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# Study on the heat transfer in the closed-loop of liquid helium

**Y.S. Choi** *, **D.L. Kim, H.S. Yang, B.S. Lee**

Korea Basic Science Institute, Daejeon 305-333, Korea

***Abstract*-- The thermal characteristics of the helium circulation by a cryocooler are presented. This study is motivated mainly by our recent development of a closed-loop cooling system for Cyclotron K120 superconducting magnets without any replenishment of the cryogen. A channel is attached on the outer surface of the magnet form and the liquid helium passes through inside of the channel in order to cool the superconducting coils indirectly. A two-stage cryocooler as a heat sink is located at the top to recondense helium coming from the superconducting magnet form. The heat transfer in the natural circulation loop is discussed and the main dimensions of cooling system are determined.**

## 1. INTRODUCTION

The Korea Institute of Radiological and Medical Sciences (KIRAMS) has initiated the development program of a Cyclotron K120 as one of the next cyclotrons for medical application. As a research partner, the Korea Basic Science Institute (KBSI) has been involving this program to develop a 3.5 Tesla superconducting magnet system. The main superconducting magnet should be designed to accelerate three kinds of carbon ions; $C^{+2}$, $C^{+4}$ and $C^{+6}$. Several ancillary requirements such as background field, space limitations due to ion beam-line and cryogenic cooling system need technical attention. As a first step, a general design concept of cooling system for the main superconducting magnet is introduced in this paper. The natural circulation of liquid helium as a key technology for cryogenic cooling system is discussed and the dimensions of natural circulation loop are also determined from the empirical correlations.

## 2. CRYOGENIC SYSTEM FOR CYCLOTRON K120

The superconducting magnet system for the Cyclotron K120 is mainly composed of two cryostats; a magnet cryostat and a supply cryostat (see Figure 1). In a magnet cryostat, two sets of superconducting coils are located in the middle of cryostat, and suspended by eight gravitational and four lateral supports. A round tube or cooling channel is attached on the outer surface of superconducting magnet form and the liquid helium passes through the cooling channel in order to cool the superconducting coils indirectly. The two-stage cryocoolers are located at the top

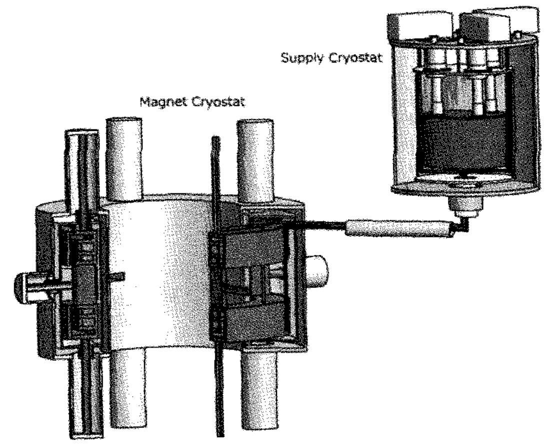


Fig. 1. Superconducting magnet system for Cyclotron K120.

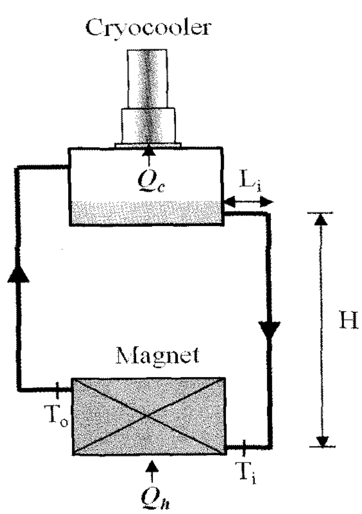


Fig. 2. Schematic of natural circulation flow.

of the supply cryostat to recondense helium from the superconducting magnet form. The helium is condensed and flows back to the superconducting coils through the liquid tube. The cryogenic cooling system, therefore, is a closed-loop system and schematically represented as Figure 2. The circulating helium removes heat from a

* Corresponding author: ychoi@kbsi.re.kr

superconducting magnet and transports it to the cold head or heat sink, resulting from the buoyancy force caused by the thermally induced density difference in a body force field [1-3].

## 3. HEAT TRANSFER IN THE NATURAL CIRCULATION LOOP

A number of experimental and theoretical studies have been performed on the natural circulation, suggesting useful correlations in a standard form [2], [3].

$$\mathrm{Re} = \frac{4\dot{m}}{\pi \mu D} = fn(Gr_m, \frac{D}{L}) \quad (1)$$

where Re is the Reynolds number composed of the mass flow rate, the viscosity of fluid and the inner diameter of loop. The modified Grashof number, Grm, is defined as

$$Gr_m = \frac{D^3 \rho_0^2 \beta g \Delta T_r}{\mu^2}\ ;\ \Delta T_r = \frac{Q_h H}{A \mu C_p} \quad (2)$$

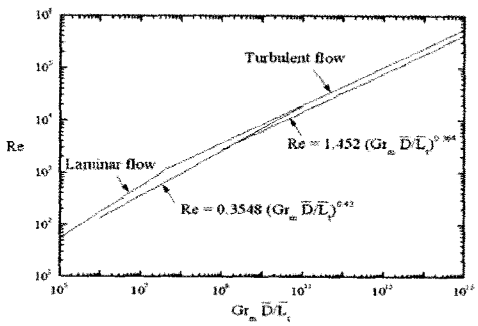


Fig. 3. Empirical correlations of natural circulation flow.

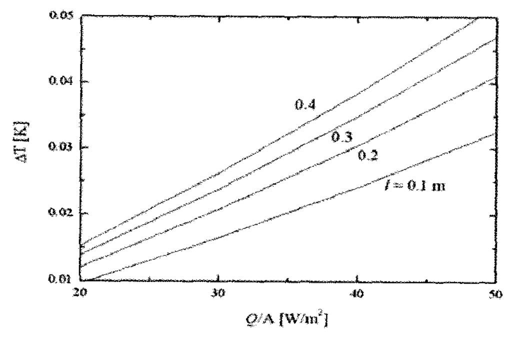


Fig. 4. Condensation temperature drop vs. heat transfer.

In Eq. (1), D/L is the shape (diameter-to-length) ratio of the loop. Figure 3 is the existing plot of the Reynolds number as a function of the modified Grashof number with various flow types and shapes [3]. The Reynolds number increases with the Grashof number, because the Grashof number is proportional to the ratio of the buoyancy force to the viscous force and the intensified buoyancy force results in high mass flow. In Eq. (1) and (2), the parameters could be categorized into two large classes: properties of fluid and natural circulation loop dimensions. The properties of fluid including viscosity(μ), density(ρ), thermal expansion coefficient (β) and heat capacity ($C_p$) are obtained from the commercial code, HEPAK [4].

In the recondensing unit, the cooling power of cryocooler per unit area across the condenser can be expressed as a function of the condensation temperature drop and properties of fluid [5].

$$\left(\frac{Q_c}{A}\right) = (\Delta T_c)^{0.75} \left(\frac{\mu l}{\rho^2 g h_{fg} k^3}\right)^{-0.25} \quad (3)$$

Figure 4 shows the condensation temperature drop with respect to the cooling power with various extended surface of condensing plate. The condensation temperature drop increases with the cooling power for a given extended surface. Also the condensation temperature drop increases with the extended surface for a given cooling power. Extending the condenser surface is one of the way to increase heat transfer, however, the fin efficiency of the extended surface decreases because the extended surface itself represents a conduction resistance to heat transfer from the original surface [6].

## 4. SUMMARY

The concept of cooling system for the superconducting Cyclotron K120 has been presented. The thermal characteristics of the natural circulation loop for cooling superconducting magnet was investigated with emphasis on the cooling design point. Based upon the existing empirical correlations, the main dimensions of natural circulation loop were determined and summarized in Table 1. A prototype to confirm the feasibility of our design will be made in the near future. Any necessary modifications will be incorporated into the final cooling system design, which will be tested before installation into the superconducting Cyclotron K120.

TABLE I
CRYOGENIC COOLING LOAD AND MAIN DESIGN PARAMETERS OF NATURAL CIRCULATION LOOP.

| | | 1st stage (60K) | 4.2 K |
|---|---|---|---|
| Cooling load | Support conduction | 11.4 | 0.58 |
| | Thermal radiation | 22.9 | 0.03 |
| | Current lead | 52 | 0.4 |
| | Instrumentation & Pipe | 17.7 | 0.94 |
| | Joint & Joule heating | 6.0 | 0.95 |
| | TOTAL | 110.0 W | 2.9 W |
| Natural circulation loop | Mass flow rate | 5.94 g/s | |
| | Temp. difference ($T_o$–$T_i$) | 0.1 K | |
| | Inner diameter (D) | 10 mm | |
| | Length (L) | 2500 mm | |
| | Height (H) | 1000 | |

## ACKNOWLEDGMENT

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