Fusion Engineering and Design xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Full Length Article

Electrical performance of TGPAP and DGEBF-based epoxy resin insulation materials for superconducting magnets

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ARTICLE INFO

Keywords:
Epoxy resin
Cryogenic
Breakdown strength
Flashover
Dielectric spectroscope
Space charge

ABSTRACT

For the insulation materials of the superconducting magnet, the mechanical and electrical properties should be guaranteed under stresses of cryogenic temperature and intense radiation. In this study, two types of epoxy resins were prepared, which consist of diglycidyl ether of bisphenol-F (DGEBF) and triglycidyl-*p*-aminophenol (TGPAP) as matrixes respectively, and diethyl toluene diamine (DETD), isopropylidenebisphenol bis[(2-glycidyloxy-3-*n*-butoxy)-1-propylether] (IPBE) and boron-free glass fibre were used as curing, toughing and reinforcing agents for each resin. The direct-current (dc) electric breakdown strength and flashover voltage, dielectric properties and space charge characteristics of both epoxy composites were investigated. According to the results, DGEBF composite shown a higher dielectric strength, lower permittivity and dielectric loss at cryogenic temperature and smaller shallow trap density, which makes it more potential to be used for the cryogenic insulation.

1. Introduction

Insulation system within the superconducting magnet is an important issue in research of magnetic confinement fusion reactors. Unlike quench in the superconductor which could be controlled, failure of solid insulation and subsequent arc may cause permanent damage to the equipment. Glass fibre reinforced polymer composites (GFRPs) are designed to be used as insulation materials in some part of the International Thermonuclear Experimental Reactor (ITER) magnet, such as insulation break, current lead and feeder busbar, for their sound mechanic and electric properties.

In order to fulfil requirements on mechanical properties under designated conditions of superconducting magnet, epoxy resins are commonly modified by using different curing technics or doping of nanoparticles [6–9]. In the previous studies, to enhance the mechanical properties at cryogenic temperature and radiation resistance, two types of GFRPs were fabricated by vacuum press impregnation (VPI) process, which shown sound mechanical performance at cryogenic temperature and high radiation resistance [10–13].

It has been found that volume resistance and electrical breakdown strength are enhanced and dielectric loss are reduced at cryogenic temperature for some polymers, therefore, it is commonly considered that electrical performance of insulation materials utilised at room temperature can be maintained at lower temperatures. However, insulation deteriorations of polymer dielectrics have also been detected at cryogenic temperatures, including the decrease in partial discharge inception voltage [1,2], aging resistance and resistance of electrical tree propagation [3,4], and some polymers show a decline trend in electrical strength as temperature decreasing [5]. Therefore, it is necessary to investigate the electrical properties of insulation materials at cryogenic temperature.

In this study, the electrical properties at cryogenic temperatures were investigated. To avoid the influence from impurities like nitrogen drops, electric properties of GFRPs, including direct current (dc) breakdown strength, surface flashover voltage at room and cryogenic (78 K) temperatures, dielectric spectroscopy and space charge characteristics, were investigated under vacuum, and the mechanism of electrical property changes were analysed. It was found that electric breakdown strength and flashover voltage for both GFRPS were enhanced at temperature down to 78 K, and DGEBF systems present higher dielectric strength, flashover withstand voltage, lower permittivity at low temperature, and smaller shallow trap depth density.

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https://doi.org/10.1016/j.fusengdes.2017.10.022
Received 1 December 2016; Received in revised form 4 September 2017; Accepted 30 October 2017

Please cite this article as: Wang, S., Fusion Engineering and Design (2017), http://dx.doi.org/10.1016/j.fusengdes.2017.10.022

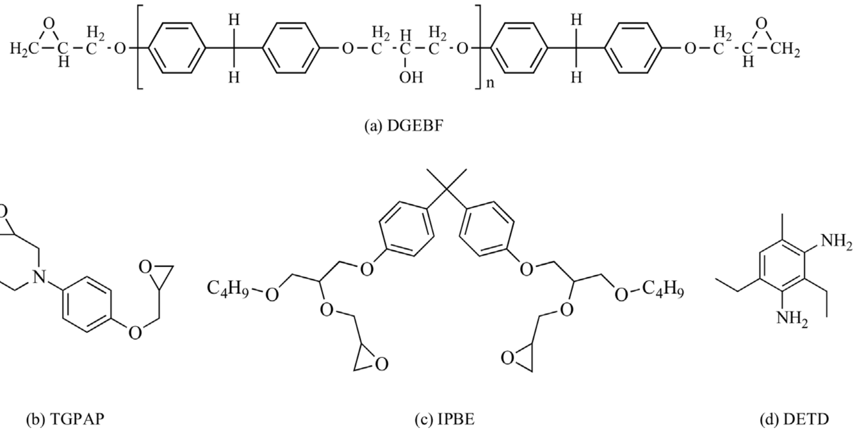

Fig. 1. Chemical structures of DGEBF, TGPAP, DETD and IPBE.

2. Samples and test procedures

2.1. Samples preparation

Two types of GFRPs using diglycidyl ether of bisphenol-F (DGEBF) and triglycidyl-*p*-aminophenol (TGPAP) as baseline epoxy resins were prepared respectively, which are cured with diethyl toluene diamine (DETD) and reinforced by boron-free fibre grass, and 10 wt% of isopropylidenebisphenol bis[(2-glycidyloxy-3-*n*-butoxy)-1-propylether] (IPBE) were introduced to toughen each of the resin systems. The chemical structures are given in Fig. 1. The specific fabrication procedures were described in [10,13]. The composites were cut into 50 mm × 50 mm × 0.5 mm samples for electrical tests.

2.2. Test apparatus and procedures

Electrical breakdown and flashover withstand voltage of composites were investigated under conditions of vacuum and different temperatures. A test chamber was developed to provide vacuum condition of 10^{-5} Pa, and the temperatures from 78 K to 300 K can be regulated by a 2 stage Gifford-McMahon (GM) refrigerator. Test fixtures with high cooling efficiency were designed according to IEC standard 60243 [14], and all the electrodes are made of stainless steel. The breakdown test fixture consists of a hemisphere electrode of 6 mm diameter, and a plate electrode of 25 mm diameter and 5 mm thickness placed directly on the cool head of GM refrigerator. Sample can be cooled by close contact to the cool head. For the flashover test fixture, a pair of cylinder electrodes of 2 mm diameter and 200 mm height are fixed in parallel with a space of 5 mm and sample is fixed on an epoxy resin platform with height of 20 mm to guarantee the sample surface being stressed by a strong tangential electric field (Figs. 2 and 3). Sample is cooled by gaseous helium media, which is pumped out before flashover tests.

Each sample was pre-treated according to IEC standard 60212 [15], and dc breakdown and flashover tests were conducted at temperatures of 78 K and 300 K, respectively, while under air pressure of 10^{-5} Pa.

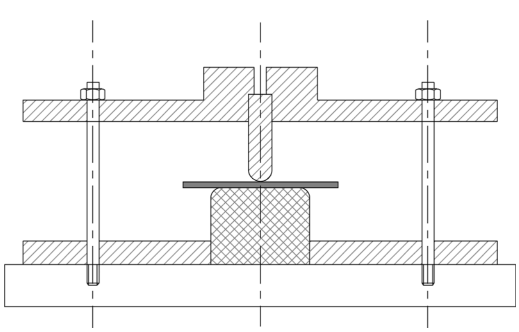

Fig. 2. Breakdown electrodes configuration.

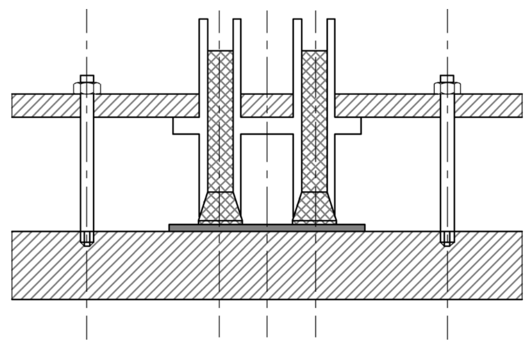

Fig. 3. Flashover electrodes configuration.

The dc ramp voltage with rising rate of 1 kV/s was applied. Cumulated breakdown probabilities were calculated by following approximation according to IEEE Guide 930 [16],

$$F(i,\,n) \approx \frac{i-0.44}{n+0.25}\times 100\% \tag{1}$$

where F is the probability of electric failure, i is the rank of breakdown strength results in ascending order, and n is the breakdown times for each type of dielectrics, which is 15 in this study.

Dielectric properties of composites including permittivity and dielectric loss were measured by a Novocontrol Alpha-A high-performance frequency analyzer (GmbH, Germany). All the measurements were carried out in frequency range of 10^{-1}–10^{6} Hz, and at temperature range of 173–473 K.

Thermally stimulated current (TSC) method were exploited to investigate the space charge characteristics of dielectrics. Samples were polarised by electric field of 10 kV/mm at 323 K for 20 min, and then cooled to 173 K rapidly. Depolarisation current was measured while the sample was heated with a rate of 3 K/min. The temperature regulation and polarisation procedure of the TSC test are shown as Fig. 4.

In the dielectric spectroscope measurements and TSC tests, both sides of sample surface were evaporated with gold layers to make well conduct to the electrodes.

3. Test results

3.1. DC electric breakdown strength

DC breakdown test results are shown in (Fig. 5) . Breakdown voltage of DGEBF based resin was higher at 300 K and 78 K. Dielectric strength of both composite was enhanced at lower temperature. To be specifically, the averaged breakdown strength was increased by 8.5% and 11.2% at 78 K for DGEBF and TGPAP, respectively .