Cryogenics for an HTS degaussing system demonstrator

I Hanse, MSc[a*], D P Wikkerink, MSc[b], ing. C Vermeer[a], ing. H J Holland[a], dr. M M J Dhallé[a], prof. dr. ir. H J M ter Brake[a]

[a]*University of Twente, Enschede, The Netherlands*
[b]*Delft University of Technology, Delft, The Netherlands*
*Corresponding author. Email: i.hanse@utwente.nl

Synopsis

This paper describes the design, construction and test results of a high temperature superconducting (HTS) degaussing demonstrator system. Such a system compensates the local disturbance in the earth's magnetic field caused by the ferromagnetic hulls of ships, to prevent detection by active or passive magnetic field sensors. This is done by placing coils around the ship, creating a magnetic field opposing the effect of the earth's magnetic field. Degaussing systems for large naval vessels typically need currents of up to 1 or 2 kAturns, which gives rise to sizeable ohmic losses in conventional copper coils. These losses can be reduced if high temperature superconductors are used, since they have no electrical resistance when cooled down to temperatures below 90 K. For the demonstrator, 3 coils able to generate fields in 2 directions were realized both with HTS and copper to get a representative degaussing performance. A dedicatedly designed cooling system maintains the superconductors at a temperature of 77-85 K using (subcooled) liquid nitrogen. Due to the relatively small laboratory scale that this first 1.5 m long demonstrator system which was produced, the copper degaussing system is still more efficient than the HTS system because of the cooling power needed. A large fraction of this cooling power is needed to cool away parasitic heat loads, that hardly increases if the size of the system increases. Thereafter the performance of both systems was compared to evaluate on what scale HTS degaussing systems become more efficient than copper degaussing systems.

Keywords: HTS; Degaussing; Cryogenics; HTS Degaussing; Magnetic field; Energy efficiency

1 Introduction

Ships are generally constructed using magnetic steel materials. Typical values for the magnetic permeability of construction steel are 50-150 (Sandomirskii, 2013). Therefore, a ship creates a local disturbance in the geomagnetic field around it, which is called its magnetic signature and can be detected from a distance by active or passive magnetic field sensors. Since naval vessels prefer to remain undetected, degaussing systems are often installed aboard navy ships. Degaussing systems consist of sets of coils that create a magnetic field in the direction opposite to that of the earth, removing the magnetic signature of the ship and making it less detectable. One problem of conventional degaussing systems is the power usage. Large currents are needed to degauss a ship, creating large ohmic losses. The power consumption of conventional degaussing systems can range up to several hundreds of kW (Ross et al., 2012). High Temperature Superconductors (HTS) can be used to reduce the power consumption of degaussing systems. Superconductors are materials with no electrical resistance at low temperatures, making them very good for large-current applications. High temperature superconductors become superconducting at temperatures below roughly 90 K, which means a cryogenic cooling system is necessary.

This paper reports on an ongoing project to study the feasibility of an HTS degaussing system as an energy-efficient substitute for conventional copper degaussing systems. HTS offers several benefits with respect to copper because HTS materials have no electrical resistance and allow for a high current density. This means that both the power as well as the weight of the degaussing system can be reduced by using HTS instead of copper cables. A weight reduction of 80% is reported by Kephart et al (Kephart et al., 2011). Values of the reduction in power consumption are still uncertain, and one of the main aims of this project was to investigate this aspect. To achieve this, a small-scale HTS degaussing sytem was built and tested at the University of Twente. The test-piece is a 1.5 m long steel pipe, made from construction steel with a magnetic permeability of roughly 100. Around the steel pipe, three HTS degaussing coils and three copper degaussing coils are placed to compare the performance of the two systems as measured using fluxgate magnetometers. The degaussing systems consist of one M-coil (creating a field in the vertical direction) and two L-coils (creating a field in the longitudinal direction) as can be seen in Figure 1. The HTS cables are kept at a suitable operational temperature using subcooled liquid nitrogen. This paper discusses the performance of the cooling system and the extrapolation of its power consumption to larger-scale degaussing systems.

https://doi.org/10.24868/issn.2515-818X.2020.068

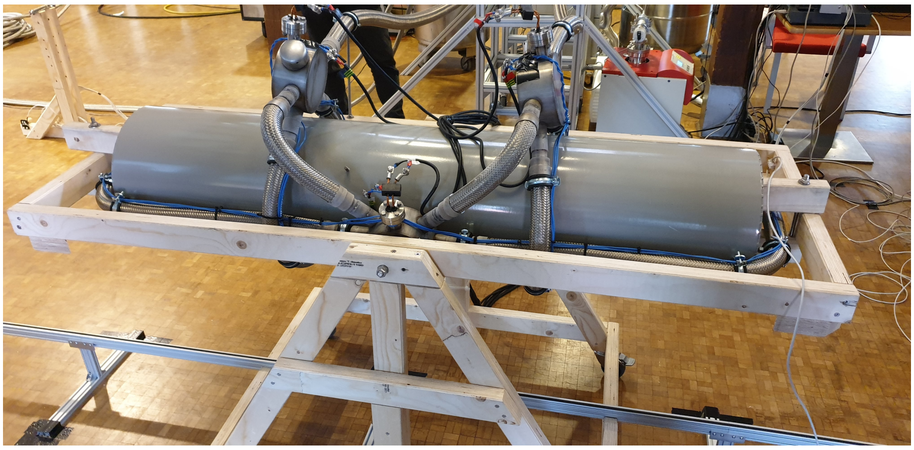


Figure 1: A picture of the steel pipe with two sets of coils around it. The stainless steel cryostats around the pipe contain the HTS coils, the blue wires next to the cryostats are the copper coils.

2 Cryogenic design

Superconductors need to be cooled below their critical temperature. The cable that was used in this case consists of YBCO tape that was wound around a flexible core. YBCO has a critical temperature (T_c) of 93 K but must be cooled to a lower operational temperature to have some thermal margin. To accomplish this, a cooling infrastructure is created. When building the cooling system, there are two priorities that have to be taken into account: the power consumption of the system has to be minimized and it should be possible to scale the system to a larger size.

Typically, cooling of superconducting systems can be accomplished with two distinct strategies: either with conduction-cooling or by direct contact with a cryogen. For an extended degaussing system, conduction cooling is not an option because it will create large temperature gradients along the HTS cable thus cooling using a cryogen was chosen. The choice of cryogen depends on the temperature range that is needed. The temperature should be significantly lower than 93 K to allow for sufficiently large currents inside the cable, because the critical current density of the cable increases with decreasing temperature. At the same time, a lower temperature will increase the power consumption of the system because the efficiency of coolers decreases when they have to cool down to lower temperatures. A temperature range from roughly 60 to 80 K is cold enough to make a cable superconducting. This leaves (subcooled) liquid nitrogen, (subcooled) liquid oxygen and helium gas as options for the cryogen. For this demonstrator project, subcooled liquid nitrogen was chosen because of its large heat capacity and large temperature range in which it can be used (65 - 77 K).

By using subcooled instead of boiling liquid nitrogen, there will be no bubbles inside the system which reduces the chance of local hotspots due to reduced cooling capacity. To guarantee that liquid nitrogen is available at all times, a closed liquid nitrogen system was designed so that there is no need to refill the system. A schematic of the cryogenic system is shown in Figure 2. On the left side of the system (valve 1), liquid nitrogen is inserted, which then flows through a heat exchanger where it is subcooled by a cooler. After this, the subcooled liquid nitrogen is transported to the three degaussing coils before it goes back to the nitrogen pump and restarts its cycle. At the end of the circuit, just before the nitrogen pump, a degasser is placed. This is a device which is used to remove the nitrogen gas from the system to make sure there is only liquid nitrogen in the circuit. The cooler is connected to the heat exchanger with a copper thermal link. A heater is attached to control the temperature, these parts are placed inside a large vacuum box. The pressure inside the vacuum box is monitored as well as the pressures at the beginning and end of the nitrogen circuit. The temperatures of several parts of the cooler box are monitored as well. Vacuum insulated flexible cryostats are used to transport the liquid nitrogen from the cooling box to the HTS cables, which are also placed inside the vacuum insulated cryostats. For each of the three coils, a connection box was constructed where the HTS cables are connected to current leads and where the subcooled liquid nitrogen is transported through the coils. Pictures of a connection box and the cooling box are shown in Figures 3a and 3b.

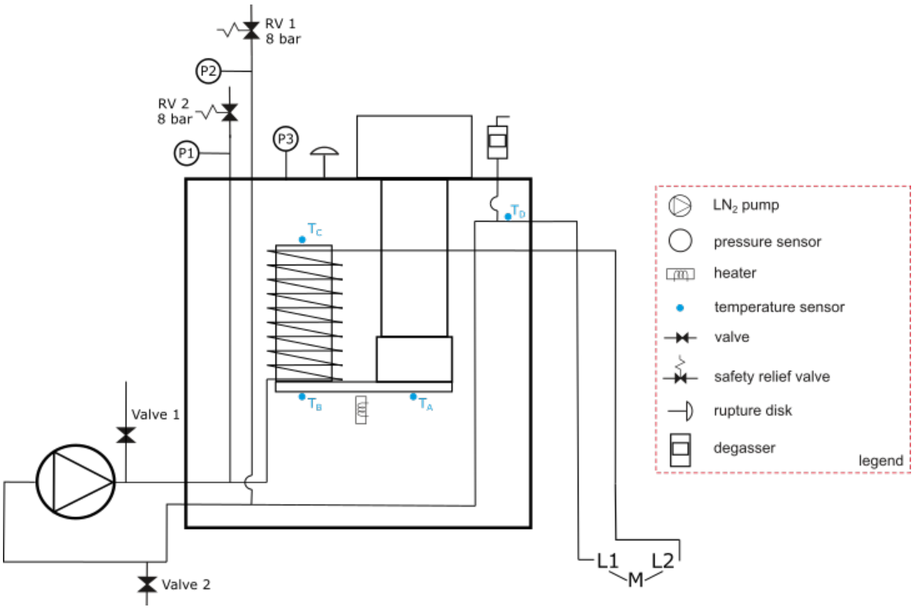
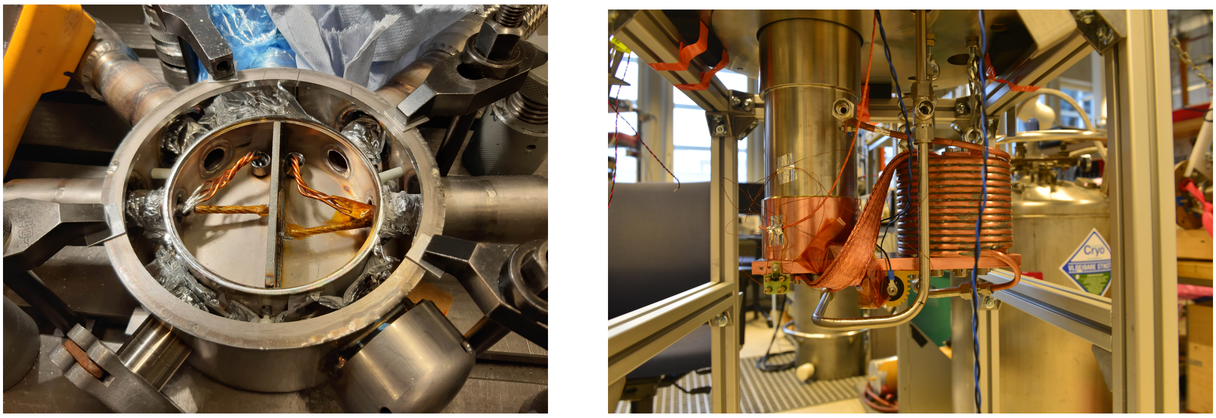


Figure 2: A schematic of the different parts of the cooling circuit consisting of a nitrogen pump, a heat exchanger, a cooler and several valves and sensors. L1, L2, and M denote the different degaussing coils.



(a) A picture of the inside of the connection box, containing the current leads and HTS cable.

(b) A picture of the inside of the cooling box, containing the cooler, thermal link and heat exchanger.

Figure 3: Pictures of the connection box and cooling box.

3 Energy efficiency

The heat loads on the system can be calculated. For this purpose, the system is divided into several parts, namely the cooling box, the connection boxes, the coils, the transfer lines and the current leads. The heat loads are calculated for the small-scale demonstrator system, and for a larger system. Similarly, the power consumption of a copper degaussing system of the same size is calculated.

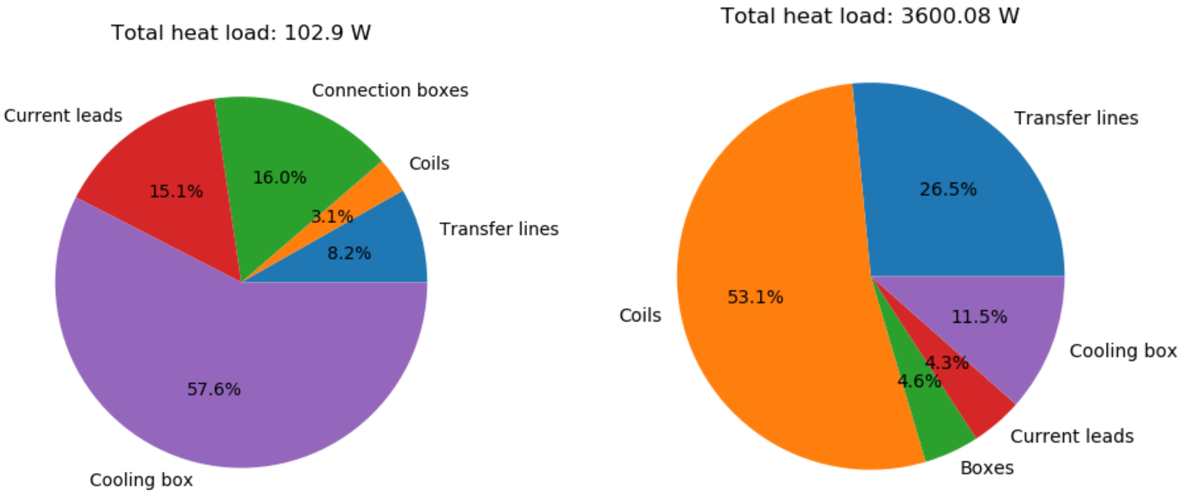
The heat loads in the different parts of the test set-up were estimated using analytical equations and are shown in Figure 4a. The heat load on the cooling box stems from radiation and from conduction through the cooler, through structural supports and through pipes. The heat load through the current leads gives a large contribution to the total heat load because the current leads were optimized for a current of 100 A, more than needed for this small test set-up. The heat load on the connection boxes comes from radiation and conduction through the support structure. The heat load on the coils and transfer lines comes from the heat leak of the cryostat, which is estimated as $0.4\,\mathrm{W\,m^{-1}}$.

When increasing the size of the HTS degaussing system, the relative contribution of the coils and transfer lines becomes much more important. For a larger system, the same cryogenic infrastructure can be used to pump around and subcool liquid nitrogen (possibly with a larger cooler), meaning that the heat load on the cooling box stays

https://doi.org/10.24868/issn.2515-818X.2020.068

largely the same. For a larger degaussing system, a larger number of ampere-turns is needed to create a sufficiently large degaussing field, this can be realized by increasing the current or the number of turns. Because the heat load through the current leads becomes much more significant with larger currents, it is more energy efficient to increase the number of turns. The heat load on the connection boxes stays the same and only increases if more degaussing coils are used. The contribution from the coils and transfer lines scales directly with the total length of these parts, which becomes the dominant part for large ships.

The heat load of a HTS degaussing system for the LCF Frigate (as discussed by Ross(Ross et al., 2012)) is estimated and shown in Figure 4b. The total length of this ship is 144 m, the width of the ship is 17.5 m. Using these values, the length of the degaussing coils can be calculated. It is assumed that there are 30 degaussing coils on this ship, with a total coil length of 1910 m, the transfer line length is assumed to be half the length of the coils. The cryostat has a heat leak of 1 W m^{-1}, 7 different cooling boxes are needed on the ship.



(a) The contribution of different heat loads in a small-sized HTS degaussing system.

(b) The contribution of different heat loads estimated for the HTS degaussing system of a LCF Frigate.

Figure 4: The calculated heat loads from the small-scale HTS degaussing system is compared to the heat loads from a ship-sized HTS degaussing system.

The heat loads shown in Figure 4, are heat loads into a cryogenic system at 80 K. The power needed to cool away these heat loads is calculated using the carnot efficiency and the cooler efficiency. The carnot efficiency is given as

$$\eta_{Carnot} = \frac{T_c}{T_h - T_c} \tag{1}$$

Where T_h is the warm temperature and T_c is the cold temperature. With 293 K for T_h and 80 K for T_c, η_{Carnot} becomes 0.38. The cooler efficiency can be estimated based on a study by Kittel (Kittel, 2007), which gives a cooler efficiency of approximately 0.1 (while becoming more efficient for larger systems). Using these numbers together with the heat loads from Figure 4 gives a power consumption of 2.7 kW for our small-scale HTS degaussing system and a power consumption of 94.7 kW for a ship-sized HTS degaussing system.

The power consumption of a copper degaussing system of the same size is calculated. The cable length is assumed to be 2865 m, the current density is 2.5 A mm^{-2} and the current needed in the system is 1500 Aturns (Varma, 2014; SAM, 2011). Using these value, the ohmic losses in the copper degaussing system are of the order of 180.5 kW, almost double the power consumption of the HTS degaussing system. From Figure 4b, it can be seen that the quality of the cryostat is very important. If a heat leak of 0.8 W m^{-1} is assumed instead of 1 W m^{-1}, the power consumption is reduced by more than 15%, from 94.7 kW to 79.7 kW.

4 Cryogenic measurements

A HTS degaussing system was built and tested. Unfortunately, a small leak in the liquid nitrogen system was detected which could not easily be fixed. It is probable that this leak is located in the connection boxes. The current leads are glued into the stainless steel connection boxes, this connection might have cracked, allowing liquid nitrogen to seep through. The leak in the nitrogen system caused the vacuum quality to deteriorate as soon as liquid nitrogen flowed through the system. For this reason, the main focus will be on cooldown and warm-up curves where no liquid nitrogen is present in the system. Additionally, there were technical problems with the cryocooler, which means a less powerful cryocooler than originally planned had to be used. Therefore, a closed nitrogen system could not be achieved, because the cryocooler was not powerful enough to keep the liquid nitrogen subcooled.

In the figure below, a complete cooldown and warm-up of the HTS degaussing system is shown. The location of the temperature sensors is shown in Figure 2. Temperatures T_A, T_B and T_C are near the cooler while temperature sensor T_D is attached to the nitrogen pipe leaving the degaussing system. Temperature sensor T_D thus gives an indication of the temperature at the end of the system. A complete cooldown and warm-up curve is shown in Figure 5. The system is cooled down using a cryocooler. At this point, only the large masses in the cooling box are reduced in temperature while the HTS cables stay warm. The temperature is stabilized around 80 K using a heater, before liquid nitrogen is inserted to cool down the HTS cables as well. At this point, the vacuum pressure increases to roughly 2 mbar inside the vacuum box. The system is kept cold for a while to perform measurements before it is warmed up again.

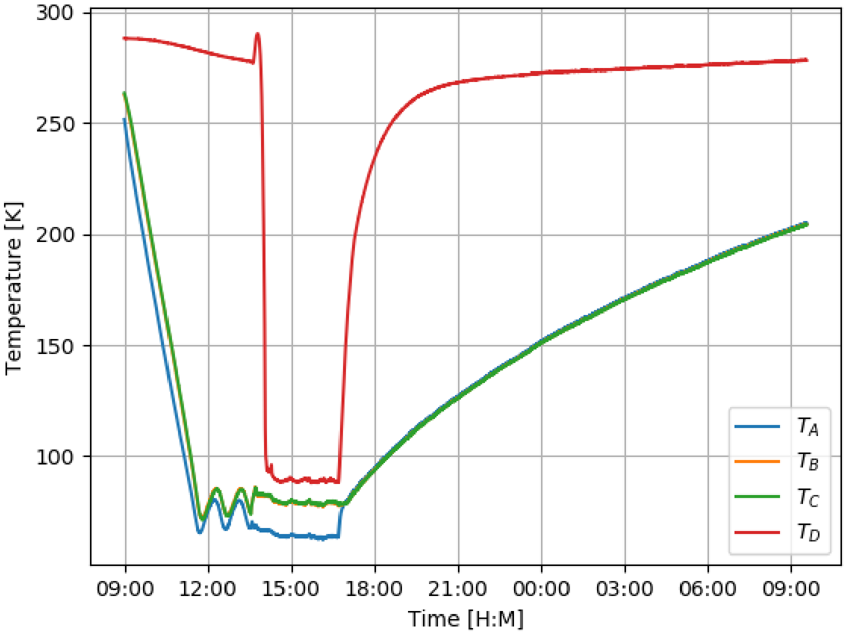
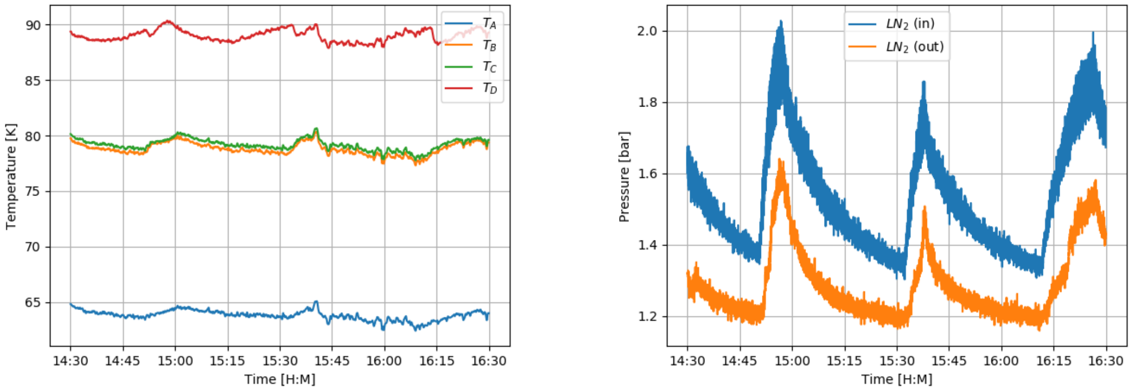


Figure 5: The complete cooldown and warm-up of the HTS degaussing system is shown. Initially, the system is cooled down using a cryocooler. At 13:30, liquid nitrogen is inserted into the system. The system is warmed up again starting at 16:40.

Figures 6a and 6b show the temperatures and nitrogen pressures as soon as the system is cold. Temperature sensor T_B gives the inlet temperature of the liquid nitrogen. At this point, the inlet temperature is lower than the boiling point of liquid nitrogen (84 K at 2 bar), meaning that the nitrogen is indeed subcooled. Temperature sensor T_D gives the nitrogen temperature at the end of the system, at this point the nitrogen is (partly) evaporated. The cooler is not powerful enough to keep the liquid nitrogen throughout the system subcooled. It can be seen from Figure 6 that the temperatures of the system can be tuned by changing the nitrogen pressure and pressure difference.

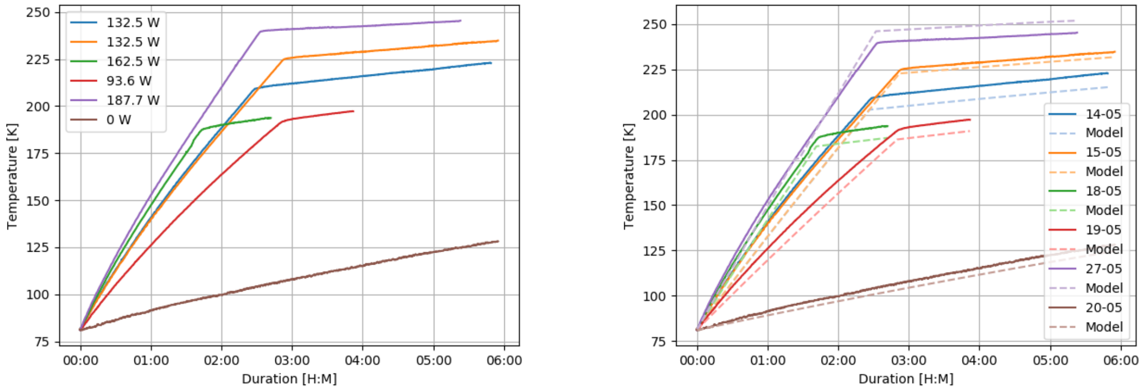
By looking at the warm-up of the system in some more detail, the heat leak into the cooling box can be estimated. Figure 7 shows several warm-up curves where different amounts of heater power are applied. In Figure 7b, the warm-up curves are shown together with a simple model of the temperature which is fitted with a heat leak of 25.1 W (i.e. much smaller than anticipated in Section 3).



(a) The temperatures of the HTS degaussing system.

(b) The ingoing and outgoing pressure of the liquid nitrogen.

Figure 6: The temperatures and nitrogen pressures are plotted as function of time.



(a) The warm-up of the cooling box is shown as a function of heater power.

(b) The warm-up curves are shown, together with a simple model of the temperature.

Figure 7: The warm-up curves are shown for several different heater powers.

5 Discussion and further research

A laboratory-scale HTS degaussing system was designed, built and tested. The preliminary results are discussed in this paper. The system was designed so that it can be scaled up to a full-scale HTS degaussing system. A cooler is used to subcool liquid nitrogen which is then used to cool HTS coils. Connection boxes were built to induce the current in the coils and to divide the liquid nitrogen between them. The coils are placed in vacuum insulated flexible cryostats.

In Section 3, it was discussed how HTS degaussing becomes more efficient as soon as the size of the system increases. For small systems, copper degaussing is much more efficient than HTS degaussing. For larger systems, HTS degaussing becomes more efficient than copper degaussing systems. This was demonstrated by estimating the power consumption of an M Frigate.

The HTS degaussing system was tested to analyse its cryogenic performance. The cooler is used to subcool the liquid nitrogen. The HTS cables were cooled down below their critical temperature. The measurements that were performed show that the heat leak into the cooling box is roughly 25 W at 80 K. This is smaller than predicted, indicating that the design of the cooling box worked better than expected.

Some parts of the cryogenic system still need improving. A leak in the nitrogen system was detected, which caused the vacuum quality of the system to deteriorate. The current leads were glued into the connection boxes, it is likely that the glue has cracked, causing a leak in the nitrogen system. Improving this will improve the vacuum

https://doi.org/10.24868/issn.2515-818X.2020.068

quality and thus reduce the heat leaks in the system. Additionally, it was not possible to create a closed liquid nitrogen system because the cooler that was used was not powerful enough. More tests will be performed to create an actual closed subcooled liquid nitrogen system.

Acknowledgement

This project has been made possible by support from the maritime system integrator RH Marine, DMO and the institute for scientific development IWO.

References

J. T. Kephart, B. K. Fitzpatrick, P. Ferrara, M. Pyryt, J. Pienkos, and E. M. Golda. High temperature superconducting degaussing from feasibility study to fleet adoption. *IEEE Transactions on Applied Superconductivity*, 21(3): 2229–2232, 2011.

P. Kittel. Cryocooler performance estimator. *Cryocoolers*, 14:563–572, 2007.

R. Ross, C.G. Meijer, and R.J. Mheen. Degaussing by normal and superconductive windings. *INEC 2012 - 11th International Naval Engineering Conference and Exhibition*, 01 2012.

Degaussing System DEG COMP MOD 2. SAM Electronics, 2011. 1.054.

S.S. Sandomirskii. Maximum magnetic permeability of magnetically hard steel and the limiting hysteresis loop. *Steel in Translation*, 43:530–534, 2013. doi: https://doi.org/10.3103/S0967091213080123.

R.A. Raveendra Varma. Design of degaussing system and demonstration of signature reduction on ship model through laboratory experiments. *Physics Procedia*, 54:174 – 179, 2014. ISSN 1875-3892. doi: https://doi.org/10.1016/j.phpro.2014.10.056. International Conference on Magnetic Materials and Applications, MagMA-2013.