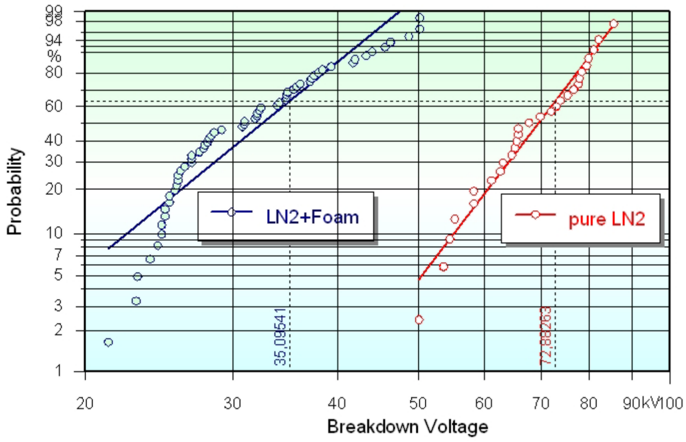

Figure 3: Weibull plot of AC breakdown tests with 2kV/s

2.2 *Relative Permittivity*

For the measurement of the relative permittivity an electrode configuration following the standard DIN-VDE 0303 Part 4 of normal insulation materials was chosen. A thickness of 10 mm for the foam was selected. Some small adaptations were done to the test standard, for this reason an electric field calculation was done. Figure 4 shows the construction and calculated field distribution.

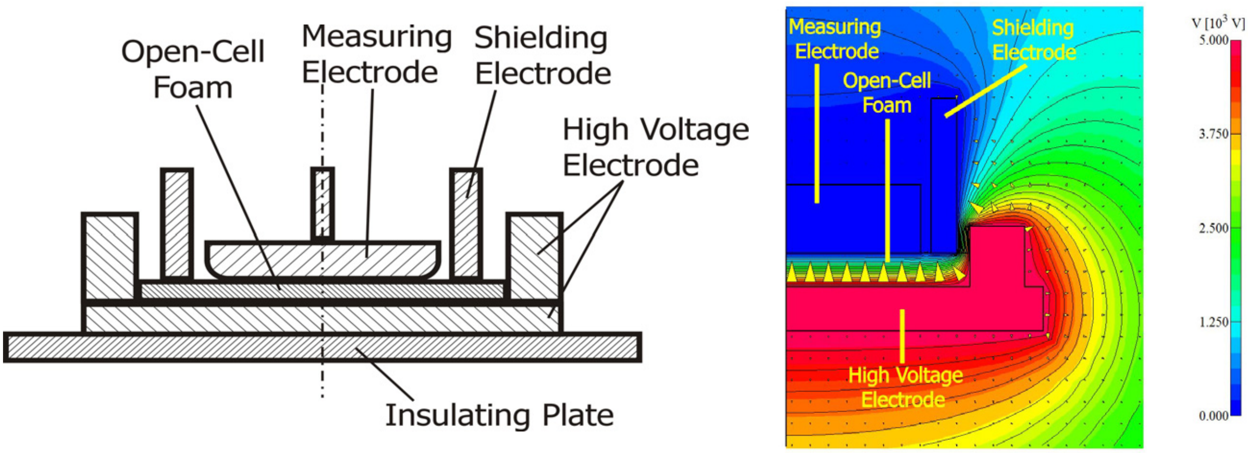

Figure 4: Electrode configuration (left) and field distribution (right) for relative permittivity measurement

For the determination of ε_r the capacitance was measured with a Schering Bridge. The first measurement was done with foam in air and after impregnating the test vessel (electrode configuration with foam) with LN_2 it was cooled down to 65K and measured again. From the ratio of the capacities C_{LN2} and C_{vacuum} the ε_r can be calculated as follows:

$$\varepsilon_r = \frac{C_{LN2}}{C_{vacuum}} = \frac{6{,}242\,pF}{4{,}509\,pF} = 1{,}384 \qquad (1)$$

The ε_r of LN_2 in literature is 1.44, this means that the measured value is 4 % less. The cause can be found in probable measuring errors which can be caused by the geometry of the electrode configuration at room temperature and 65 K, expansion due to thermal differences, temperature behaviour of resistance of test leads, differences in shielding and the degree of accuracy of the Schering Bridge. Making a numerical estimation of the thermal degradation of the test leads a difference of 28 % for the ohmic resistance is given, this shows that the measuring error of 4 % is inessential to the whole test setup.

3. Rotational Symmetry Insulation Models for Cable Insulation

A possible application in high voltage engineering could be a cable insulation system with cold dielectric design. For this reason a model of a radial homogenous insulation was constructed. The inner conductor was realized with a flexible aluminium tube, the insulation with a precast tube of open-cell foam and the shielding with a thin copper tube. The whole arrangement was placed in a LN_2 test vessel to measure the ε_r. Figure 5 shows the test cable. The breakdown strength was not of interest because the insulation thickness of the foam was 21 mm. Within a homogenous electric field (plane parallel electrodes) the expected breakdown voltage should be 245 kV.

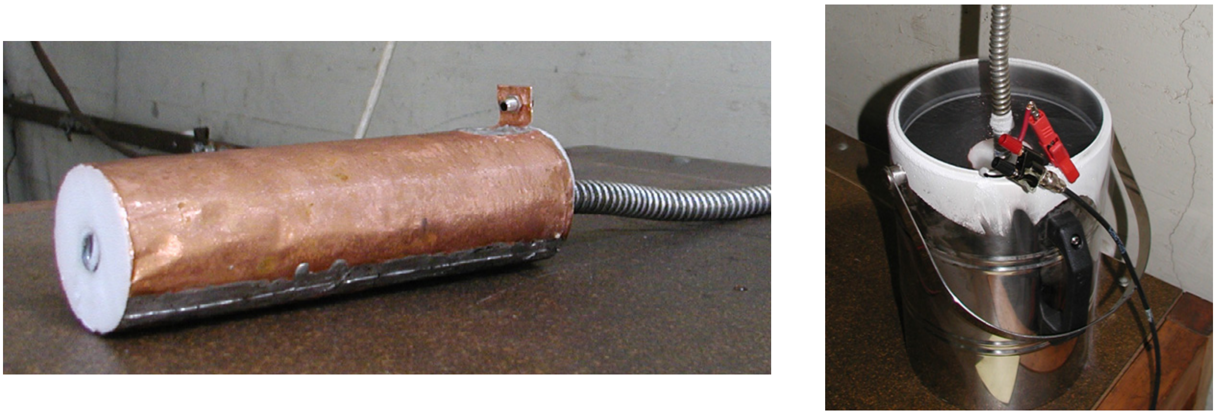

Figure 5: Cable model with open-cell foam as insulation medium (left) and test vessel (right)

On this cable model the relative permittivity has been determined. In the same procedure as the measurements at the foam disks the capacity of the insulation in air and under LN_2 impregnation was measured with a Schering Bridge. The LN_2 impregnated cable model was cooled down to 65K in a vacuum chamber. The result for the ε_r of the cable model at 65K was 1.78. The higher value of ε_r compared to the disk measurements can be reduced to impurity adsorption during manipulation. A calculation of the capacitances according to the geometrical dimensions showed a good degree of compliance:

$$\varepsilon_r = \frac{C_{LN2}}{C_{vacuum}} = \frac{27.13\,pF}{15.24\,pF} = 1{,}78 \qquad with \quad C = \frac{2\pi\varepsilon_r\varepsilon_0 l}{\ln(r_2/r_1)} \tag{2}$$

The measurements on the cable model showed two effects: the capacitance and the dielectric losses were lower. The mechanical and thermal material properties showed that an application as insulating medium for power equipment would be possible. The big benefit of the LN_2 impregnated open-cell foam is the very low relative permittivity and the combined function of electric insulating and thermal cooling. The very low value of the relative permittivity of approximately 1.8 or lower would open a wide field of applications in power engineering because the demand on reactive power is minimal compared to conventional insulation systems (ε_r of XLPE = 2.3, ε_r of PPLP = 2.6, ε_r of impregnated paper = 3.5). The capacitive load for power cables would be very low. This would mean that less or no compensation reactors for long cable systems were necessary.

4. Conclusion and Future Investigations

The LN_2 impregnated foam showed excellent behaviour concerning the permittivity. The breakdown strength compared to pure LN_2 is about the half. This weak spot can be improved in the field design for a possible application. Future investigations should show the long time stability of the used materials. During the whole time of measurements (more than 9 month) at the open-cell foam no signs of tiredness should be found. The electrical and mechanical properties in dependence of load cycles should be demonstrated in a long term trial.

5. References

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[2] Sumereder C. December 2003, Dielectric Investigations on Cryogenic Insulation Systems, Doctoral Thesis, Graz University of Technology, Department of High Voltage Engineering