Investigation of solid nitrogen for cryogenic thermal storage in superconducting cable terminations for enhanced resiliency

N Suttell\textsuperscript{1,2,4}, Z Zhang\textsuperscript{2}, J Kweon\textsuperscript{2}, T Nes\textsuperscript{3}, C H Kim\textsuperscript{2}, S Pamidi\textsuperscript{1,2}, and J C Ordonez\textsuperscript{1,2}

1 FAMU-FSU College of Engineering, Tallahassee, FL 32310, USA
2 Center for Advanced Power Systems, Florida State University, 2000 Levy Ave, Tallahassee, FL 32310, USA
3 Energy, Materials and Systems, University of Twente, Drienerlolaan 5, 7522 NB Enschede, Netherlands
4 Author to whom any correspondence should be addressed: nicksuttell@gmail.com
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Abstract. Low heat capacity of helium makes the helium gas cooled high temperature superconducting (HTS) power devices susceptible to large temperature rises during unexpected heat loads such as electrical faults or cryogenic system failures. Cryogenic thermal storage in the form of solid nitrogen designed in the terminations is explored as a means to increase the thermal stability and operational time of HTS power cables in the event of unexpected heat loads. An external tank containing activated charcoal is used as an adsorption buffer tank for nitrogen gas. The use of activated charcoal minimizes the volume of the buffer tank and prevents pressure rises during melting and boiling of the solid nitrogen. Calculations of the cryogenic thermal storage needed and a description of the experimental setup used to understand the design constraints are discussed.
1. Design concept of a solid nitrogen thermal buffer

Gaseous helium (GHe) cooled HTS power devices are being considered for special applications where using liquid nitrogen is unsafe and less feasible. These applications include all-electric ships, aircrafts, and other applications involving significant changes in elevation or within enclosed spaces. Figure 1 shows a diagram of the GHe cable termination used at the Florida State University, Center for Advanced Power Systems (FSU-CAPS). The increase in thermal loads during a fault is caused by Joule heating within the copper terminal located in the termination (Figure 1). The total thermal load on the helium gas within the termination under normal operation is approximately 150 W. An increase of 200 W on average during a fault increases the total load to 350 W. The fault lasts a very short time, but the energy it deposits takes more time to remove. GHe has a low heat capacity per unit volume relative to liquid nitrogen (LN2). This makes GHe-cooled high temperature superconducting (HTS) power cable systems operating at 50 K susceptible to large temperature increases in the case of unexpected heat loads.

To mitigate this drawback, designing thermal storage within the cable terminations is explored to enable continued operation while the system is shut down and alternative power supply is arranged to supply the emergency loads. Similar studies on SN2 thermal buffers for superconducting MRI machines and other magnet systems have been proposed as efficient methods for improved reliability [1]. This effort is a part of the research and development on GHe-cooled HTS systems at the FSU-CAPS [2]. Additionally, efforts to develop novel designs to improve capability of managing thermal loads have been done at CAPS [3]. The concept of using solid nitrogen (SN2) as a thermal battery has been studied previously [4] [5] & [6], but this is the first time SN2 has been used for HTS applications in conjunction with a pressure controlling gas adsorption system.

The thermal storage component in this study incorporates a SN2 block anchored to the copper terminal within the HTS cable termination. The block of SN2 is connected to an external buffer chamber filled with activated carbon creating a self-contained system as shown in Figure 1. The purpose of the carbon is to adsorb the gaseous nitrogen (GN2) that is generated when SN2 melts and boils during a heat surge within the termination. When the system returns to normal operation following the heat surge, the nitrogen gas re-condenses and solidifies. The analysis presented in this paper only considers the 200 W
of heat that is theoretically assumed to transfer from the copper terminal to the SN2. It is also assumed that the targeted extension of the operation of the cable system is 5 minutes while systematic shut down of the system is activated. This translates to a total energy of 60 kJ in the termination that needs to be removed. The value of the heat flux in this situation is 1.5 kW/m².

The proposed concept of a solid nitrogen cryogenic thermal storage system takes advantage of two phenomena: the latent heat of fusion and vaporization of nitrogen and nitrogen adsorption onto activated carbon. In the event of an unexpected heat load on the HTS cable system due to fault currents or cryogenic system failure, the SN2 will absorb the heat flux due to Joule heating from the copper terminal. Interception of heat at the terminations keeps the helium gas cryogen flowing through the termination at a lower temperature thus allowing continued operation of the cable. As the SN2 melts, the latent heat of fusion will absorb extra heat (approximately 25 kJ/kg) in the process. If the heat surge is large enough, the liquid nitrogen (LN2) will start boiling. The latent heat of vaporization of the LN2 will provide nearly an order of magnitude of more heat absorption (about 200 kJ/kg) than the latent heat of fusion while keeping the temperature at 77 K.

The novelty of this study is the introduction of activated carbon that adsorbs the GN2 produced during large heat loads to keep the pressure low. It is desirable to maintain low pressure throughout this process because at higher pressures LN2 boils at a much higher temperature, therefore, the LN2 latent heat of vaporization cannot be utilized, and the temperature in the cable terminations will go above the desired temperature of 77 K. At 0.2 MPa, the boiling point of nitrogen is 83.7 K which reduces the critical current and approaches the critical temperature of the HTS REBCO material of ~ 90 K. Therefore, it is necessary that the vapor of the LN2 pressure does not exceed 0.2 MPa. Figure 2 shows a theoretical temperature versus time graph of a 240 g nitrogen sample undergoing its phase transitions under a heat load of 200 W and at a constant pressure of 0.1 MPa. A simple lumped analysis was performed using temperature dependent material properties and the aforementioned constraints to produce the results shown in Figure 2.

2. Experimental tests

2.1. Gas pycnometer test
Adsorption occurs when molecules or atoms of a fluid stick to a solid surface. Unlike absorption, in which the fluid permeates the solid, adsorption is a surface phenomenon, and it is related to surface

Figure 2. Theoretical temperature versus time graph of 240 g sample of nitrogen under a heat load of 200 W and at a constant pressure of 0.1 MPa.
energy [7]. The solid material doing the adsorbing is called the adsorbent, whereas the surrounding fluid that is being adsorbed is called the adsorbate. This study focuses on the adsorptive properties of nitrogen gas (adsorptive) onto activated carbon (adsorbent) to create a layer of nitrogen gas on the carbon surface (adsorbate). The total mass of fluid adsorbed is a function of the nature of the adsorbent-adsorbate system and the equilibrium temperature and pressure. The ratio of nitrogen mass to activated carbon mass at constant temperature is expressed in Equation 1,

\[
m_a / m_s = \ln(p)_T
\]  

where \( m_a \) is adsorbate, or adsorbed nitrogen mass, \( m_s \) is adsorbent, or solid mass, \( p \) is the equilibrium pressure, and \( T \) is the temperature. Equation 2 is commonly referred to as an adsorption isotherm.

It is important to have the relevant adsorption isotherm data for the system of interest. For this study, only the adsorption equilibrium is of concern because the timescale of the adsorption process is much smaller than that of the nitrogen phase transition and heat diffusion. Additionally, long-term adsorption effects are not of interest in this study. To obtain an adsorption isotherm of the GN 2 with the activated carbon used for the experiment, helium gas (GHe) was used initially to measure the void fraction of the carbon powder. This is possible because GHe is not adsorbed as much as GN 2, especially at room temperature and atmospheric pressure [8]. Furthermore, it has been verified by Fernbacher et al. that the amount of helium adsorbed onto activated carbon is an order of magnitude less than that of nitrogen [9]. Unlike water treatment or toxin removal systems, the application of activated carbon to maintain low pressures does not require a highly accurate adsorption isotherm. Therefore, the “helium density”, as it is called in the relevant community, of the adsorbent (in this case activated carbon) is accurate enough to obtain useful information [10].

A gas pycnometer is a device used in laboratories to measure the volume of porous solids using gas displacement. A pycnometer was built for this study to measure the helium density of the activated carbon powder, and to develop a nitrogen adsorption isotherm. Figure 3 shows two chambers separated by a valve. The volumes of each chamber along with the volume of the connecting tube are known. The reference volume chamber is initially pressurized with helium gas from an external source while the connecting valve is closed. The pressure transducer records the initial pressure of the gas. The valve is open so the helium gas can expand into the adsorbent chamber. The helium gas is assumed ideal in this case, and the ideal gas law was used to calculate the volume of the carbon powder.

\[
P_i V_i = P_f V_f
\]  

\( P_i \) and \( V_i \) in Equation 2 are the initial pressure and volume of the reference volume chamber from Figure 3 respectively. \( P_f \) and \( V_f \) in Equation 2 are the final pressure and total volume of both chambers in Figure 3 respectively. To obtain the volume of the carbon, \( V_i \) needs to be expressed as:

\[
V_f = V_i + V_{pipe} + V_{ac} - V_c
\]  

where \( V_{pipe} \) is the volume of the connecting pipe, \( V_{ac} \) is the volume of the adsorbent chamber, and \( V_c \) is the volume of the carbon that is impenetrable to helium gas. Equation 3 can be plugged into Equation 2 and re-arranged to get:

\[
V_c = V_i + V_{pipe} + V_{ac} - P_i V_i / P_f
\]  

An expression for the carbon is often written in terms of a void fraction \( (F_v) \):

\[
F_v = 1 - V_c / V_{cp}
\]  

where \( V_{cp} \) is the volume of the carbon powder including the voids. After conducting the helium pycnometer experiment, the void fraction for the activated carbon used in this experiment was calculated to be \( F_v \approx 0.7 \). This value has been validated from [10]. The corresponding helium density of the activated carbon was calculated to be \( \rho_{hel} = 666.7 \text{ kg/m}^3 \).
The next step is to perform a similar test using the pycnometer with nitrogen gas instead of helium. The results from this second part of the pycnometer test along with the void fraction of the activated carbon calculated in the first part will be used to calculate the adsorption isotherm of nitrogen gas and activated carbon. The mass of nitrogen that is adsorbed can be found by calculating the initial and final mass of un-adsorbed GN2 based on the pressure data and the known volumes shown in Equation 6,

\[ m_a^g = m_i^g - m_f^g = \left[ P_i V_i - P_f (V_i + V_f - V_c / F_v) \right] / R_{N2} T \]  

(6)

where \( m_a^g \) is the mass of adsorbed nitrogen gas, \( m_i^g \) is the initial mass of un-adsorbed nitrogen based on initial pressure and volume, and \( m_f^g \) is the final mass of un-adsorbed nitrogen based on final pressure and volume. On the right side of Equation 6, \( R_{N2} \) is the gas constant for nitrogen, and \( T \) is the temperature. Figure 4 shows the adsorption curve that was obtained from the gas expansion pycnometer experiment. This graph plots the rate of adsorption versus the equilibrium pressure at different masses of carbon

![Figure 4. Adsorption isotherm for nitrogen on activated carbon. \( q \) is the rate of adsorption in number of moles of nitrogen per kilogram of active carbon powder](image)
powder for verification. These results are in good agreement with adsorption isotherms experimentally obtained from [11]. The trend line generated from the adsorption isotherm obtained from Figure 4 is shown in Equation 7.

$$q = -4 \times 10^{-5} P_f^2 + 0.0145 P_f + 0.0065$$

(7)

Where $q$ is the adsorption rate in mol/kg and $P_f$ is the final pressure of the system. So, if the system is to be kept at a pressure of 0.1 MPa, then the activated carbon will adsorb 1 mole of nitrogen gas per 1 kg of carbon. The adsorption isotherm can now be used to determine the required volume of activated carbon necessary to maintain low nitrogen pressure for the cryogenic experiment. The following section will describe the status of the cryogenic experiment.

2.2. Cryogenic experimental set up for adsorption of nitrogen by carbon

The cryogenic experiment to simulate excessive heat load within the HTS cable system is currently being built. The conditions for this case include a power dissipation of 200 W transferred to the SN2 from a heater wire for approximately 5 minutes all while keeping the system pressure at 0.1 MPa. This translates to 60 kJ of heat, and Equation 8 can be used to calculate the amount of SN2 required to absorb the heat immediately after completely boiling.

$$m_{N2} = \frac{W_{elec} t}{h_f + \int_{T_1}^{T_2} c_p dT + h_v}$$

(8)

$c_p$ is the temperature dependent specific heat of LN2, and $h_v$ is the latent heat of vaporization for N2. The mass of solid nitrogen at 63 K required to absorb 60 kJ and raise the temperature of the nitrogen through both of its phase transitions (solid to liquid and liquid to gas) was calculated to be 240 g. Using the calculated nitrogen mass obtained from Equation 8 with the adsorption rate of $q = 1$ mol/kg calculated from Equation 7, the required mass and volume of carbon can be calculated. For this case study, the required volume of activated carbon to maintain a pressure of 0.1 MPa is $V_{ac} = 0.024$ m$^3$. The

Figure 5. SN2 cryogenic thermal storage experimental system.
calculations show that using nitrogen adsorption on activated carbon saves over 80% of the volume that would otherwise be necessary if adsorption were not employed.

A SN$_2$ cryogenic vessel with a volume of 1.83 L is placed in a vacuum insulated cryostat shown in Figure 5. The solid nitrogen chamber has a stainless steel flange, with copper rods protruding from the internal surface for increased heat transfer to the nitrogen. This chamber is thermally anchored to the cold head of a Cryomech AL330 cryocooler which is wrapped with a resistive heater to allow application of a controlled heat load as a way to simulate the heat surge in the HTS termination. The solid nitrogen chamber is fitted with a feedthrough for temperature sensor wiring and a port for nitrogen gas transfer. Two temperature sensors are located in the SN$_2$ chamber to measure the temperature of the fluid directly. One of the temperature sensors is on the top, close to the cold head. The second temperature sensor is located at the bottom to allow measurement of the temperature gradient across the storage chamber. The room temperature carbon adsorption chamber is connected to the cryogenic solid nitrogen chamber using a $\frac{1}{2}''$ pipe with valves to separate the chambers to allow isolation of the two chambers, when necessary, during the experiments. Pressure transducers are used to monitor the vacuum and GN$_2$ pressure during the heating process. The cryogenic chamber is initially pressurized with nitrogen gas until it is filled with the required mass calculated above of $m_{N_2} = 240$ g, and the cryocooler is turned on.

The cryocooler cools the gas down to a temperature of approximately 60 K to solidify the nitrogen. Once the temperature starts going below ~60 K, indicating the nitrogen is completely solidified, the valve to the adsorbent chamber is opened, and the heater is used to apply 200 W of heat load to the solid nitrogen chamber for approximately 5 minutes to convert it to its gaseous state. Once both temperature readings reach 78 K it can be assumed that nearly all the nitrogen has evaporated, and the pressure reading is recorded and compared to that of the calculations discussed above.

Figure 6. Cryomech AL330 cryocooler and SN$_2$ chamber nearing final preparation for testing at FSU-CAPS.
2.3. Conclusion and future work

The exploratory study presented in this paper shows promise that a SN$_2$ thermal buffer anchored to the copper lead within the GHe-cooled HTS cable termination will improve system resiliency. Furthermore, calculations show that using a separate room temperature chamber filled with activated carbon reduces the buffer system volume by 80% while keeping the pressure during the heat surges at 1 bar and prevent the boiling point of nitrogen from increasing above 77 K.

Figure 6 shows the experimental setup used for understanding the dynamics of nitrogen adsorption. This system will also be used to study the design constraints of using SN$_2$ as an effective means to include cryogenic storage in HTS cable terminations or other HTS devices to enhance thermal stability and system resiliency. This study will continue with the experiments focused on determining the capabilities of various types of commercially available activated carbon. The experimental results will also be used to validate the calculations on required volume of the carbon and study the limitations of the thermal battery system leading to an efficient and effective cryogenic thermal storage built into HTS power devices.

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