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ABSTRACT

ALUHEAT project aims to build a cryogen-free superconducting induction heater. In this paper, the cryogenic design, which includes heat loss calculations, mechanical analysis, optimization of current leads and description of cooling conditions, is presented in detail. The induction heater consists of two magnets in separate cryostats and the billet to be heated is rotated between the cryostats. Short distance between the magnet and cryostat wall, large forces between the magnets, and the need to rotate the billet create application specific requirements that must be taken into account. Finite element analysis is used to design the cryostat to withstand the forces created by the vacuum and magnetic field. Finally, thermal interface, radiation shield, magnet support and apparatus to rotate the billet are designed and all components assembled into the complete system.

KEYWORDS: Induction, MgB_2, Efficiency, Superconducting
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INTRODUCTION

ALUHEAT project aims at building a cryogen-free superconducting induction heater. In an induction heater the changing magnetic field induces eddy currents that heat up a billet placed inside the magnet. Conventional induction heaters use alternating current in a copper coil to create the changing magnetic field (figure 1a). Unfortunately, significant ohmic losses are generated and the total efficiency decreases drastically. The basic idea of superconducting induction heater is to improve the total efficiency. This cannot be done by simply feeding a superconducting coil with AC current due to the AC losses of a superconductor. However, the heating can be attained if a billet is rotated in an inhomogenous DC magnetic field created with a superconducting coil (figure 1b). Small demonstration devices in which a superconduting coil is supplied with DC current have already been introduced by SINTEF in Norway [1]. Since superconductors are lossless at the direct currents and the input power is needed only to cool down the superconducting coil and rotate the billet. The superconducting induction heater is more efficient compared to the conventional one when heating low resistivity materials like copper or aluminum. Efficiency in conventional induction heaters is only around 55% [1,2] whereas with superconductivity the efficiency can be increased to around 90%. This is substantial increase and since the total power of heaters usually exceeds 1 MW significant cost savings can be achieved.

SYSTEM OVERVIEW

Aluminum billet was placed between two parallel disc-shaped cryostats each having the diameter of 1.6 m and the thickness of 0.5 m. One Gifford-McMahon cryocooler with the cooling power of 15 W @ 20 K and 80 W @ 80 K cools down each cryostat. The decagonal radiation shield having RRR of 100 was composed of two end plates and ten similar plates on the sides as shown in the figure 2. Both the radiation shield and the magnet hang from a steel plate attached to the cryostat top. Interface of the coil have RRR of 250 and it will be

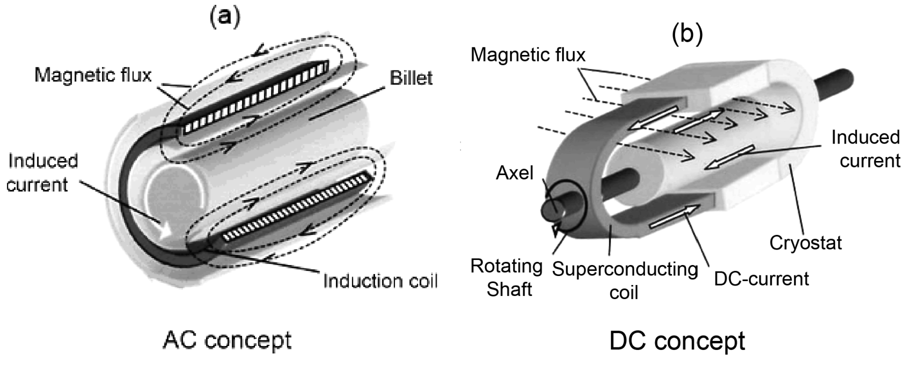

FIGURE 1. (a) Conventional induction heater, (b) Superconducting direct current induction heater.

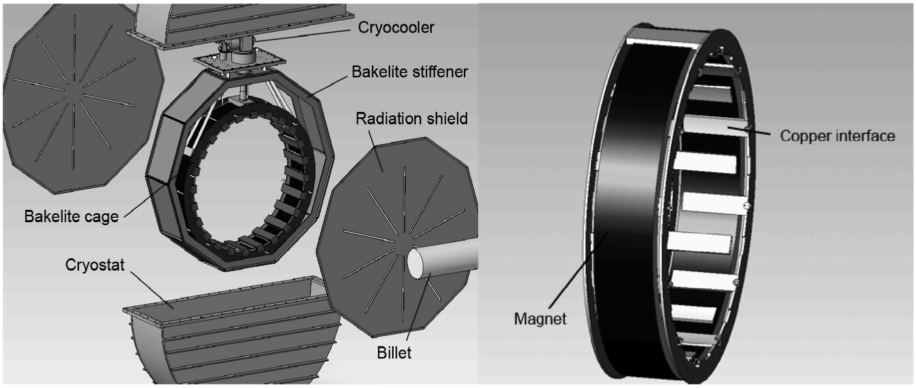

FIGURE 2. Structure of one disc-shaped cryostat

assembled as mechanically flexible comblike structure that ensures good thermal homogeneity over the magnet and reduces eddy current losses during the ramping. A small gap is left at the both sides between the interface and the coil due to differences in thermal contraction. The combs of the interface will be attached to the coil with Stycast 2850-FT epoxy resin. All the thermal contacts, which do not need to be electrically insulated, will be copper-copper pressure joints with Apiezon N grease between the surfaces. Electrically insulated contacts are achieved using thin layers of aluminium nitrite on both surfaces and Apiezon N grease between the contacts.

Since the magnets are very close to each other they must be supported against horizontal magnetic force which pulls them together. Therefore, the magnet will be surrounded with a bakelite cage fixed to the cryostat walls using G-10 epoxy-fiberglass tubes. These tubes will prevent the coil movement during the operation. Furthermore, an extra bakelite support is used to prevent the deformation of radiation shield due to the Lorentz forces during a quench.

CRYOGENIC DESIGN

Coil design

The design of a coil system depends on the requirements of the particular heater. Dimensions of the billet to be heated, mechanical system of the heater and desired temperature profiles set the frames, whereas conductor properties and chosen coil winding technique determine the final shape of the coil. The coil system outlined here was designed for billets with the diameter of 215 mm and with lengths up to 700 mm. The magnetic field was generated by a Helmholtz configuration of two vertically mounted superconducting coils which were located at the distance of about 800 mm. When the billet was placed between the cryostats the magnetic field was oriented in perpendicular to the billet axis.

The use of MgB_2 superconductors makes the coil design flexible in terms of conductor length. MgB_2 superconductors are relatively inexpensive and as the coil operates in DC, additional conductor length does not yield additional energy losses. In this investigation, the coils had a outer diameter of 1100 mm, thickness of 50 mm and the height of 180 mm as presented in figure 3. Each coil was built up of 16 double pancake coils, with joints on the outer side. The MgB_2 tape was first insulated with a 25 μm thick kapton foil. Then the

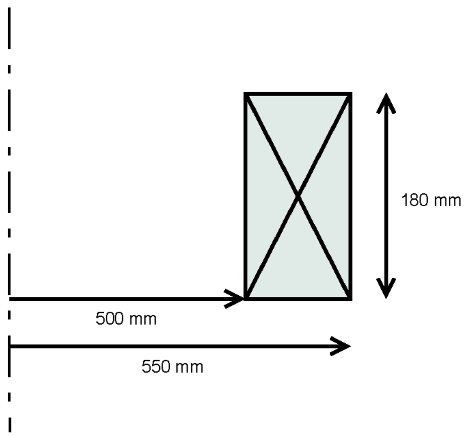

FIGURE 3. MgB_2 coil dimensions

pancakes were wound with a wet layer technique using Stycast 2850-FT. Afterwards they were stacked together and reinforced with epoxy impregnated glass-fibre tapes.

The current in the coils, and hence the magnetic field, depends somewhat on the particular billet to be heated. A typical value of the magnetic field was about 0.5 T in the centre of the billet at rest and the coils themselves were exposed to the magnetic field of about 1.6 T at the corners closest to the billet.

Heat losses

The coil is in a vacuum and therefore heat is transferred into the system only by conduction and radiation. Radiation shield and multilayer insulation reduces the heat flux P_r radiated from the outer cryostat wall to the magnet. The radiated heat fluxes coming to the radiation shield and to the magnet were calculated with analytical formulas from ref. [3]. Furthermore, the influence of the multilayer insulation on the radiated heat was taken into account as $P_{r,rs}(n) = P_{r,rs}(0)/(n+1)$, where n is the number of multi-insulation layers (MLI) and $P_{r,rs}$ the heat radiated to the radiation shield from the outer cryostat wall. In this case, 30 layers of MLI were used as a compromise which decreased the thermal radiation to the acceptable level but kept the distance between the coil and the billet short.

The G-10-epoxy support tubes will be constructed of two parts. The length of the first part from the top of the cryostat to the radiation shield was 62 mm and the length of the second part from the radiation shield to the magnet was 510 mm. In both parts the inner and outer diameters were 14 mm and 20 mm, respectively, yielding the cross-section of 1.60 cm^2 per tube. The heat flux, P_s, conducted from the room temperature to 20 K via the four supporting G-10-epoxy tubes was solved from the 1D heat transfer equation with Finite Element Method (FEM). Temperature dependent thermal conductivity of the G-10 tubes was obtained from ref [4].

The current leads were designed to operate at 250 A in such a way that the sum of conductive and ohmic losses, P_l, in the lead was minimized. In conduction cooled systems the current leads are usually divided into two parts. The first part from the room temperature to the radiation shield is often made of normal metal like brass or copper. The second part from the radiation shield to the magnet is made of high temperature superconductor (HTS). In the normal conducting part the optimal value for the ratio IL/A, where I is the current, L the length and A the cross-section of the lead, can be derived from ref [5]. For brass leads the optimal IL/A ratio was $6.5 \cdot 10^5$ A/m and for copper leads $3.5 \cdot 10^6$ A/m. Since the distance between the radiation shield and the cryostat was only 67 mm, the optimal diameter of round copper wire at 250 A would be only 2.4 mm. Small cross section is difficult to construct and is more vulnerable in case of overcurrents. Copper leads could be made longer by bending the leads. In this case the optimal diameter increases. However, since bending the leads is difficult and while the optimal diameter for brass lead was 6 mm, the brass was chosen as a material for the normal conducting part whereas commercial YBCO leads were used in the second part. The diameter of these YBCO leads was 11 mm and conductive heat leak 130 mW per pair. Summary of all loss components is shown in table 1.

MECHANICAL DESIGN

Rotation of the billet

The mechanical system for billet rotation is important for total system performance since it determines the way mechanical energy is transformed into heat. By rotating the billet in the magnetic field eddy currents are generated at the billet surface and thereby Joule heating arises. Essentially, the higher the rotational speed, the faster the heating. Unfortunately, unbalanced forces also increase with speed and clamping requirements for proper torque transfer to the billet vary greatly with speed. So a trade-off between technological effort, process stability, system efficiency and cost was required. This led to various mechanical system designs all of which finally assumed a steady-state rotational speed of about 3000 rpm. Figure 4 illustrates the basic concept of the mechanical system for billet rotation and its main components. The motor drive unit comprises a frequency converter for continuous control of rotational speed and is terminated mechanically in a coupling element for flexible attachment to the rotation axis. For stability reasons all these heavy components must be firmly attached to a rigid base frame at the bottom. This frame supports also a small sub-unit that is movable on horizontal slides. The movable unit accommodates the billet and fixes it during rotation. It defines the rotational axis and provides the clamping elements for holding and turning the billet at its ends. Loading of the billet is preferably carried out outside of the magnetic field. The sliding unit is moved out from the space between the cryostats. The billet is fed

TABLE 1. Heat losses to the system

Loss component	To radiation shield	To magnet
Radiated heat, P_r	10 W*	2 W
Losses in current leads, P_l	16 W	0.1 W
Conduction via supports, P_s	5 W	0.4 W
Pancake resistive joints	0 W	≈ 1 W
Total	31 W	3.5 W

* with 30 layers of MLI

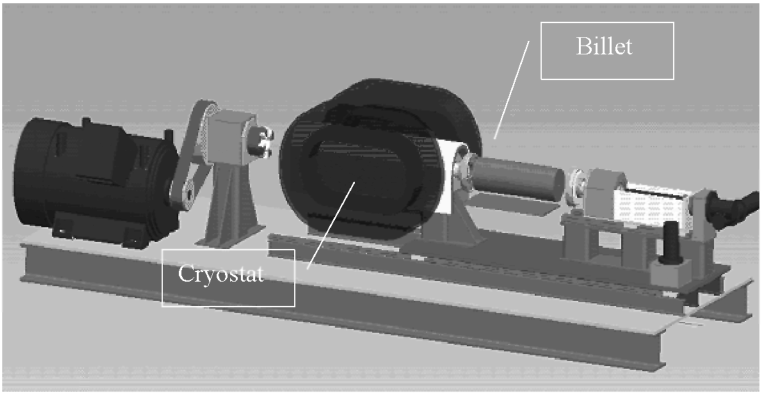

FIGURE 4. Basic concept of mechanical system for billet rotation. Motor drive is displayed in left. Billet and movable sub-unit are shown out from space between cryostats. Rotation is achieved using unique gripping system. Supports structures have been omitted for better clarity.

horizontally and/or vertically into the clamping unit and held at both ends with grippers running in journal bearings as known from turning machines. The unit is then slid back until the billet is located between the cryostats in the center of the magnetic field. At this position, the coupling mechanically connects the clamped billet to the motor drive and rotation can be started. For safety reasons, there is a rigid cage fully surrounding the billet in this position. So, even if the billet breaks apart, there is no risk of damage in the surroundings at any time during rotation.

Cryostat mechanical analysis

System consists of two high field superconducting magnets very close to each other. Forces affecting the system are shown in the figure 5. $\mathbf{F}_{st}$ is the force affecting the cryostats when the billet does not rotate but the operation current is switched on. This is the worst case scenario since when the billet starts to rotate it experiences a changing magnetic field and eddy currents are induced. Then, the magnetic flux distribution of the system changes and therefore the force turns and its magnitude drops significantly. Force $\mathbf{F}_{st}$ was calculated by integrating the Lorenz force over the cross section of the coil to be 31 kN at normal operation conditions. The magnitude and the direction of the force $\mathbf{F}_{rot}$ during the billet rotation was calculated in an infinitely long racetrack coil with 2d FEM. In case of a solenoid direction of the $\mathbf{F}_{rot}$ will be the same and the magnitude much smaller compared to the F_{st}. Therefore, the worst case is when the billet is not rotated while the magnets are energized.

Due to the electromagnetic forces the magnet support has to be fixed to the broad sides of the cryostat in order to prevent movements during operation. This was achieved with six G-10 epoxy fiberglass tubes at the both sides of the coil. Also large vacuum forces affect the broad sides of the cryostat and thus very massive supports are needed to prevent it from deforming. Figure 6 shows von Mises stresses due to the vacuum in the broad side of the cryostat. Von Mises stress gives overall magnitude of the stress tensor across the cryostat and is most applicable to ductile materials. Corresponding strain can be calculated when material properties are known. The broad sides were designed to withstand the vacuum forces with the safety factor of two. Designed broad side plates were 18 mm thick and had 30 mm high support steel bars welded to them.

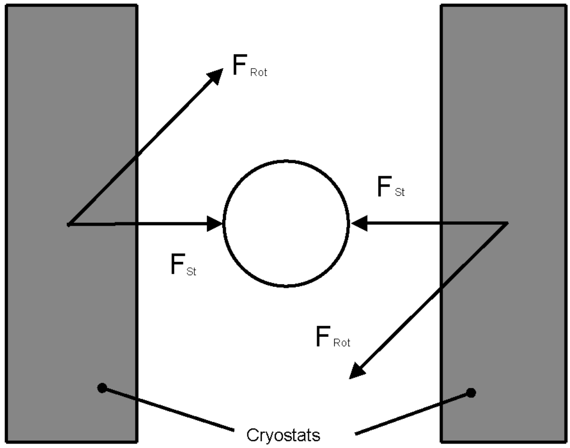

FIGURE 5. Forces affecting the cryostats with and without an rotating billet.

CONCLUSIONS

In this paper the cryogenic design of superconducting induction heater was presented. The superconducting induction heater is a new technology used to increase electrical efficiency while heating high conductivity metals like copper and aluminium. The billet to be heated was placed between two disc shaped cryostats and rotated in an inhomogeneous magnetic field to achieve the heating effect. A superconducting heater is expected to cut down the costs of heating considerably due to the poor efficiency of the conventional heater. The mechanical system for the billet rotation and cooling of the magnet are very important since they have direct effect on the system efficiency. When the billet is rotated the eddy currents are

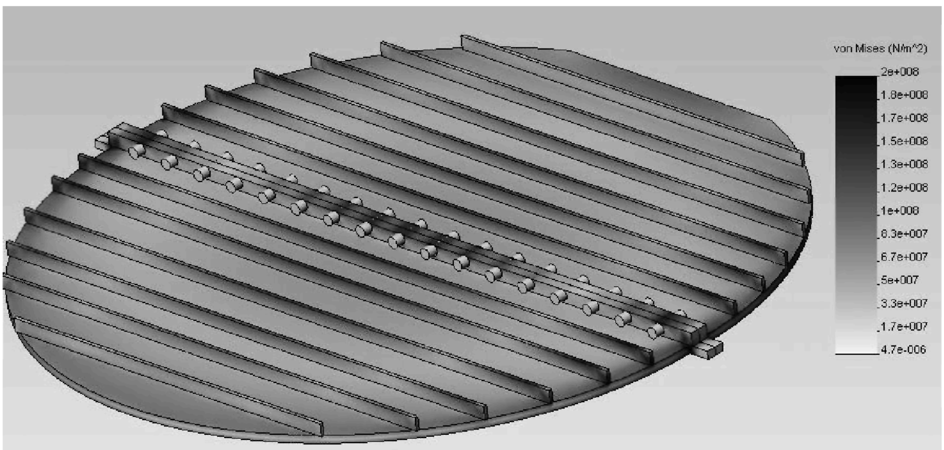

FIGURE 6. von Mises stress distribution in broad side of cryostat created by vacuum forces.

generated at the billet. The higher the rotational speed, the faster the heating. Unfortunately new problems arise with higher rotation speed and therefore a steady-state rotational speed of about 3000 rpm was selected. The system consists of two high field magnets close to each other and thereby large forces tended to pull the magnets together. Special G-10 epoxy supports fixed between the magnet and the cryostat walls will be used to keep it in place. Also the vacuum forces affecting inward at the broad sides of the cryostats are large and therefore steel support bars were designed to stiffen the sides. Height of the steel stiffeners should be kept are small as possible since they widen the gap between the coil and the billet thus reducing efficiency.

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