Dielectric Properties of Cryogenic Gas Mixtures Containing Helium, Neon, and Hydrogen

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Abstract. Past efforts of cooling high temperature superconducting (HTS) power cables by gaseous cryogens focused exclusively on helium. The limited dielectric strength of helium gas necessitated alternatives that could be used in the temperature range suitable for HTS power applications. This paper presents the benefits of gas mixtures containing helium with small concentrations of hydrogen or neon to mitigate the limited dielectric strength of pure helium gas. The expectation was that such gas mixtures could improve dielectric characteristics while maintaining the thermal, non-flammable and non-corrosive properties of pure helium gas. The AC breakdown voltage of helium gas mixtures containing 4 mol% neon or 4 mol% hydrogen respectively have been measured and compared to those of pure helium and pure neon. All measurements were performed at 77 K at gas pressure levels between 0.5 and 2.0 MPa. While the 4 mol% neon mixture did not result in any improvement over pure helium, the 4 mol% hydrogen mixture resulted in 80% higher breakdown strength. This is expected to enable higher operating voltages for gas cooled HTS power devices.

1. Introduction

High temperature superconducting (HTS) power cables are expected to enable electric power distribution of unprecedented power density as is required on future all-electric ships. However, shipboard applications prohibit the use of liquid nitrogen (LN2) since there exists a risk for asphyxiation hazards in case of a LN2 leak. The US Navy considers helium gas (gHe) as a viable option to cool HTS power cables without the risk for asphyxiation hazards since the gas inventory is smaller by several orders of magnitude and helium does not accumulate in the lower sections of the ship.

Cooling the HTS cable with gHe has a number of additional advantages. Most importantly, it allows a wide temperature range including temperatures at which LN2 solidifies. The temperature range below the LN2 range increases the critical current in the individual HTS tapes and therefore the power density of the HTS cable. Another benefit is the tunability, allowing certain interconnects to operate temporarily at lower than nominal temperature during times of high demand.

Past efforts of cooling HTS power cables by gaseous cryogens focused exclusively on pure helium gas [1]. An investigation was undertaken to determine the benefits of mixing small amounts of hydrogen or neon gas to helium to mitigate the limited dielectric strength of pure helium gas. The authors expected that this could potentially improve dielectric characteristics while maintaining the thermal, non-flammable and non-corrosive properties of pure helium gas.
From the dielectric point of view, hydrogen gas is far superior to helium and neon. Hydrogen gas has approximately 50% of the dielectric strength of nitrogen gas at room temperature [2]. The noble gases helium and neon exhibit a dielectric strength 15% and 25% respectively that of nitrogen gas at room temperature. It is known from other gas mixtures studies at room temperature that even a small amount of a superior gas can considerably improve the dielectric strength of the mixture more than the ratio would suggest. Typical examples for such investigations is the addition of small fractions of SF$_6$ into N$_2$ [3] or CO$_2$ to a SF$_6$-N$_2$ mixture [4]. Theoretical models to explain and predict the dielectric strength of gas mixtures are currently being developed [5].

The dielectric properties of pure helium gas at temperatures in the range of 50 K to 80 K have been studied in past HTS cable projects at Florida State University. The challenges with pure helium’s low breakdown voltage have led to the investigation of potential alternative cooling gases. The dielectric strength of helium gas mixtures containing 4 mol% of neon and 4 mol% of hydrogen have been measured and compared to pure helium and pure neon. The 4 mol% mixture ratio of hydrogen was selected to ensure that the gas mixture was inflammable in air. All experiments were performed at 77 K at pressures between 0.5 and 2.0 MPa.

2. Methodology

The dielectric properties of the gases were examined by completing alternating current (AC) breakdown tests at various pressure levels while at cryogenic temperatures. The AC breakdown tests were performed by determining the voltage required to arc across a pair of electrodes installed inside a pressure vessel, filled with the various gas mixtures and immersed in a cryostat filled with LN$_2$. The electrodes have a profile similar to a Bruce profile, are highly polished, and consist of 316 stainless steel. The gap distance was adjustable, however was kept at 2 mm as this appeared to be a good trade-off between voltage resolution and upper voltage limitations of the setup. The experiment installed within the pressure vessel is schematized in Figure 1.

**Figure 1.** Schematic of the experimental setup to characterize cryogenic gas mixtures (not drawn to scale).

**Figure 2.** The electrode system with uniform field in the gap between the electrodes.

In Figure 2 it can be seen that the top electrode was connected to the voltage source and the bottom electrode was grounded. The gap between the electrodes was set to 2 mm using a precision gauge block. The electrodes were not changed throughout the duration of the experiment to ensure that the
results obtained from the gas mixtures were comparable. On completion of the experiment, the gap
distance between the electrodes was re-measured and confirmed to be 2 mm. This shows that the
electrodes did not become loose while performing the experiments at cryogenic temperatures.
However, the distance between the electrodes is expected to be slightly different from 2 mm due to the
thermal contraction of the materials at 77 K. The electrodes as well as all the other parts inside the
pressure vessel were thoroughly cleaned by isopropyl alcohol before closing the vessel.

Before the beginning of the experiments, the pressure vessel was evacuated to $10^{-4}$ mbar or lower
for at least 12 hours using a turbomolecular pump. The vessel was subsequently flushed twice with
industrial grade helium gas to ensure all contaminants were removed before being filled with research
grade helium gas of 99.999% purity. The pressure vessel was then immersed in a cryostat filled with
LN2 and the pressure inside the pressure vessel was adjusted to 2.0 MPa. The AC breakdown tests
were not undertaken until equilibrium had been reached for the gas pressure, which ensured that the
temperature of the helium gas and all components reached 77 K. Throughout the experiment LN2 was
added to the cryostat to ensure that the whole pressure vessel including the bushing was immersed in
liquid nitrogen.

Initially, ten AC breakdown tests were performed to “season” the surfaces of the electrodes. It is a
well-known effect that new electrodes tend to show lower breakdown voltages for the first few
breakdown events. After seasoning the electrodes, fifteen AC breakdown tests were performed at
2.0 MPa with these results being recorded. The pressure within the vessel was reduced to 1.5 MPa,
then 1.0 MPa and finally 0.5 MPa with fifteen AC breakdown tests being performed at each pressure
level. Once the AC breakdown tests at 0.5 MPa had been completed, the pressure within the pressure
vessel was released and a dry scroll vacuum pump was connected to remove the remaining helium gas
from the vessel.

This process was then repeated for the 4 mol% neon, pure neon and 4 mol% hydrogen gases. A
lack of sufficient quantities of pure neon gas restricted the maximum operating pressure to 1.8 MPa.

It should be noted that there are some indications that helium and neon are mixed very slowly at
77 K due to slow diffusion at cryogenic temperatures. Therefore, the gas mixtures were ordered pre-
mixed in high pressure steel tanks from a gas supplier. While the exact mixing procedure is unknown
to the authors, there is no reason to assume the mixture would be inhomogeneous. Once the gases are
mixed at room temperature, there were no indications that they would separate and stratify later during
the experiment at cryogenic temperature.

On completion of the experiment, the electrodes were inspected by scanning electron microscopy
(SEM) to check if the discharge activity created craters that might have locally enhanced the electric
field, therefore resulting in a decrease of the breakdown voltage. While the craters were visible in the
SEM images, they are of similar size as the machining marks (surface roughness) and thus expected
not to play an essential role. The energy in the discharge pulses is very limited due to a high source
impedance.

3. Experimental Results

The result of the average AC breakdown voltage for the pure helium, pure neon, helium with 4 mol% 
neon and helium with 4 mol% hydrogen gas mixtures can be seen below in Figure 3. The error bars in
Figure 3 show the range of voltages recorded (maximum and minimum) at each pressure level for each
gas mixture.
Figure 3. AC breakdown voltage as a function of pressure at a 2-mm gap distance in homogeneous field for helium, neon, 4 mol% hydrogen in helium, and 4 mol% neon in helium mixture.

Analysis

From Figure 3, two distinct trends were observed when helium gas was mixed with neon and hydrogen. Firstly, when a small amount of a stronger dielectric gas is mixed with a weaker dielectric gas there is an increase in AC breakdown strength. Adding 4 mol% hydrogen to helium, the AC breakdown voltage increased by approximately 80% for all pressure levels tested. Hydrogen is a diatomic gas with a dielectric strength far superior than those of noble gases. The second trend is the addition of a small amount of weaker dielectric gas being mixed with a stronger dielectric gas does not have any significant effect on AC breakdown voltage. The dielectric properties of neon are significantly lower than those of helium; however, the AC breakdown voltage for the pure helium and 4 mol% neon gas mixture is approximately identical with the pure helium gas for all pressure levels. While we do not see a reason to add neon gas to the mixture, it is good to know that a small amount of (unintended) impurities does not have a negative effect on the dielectric strength.

4. Conclusion

Breakdown experiments in homogeneous electric fields at a temperature of 77 K and pressure levels between 0.5 MPa and 2.0 MPa suggest that adding 4 mol% hydrogen by volume to helium increases the dielectric strength by approximately 80% while the mixture is still considered non-flammable at any ratio with air. This is promising for the application of high temperature superconducting power apparatus such as cables when a gaseous cryogen is preferred. A mixture of 96 mol% helium with 4 mol% neon did not indicate any change of the dielectric properties compared to those of pure helium gas. More experiments are planned to investigate different mixture ratios of helium with hydrogen. Additional experiments are currently being performed to investigate the thermal properties of such a mixture. A patent for cryogenic gas mixtures is pending [6].
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