DESIGN OF TEST CRYOSTAT FOR SUPERCONDUCTING SOLENOID MAGNETS

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Abstract

The cylindrical cryostat for testing superconducting magnets is designed. It consists of two vessels, the inner one for cooling the superconducting magnets with liquid helium and the outer one for providing the heat sink of 77K thermal shield with liquid nitrogen. The thermal shields are placed between the liquid helium vessel and the external housing, which are wrapped with multi-layered superinsulation. The size of the cryostat is about 800 mm in diameter and 2200 mm in height, with the liquid helium consumption rate of 0.7 liter per hour without current leads. In this article, the design features, structural and thermal analysis of the cryostat are discussed.

1 INTRODUCTION

The designed cryostat is proposed as equipment for experiments of superconducting (SC) magnets under the low temperature conditions with liquid helium (LHe) and nitrogen (LN_2) in the development of SC magnets. The cryostat consists primarily of liquid helium vessel, thermal shield with nitrogen vessel, room temperature housing, upper service flange for instruments and tools, liquid helium filling tube, LHe level sensor, and current leads. The main parameters of the cryostat are listed in Table. 1

Table 1: Main Parameters of the Test Cryostat

Parameters	Values
Diameter of LHe vessel	505 mm
LHe volume	170 liter
LN_2 volume	190 liter
Working temperature - helium vessel - nitrogen vessel	 4.2 K 77.3 K
LHe consumption rate (without current leads)	0.7 liter/hour
LN_2 consumption rate	0.7 liter/hour
Design pressure	0.25 MPa
Operation pressure - helium/nitrogen vessel - space for thermal insulation	 0.1/0.1 MPa 133x10^{-6} Pa
Height	2200 mm
Outer diameter	800 mm
Total weight	≈ 300 kg

2 CALCULATION OF THERMAL LOAD

2.1 Steady State Heat Conduction

To calculate heat flux into the LHe vessel the following sources must be taken into account:

- Heat conduction through the LHe vessel wall.
- Heat convection between the LHe vessel wall and evaporated gas helium.
- Radiation between LHe vessel and thermal shields.
- Heat conduction of superinsulation and residual gas.

The heat balance equation, which the heat transfer modes described previously are accounted, is given by

$$A\frac{d}{dx}\left[k_{ss}(T)\frac{dT}{dx}\right]-\eta\dot{m}C_p\frac{dT}{dx}+C\sigma_0\varepsilon\left(T_{th}^4-T^4\right)+k_{ins}C\left(T_{th}-T\right)=0 \qquad (1)$$

where,

A : cross-sectional area of LHe vessel wall
C : circumference of the cryostat
$k_{ss}(T)$: thermal conductivity of stainless steel
k_{ins} : thermal conductivity of thermal insulation
C_p : specific heat of helium vapour (5.21kJ/kg)
T_{th} : temperature of nitrogen thermal shield
$\dot{m}$: mass flow rate of helium vapour
σ_0 : Stefan-Boltzmann constant(5.67×10^{-8} W/m^2/k^4)
ε : effective emissivity of external cryostat wall
η : efficiency of heat transfer

2.2 Longitudinal Heat Conduction of LHe Vessel

The primary source of thermal leakage into the LHe vessel is the longitudinal heat conduction. At the distance, 150mm apart from the service flange, the LN_2 vessel is connected to the LHe vessel as shown in Fig. 1. The temperature of the connecting positions is equal to that of LN_2. If our concern is focused only in conduction, the third and fourth term of Eq. (1) can be neglected. The integration of the modified heat balance equation under the account of latent heat of LHe gives

$$\dot{Q}=\frac{A}{L}\int_{T_L}^{T_H}\frac{k_{ss}(T)}{1+\eta\left(T-T_L\right)C_p/\lambda_l}dT \qquad (2)$$

where,

$\dot{Q}$: thermal load into liquid helium by conduction
T_L : lower temperature in a cryostat
T_H : high temperature in a cryostat
L : length of cryostat
λ_l : latent heat of LHe (20.32 kJ/kg)

The distributions of the temperature in the LHe vessel from the LHe level to the room temperature flange are shown in Fig. 2 and 3. From the calculation with the Eq. 2, the heat, about 107 W, is flowed into the cryostat from the service flange ($x=0$) to the nitrogen temperature ring

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($x = 150$ mm). The most portion of this heat flux is spent for heating the cold helium gas, so about 21 W is transferred to the nitrogen temperature ring. The only 2.1 W of heat from the service flange flows to the LHe vessel. The rest, 18.9 W goes away to the nitrogen thermal screen and evaporates LN_2 at the rate of 0.43 *l/hour*. Due to the heat transfer between cold helium gas and the cryostat wall, the final thermal load to LHe is 0.167 W, equivalent to the LHe evaporation rate of 0.27 *l/hour*.

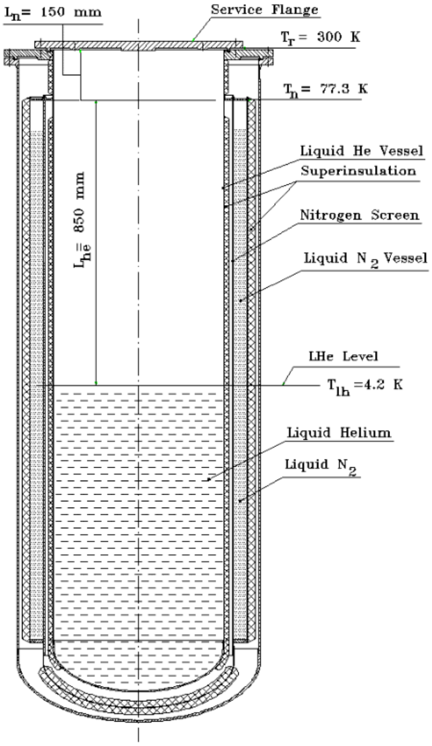

Figure 1: Conceptual layout of cryostat

2.3 Heat Conduction in the Residual Gas

At low pressure, the thermal conductivity of residual gas is proportional to the residual pressure. Therefore, to reduce the heat inleak the vacuum insulation of cryogenic vessel must be worked with residual pressure as low as 1mPa. The transferred heat from the thermal shields to the LHe vessel through the 60 layers of superinsulation, is about 0.3 W, equivalent to 0.41 *l/hour*. The estimation of heat from the room temperature wall to the nitrogen thermal screen through 30 layers of superinsulation space at pressure of 1 mPa is 10 W, equivalent to 0.23 *l/hour* of LN_2 consumption rate.

2.4 Thermal Load due to Radiation of Walls

The radiation of vessel walls is one of the dominant thermal load if the convective heat transfer is negligible by the vacuum insulation. In case of two surfaces, with temperature T_1 and T_2 respectively and with *N* layers of insulation, facing each other, the radiative heat transfer is given by

$$\dot{Q}_{rad} = \varepsilon_{eff}\sigma_0 A\left(T_2^4 - T_1^4\right) \qquad (3)$$

where, the effective emissivity is

$$1/\varepsilon_{eff} = 1/\varepsilon_1 + 1/\varepsilon_2 + 2N\left(1/\varepsilon_{in} - 1\right) \qquad (4)$$

and ε_{in} is the emissivity of insulation. With 10 layers of superinsulation of emissivity 0.07, about 0.04W of heat is transferred to LHe, equivalent to 0.05 *l/hour* of LHe consumption. Between the thermal shields and housing with 30 layers of superinsulation the radiative heat is about 2.9 W, equivalent to 0.07 *l/hour* of LN_2 consumption.

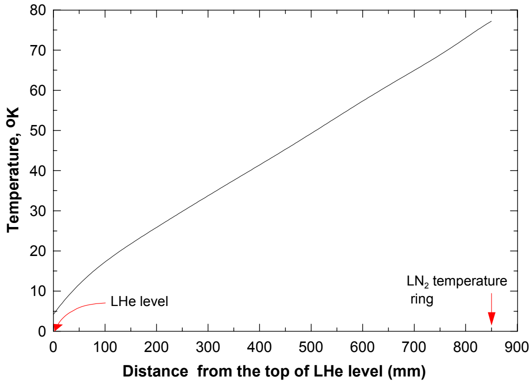

Figure 2: Distribution of temperature between LHe level and LN_2 temperature ring

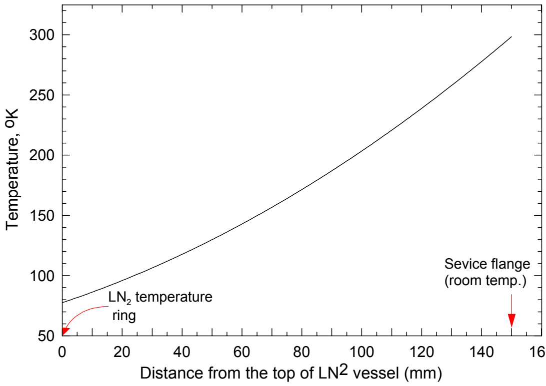

Figure 3: Distribution of temperature between LN_2 temperature ring and service flange

2.5 Thermal Load from the Current Leads

The current leads can be optimized for different SC coils respectively. The current optimization means to optimize the geometric dimensions of current leads to minimize LHe consumption. The three processes should be taken into account during current lead optimization:

- Thermal conduction through the current leads
- Joule heat by current
- Heat exchanges between cold helium gas and current leads

With the heat balance equation with above term, the relation between the current and geometric size is given, by using the optimized equation [1], as follow

$$\frac{w_0}{I} = \frac{\sqrt{L_0 - \alpha^2 T_{room}}}{e^{\alpha Z_{20}} \sin\sqrt{L_0 - \alpha^2 Z_{20}}} \tag{5}$$

$$\frac{I \cdot L}{A} = \int_0^{Z_{20}} k_{Cu}\left[T(z)\right]dz \tag{6}$$

where w_0 is heat to LHe, I the magnitude of current, L the length of current leads, A the cross sectional area, and Z_{20} for the optimized parameter, i.e, solution of

$$\cos(\sqrt{L_0 - \alpha^2} \cdot Z_{20}) = -\alpha\big/\sqrt{L_0} \tag{7}$$

L_0 :Lorentz number (2.45×10^{-8} WΩK^{-2})

α : $\eta\dot{m}C_p\big/2I$

The integration of Eq. (6) with the thermal conductivity of electric copper rod gives $IL/A=1.7\times10^7$ A/m. The optimized cross sectional area of current for the test SC solenoids is about 7.5 *mm*^{2}. The optimum heat leak per unit current, w_0/I , is found to be 2.4×10^{-3} W/A at efficiency, $\eta = 0.8$. This means the thermal load from the current leads is 0.418 W, equivalent 0.59 *l/hour* of LHe consumption.

The LHe consumption rates in each mode are summarized in Table 2.

Table 2: Liquid Helium Consumption Rate of Cryostat

Mode	LHe (l/hour)	LN_2 (l/hour)
- Wall conduction	0.27	0.43
- Insulation conduction	0.41	0.23
- Radiation	0.05	0.07
- Current leads	0.59	-
Total	1.32	0.73

3 SPECIFICATION OF SC SOLENOID COIL

The superconducting solenoid coil is only for the test of cryostat described in a previous chapter. The magnet, which consists of two SC solenoid coils [2], generates 4.1T at the center of magnet. The main specification of SC solenoid magnet is given in Table 3.

Table 3: Specification of SC Solenoid Magnet

Parameters	Values
Design B field at magnet center	4.0 T
Maximum B field (inside coil)	5.15 T
Dimension of SC coil - dimension - No of coil - no of turn/coil - supply current	 200×260×240(H) mm 2 3,465 174 A
Superconduting wire - material - diameter of wire - critical current at 5T	 NbTi (SC/Cu:0.44) 0.87 (1.02) mm 626 A
Energy	99kJ
Inductance	6.54H

4 DESIGN OF CRYOSTAT

There are three separated assembling units of the whole cryostat design as shown Fig. 4:

- External room temperature housing
- Liquid helium vessel connected with liquid nitrogen vessel and nitrogen screen
- Upper service flange of the cryostat

The housing is a stainless steel (304L) cylinder with the thickness of 4 mm. The forged bottom of a spherical form and an upper ring are welded to the cylinder. The nitrogen vessel as the heat sink of thermal shield is attached to the helium vessel with a stainless steel ring. The attaching position is chosen to optimize the distributions of temperature and heat flux in the cryostat. The nitrogen vessel consists of an inner cooper cylinder, an outer stainless steel cylinder and two stainless steel rings. The spherical thermal screen of cooper is attached to the nitrogen vessel at the bottom.

The outer surfaces of the helium and nitrogen vessels are covered with superinsulation, to reduce the radiative heat flux. At the bottom of the helium vessel there is a special container filled with absorbent (activated carbon) to extract the water out from insulating vacuum.

The safety margins, with respect to the allowable pressure, of the housing, LN_2 and LHe vessel are 38%, 20%, and 48% respectively. The working pressure of LHe vessel is 1atm, while the design pressure is 2atm because of negative pressure (vacuum) in outer space.

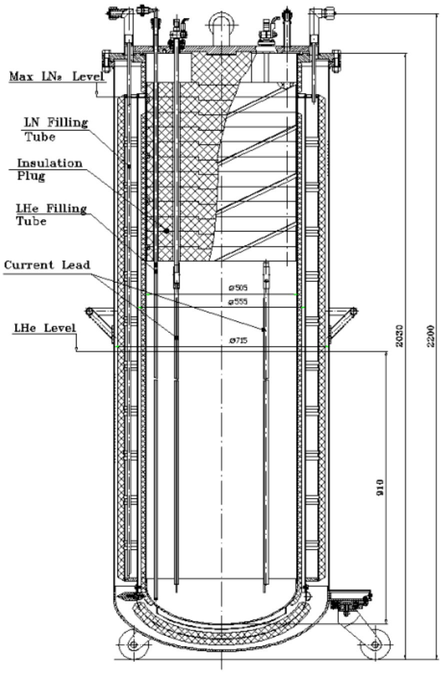

Figure 4: Assembly of cryostat

5 REFERENCES

[1] Martin N. Wilson, Superconducting Magnets, Oxford Science Publications, 1983, pp. 257-272

[2] Yukikazu Iwasa, Case Studies in Superconducting Magnets, Plenum Press, 1994, pp. 111-162