Helium Transfer Line with Conduction-Cooled Nb-Ti Superconducting Wires for COMET Muon Transport Solenoid

Takahiro Okamura\textsuperscript{1}, Makoto Yoshida\textsuperscript{1}, Masaya Oonaka\textsuperscript{1}, Hirokatsu Ohhata\textsuperscript{1}, Taekyung Ki\textsuperscript{2}, Yasuhiro Makida\textsuperscript{1}, Ken-ichi Sasaki\textsuperscript{1}, Masahisa Iida\textsuperscript{1}, Akiko Tateno\textsuperscript{3}, Masahiro Matsuo\textsuperscript{3} and Itsuo Aoki\textsuperscript{3}

\textsuperscript{1} Institute of Particle and Nuclear Studies KEK, High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan
\textsuperscript{2} Institute for Basic Science, IBS, 55, Expo-ro, Yuseong-gu, Daejeon, Korea
\textsuperscript{3} JECC Torisha Co., Ltd. 8-52, Yoshinodai 2, Kawagoe, Saitama 350-0833, Japan

E-mail: takahiro.okamura@kek.jp

Abstract. Cryogenic system of the superconducting magnet for COMET (COherent Muon to Electron Transition) experiments has been constructed in the J-PARC since FY2013. The cryogenic system can be roughly divided into superconducting magnet, refrigerator system and inter-connect system. The refrigeration system is composed of cold box and warm screw compressor system which are located on the surface. On the contrary, magnet system will be installed in the underground. Therefore the inter-connect system is mainly composed of current lead box and transfer line, which are regarded as a system for connecting between ground facility and the underground superconducting system. Since the superconducting magnet is cooled by two-phase flow helium at around 4.5 K, the transfer line has an adiabatic structure with shield line of around 50 K. In addition, conduction cooled superconducting cables are laid in parallel with the two-phase flow cooling line. In this study, simulation on the pressure drop of gas-liquid two-phase flow of helium is introduced to determine the cooling pipe diameters in the transfer line. Then the detail structures of the transfer line and cooling scheme of the superconducting cables optimized by several experiments will be presented.

1. Introduction
Cryogenic system of the superconducting magnet for COMET (COherent Muon to Electron Transition) experiments has been constructed in the J-PARC since FY2013. There are three kinds of superconducting magnets such as capture solenoid, transport solenoid and detector solenoid. Former two superconducting magnets are cooled down by two-phase flow helium which is produced and supplied from helium refrigeration system manufactured by Linde (Sulzer). Cooling capacity of the helium refrigerator is 140 W at 4.5 K in case of 500 W shield heat load. On the contrary, the detector solenoid will be cooled down by GM refrigerator. It is necessary to prepare two transfer lines to cool down capture solenoid and transport solenoid at 4.5 K. Both transfer lines have adiabatic vacuum layer with four inner pipes for the shield gas and two-phase flow of helium. In addition, superconducting cables are also laid in parallel with the two-phase flow lines. The nominal current of the superconducting cable for the capture and transport solenoid is 3 kA and 210+175 A, respectively. These superconducting cables were
mainly cooled down by thermal conduction from the two-phase flow helium line. The transfer line of the transport solenoid with the superconducting cables for 210+175 A was fabricated in the FY2018. Before fabrication process, we studied the cooling structure for cooling down the superconducting cable by thermal conduction. In this paper, overall cryogenic system for the COMET phase-I in addition to thermo-fluid dynamics evaluation such as pressure drop of gas-liquid two-phase flow of helium are firstly introduced. Then, cool down test results of the superconducting cable and how to cool down them simultaneously and homogeneously is also introduced. In addition, the detail structure of the transfer line is also introduced.

2. Cryogenic system overall

Figure 1 shows overhead view (left) and side view (right) of the cryogenic system for COMET phase I. The system is composed of mainly three sub-group systems which are refrigeration system, superconducting magnet system and inter-connect system, respectively. The refrigerator system consists of a warm screw compressor, a cold box, a high pressure line, a low pressure line, and a cooling water system. Although this figure does not show the warm compressor system and cooling tower, they are installed in another building. Superconducting system is mainly composed of capture solenoid, transport solenoid and detector solenoid, respectively. The former two superconducting magnets are cooled down by two-phase flow of helium with 4.5 K using a cold box. The latter solenoid is cooled down by G-M refrigerators which are completely independent of the former cooling system. In this paper, we focus on the cooling system for the capture solenoid as well as the transport solenoid, except the cooling system of the detector solenoid. Inter-connect system has current lead box (CLB), two transfer lines with adiabatic structure so called TRT-1, TRT-2 and diodebox, respectively. The distance between refrigeration system and superconducting magnet system is approximately 10 m to 15 m. TRT-1 and TRT-2 in figure 1 respectively have the role in supplying not only two-phase flow of helium but also helium gas with around 50 K for shield cooling. In addition, concerning the TRT-1, twelve superconducting cables are cooled down by conduction cooling from 4.5 K pipe because the excitation power supply and the current leads for the superconducting magnet are located on the ground to avoid radiation damage. CLB-1 and CLB-2 indicate current lead box for capture and transport solenoid, respectively. Table 1 shows the brief specification on the cryogenic system for phase I. Figure 2 shows the schematic cooling flow. Cooling line for the transport and capture solenoid are connected in series each other. Total evaluated heat load is around 75 W which is smaller than cooling capacity of cold box (TCF-50) shown in table 1. The required mass flow rate to cool down capture and transport magnet system is 7 g/sec to 10 g/sec
Table 1. Brief specification of the cryogenic system for COMET phase I.

| item                                           | specifications                                                                 |
|------------------------------------------------|-------------------------------------------------------------------------------|
| cold box                                       | TCF-50 @ Linde (Sulzer)                                                       |
| cooling capacity (4K)                          | 90 W @ spec., (~ 130 W @ measured)                                           |
| cooling capacity (shield)                      | 490 W @ spec., (> 500 W @ measured)                                          |
| mass flow rate for magnet cooling (4K)         | 7 ~ 10 g/sec                                                                 |
| warm screw compressor                          | MYCOM 1100 Nm³/hour (HE-250SGM, 210 kW)                                       |
| cooling water for compressor                   | 560 L/min                                                                     |
| Helium inventory                               | 120 L                                                                         |
| buffer tank (storage tank for GHe)             | 20 m³                                                                         |
| Additional refrigerator                        | GM refrigerator for CLB cooling                                               |
|                                                | Solvey refrigerator for Detector solenoid                                     |

which is calculated by considering quality distribution based on two-phase flow dynamics and heat load distribution listed in table 2.

In the last fiscal year, TRT-1 for the transport solenoid between CLB-2 and diode box were fabricated in JECC Torisha co. ltd. after solving the optimal conduction cooling structure for the 12 superconducting cables simultaneously and homogeneously using test bench in KEK.

3. Transfer line for transport solenoid

3.1. Pressure drop simulation

The cooling pipe reciprocates between underground and ground at least two times as shown in figure 2 and it is laid up and down in the vertical direction in the capture solenoid. In such a case, thermo-fluid behavior such as pressure drop and various two-phase flow instabilities should be considered carefully, however it is nontrivial to predict them accurately because there are a lot of flow patterns which depend on lots of function such as flow condition and direction of

![Figure 2](image-url)
Table 2. Cooling pipe length and heat load into 4 K stage of the cryogenic system for COMET phase I.

| Region                  | channel length | Heat Load | remarks                          |
|-------------------------|----------------|-----------|----------------------------------|
| CB-CLB1(supply) (1-2)   | 6 m            | 1.5 W     | CB-CLB1 TRT1 W/m @ w/o shield    |
| CLB1-Cryostat1b (TRT 2-3) | 16 m          | 4 W       | 0.25 W/m (TRT supply line)       |
| Cryostat 1b (3-4)       | 17+3+3=23 m   | 9 W       |                                  |
| Cryostat1b-CLB1 (TRT 4-5) | 16 m          | 4 W       | 0.25 W/m (TRT return line)      |
| CLB1                    | 3 m            | 14 W      | 2 W/bayonet × 2 additional load 10 W |
| CLB1-Cryostat1a (TRT 5-6) | 11 m          | 2.75 W    | 0.25 W/m (TRT supply line)       |
| Cryostat 1a (6-7)       | 40 m           | 35 W      |                                  |
| Cryostat1a-CLB1 (TRT 7-8) | 11 m          | 2.75 W    | 0.25 W/m (TRT return line)      |
| CB-CLB1(return) (8-9)   | 6 m            | 1.5 W     | CB-CLB1 TRT1 W/m @ w/o shield    |
| Summation               | 132 m          | 74.5 W    |                                  |

Flow Direction

\[ x(s) \text{ (W/m}^2) \]

\[ x(\xi) = x_1 + \left(G_m h_l\right)^{-1} \int_0^\xi q(s) ds \]

Flow Direction

\[ s = 0 \quad s = \xi \]

Figure 3. Schematic model to calculate local quiality, \( \chi(\xi) \) at the position, \( s = \xi \).

the cooling pipe. In order to avoid design uncertainty that results from such complexity, it is important to determine the two-phase mass flow rate so that the outlet quality is less than 0.5. In general, total pressure drop of the two-phase flow, \( \Delta p_{tot} \), is composed of friction loss, \( \Delta p_f \), acceleration loss, \( \Delta p_a \), and pressure loss due to the gravitational force, \( \Delta p_g \).

\[ \Delta p_{tot} = \Delta p_f + \Delta p_a + \Delta p_g \]

(1)

There are two different scheme to predict \( \Delta p_{tot} \) described as follows.

- Method-I: Each terms, \( \Delta p_a, \Delta p_f, \Delta p_g \) are directly calculated from two-phase flow model.
- Method-II: After obtaining the pressure loss, \( \Delta p_{lb} \), corresponding to the case where only the liquid phase flows through the pipe, how much the pressure loss of the two-phase flow
increases with respect to $\Delta p_{lo}$ is expressed by the function $f(\chi)$ using quality, $\chi$.

$$\Delta P_{tot} = f(\chi) \Delta P_{lo}$$ (2)

There are several experimental results on two-phase flow pressure drop of helium. They evaluated pressure drop based on method-II. Therefore in this paper, the pressure drop calculation based on Method-II is introduced below. There are mainly two different model so called "homogeneous model" and "Lockhart-Martinelli-Nelson (LMN) model", respectively. In the case of homogeneous model, $f(\chi)$ is described as follows [1].

$$f(\chi) = (\chi_2 - \chi_1)^{-1} \int_{\chi_1}^{\chi_2} \phi_l^2(\chi) d\chi$$ (3)

$$\phi_l^2 = \left[ 1 + \chi \left( \frac{\rho_g}{\rho_l} - 1 \right) \right] \left[ 1 + \chi \left( \frac{\mu_l}{\mu_g} - 1 \right) \right]^{-0.2}$$ (4)

where $\chi_1 < \chi_2$ indicate local quality at the position of $x_1$ and $x_2$, $(x_1 < x_2, \chi_1 < \chi_2)$. $\rho_g, \rho_l$ and $\mu_g$ and $\mu_l$ is density and viscosity of gas and liquid phase, respectively. In the case of LMN model, $f(\chi)$ is described as follows.

$$f(\chi) = (\chi_2 - \chi_1)^{-1} \int_{\chi_1}^{\chi_2} (1 - \chi)^{1.8} \phi_l^2(\chi) d\chi$$ (5)

$$\phi_l^2 = 1 + \frac{20}{X} + \frac{1}{X^2}$$ (6)

$$X = \left( \frac{\mu_l}{\mu_g} \right)^{0.1} \left( \frac{\rho_g}{\rho_l} \right)^{1/2} \left( \frac{1 - \chi}{\chi} \right)^{0.9}$$ (7)

where $X$ is Lockhart-Martinelli parameter. Mass and energy conservation equation for two-phase flow are described as follows.

$$-\left( \rho_l - \rho_g \right) \frac{\partial \alpha}{\partial t} + \frac{\partial G}{\partial s} = 0$$ (8)

$$\frac{\partial}{\partial t} \left[ \alpha \rho_l h_g + (1 - \alpha) \rho_l h_l \right] + \frac{\partial}{\partial s} \left[ G \{ x h_g + (1 - x) h_l \} \right] = q$$ (9)

where $s$ is a coordinate system taken in the pipe axis direction. In the case of steady state, first term in the equation (8) and (9) is equal to zero. Figure 3 shows the local quality, $\chi(\xi)$ at position $s = \xi \in (0, L)$. It can be calculated from heat load distribution, $q$ (W/m$^3$), mass flux, $G$ (kg/m$^2$/sec), and latent heat of helium, $h_{lg}$.

$$G(\xi) = G_1 = const$$ (10)

$$x(\xi) = x_1 + (G_{in} h_{lg})^{-1} \int_0^\xi q(\xi) d\xi, \ \xi \in (0, L)$$ (11)

Flow conditions and heat load conditions required for simulation are summarized in a table 3. According to the several experimental results, pressure drop of two-phase flow of helium can be regarded as homogeneous flow and these results tend to be in good agreement with the homogeneous model (3) and (4) [1]. On the contrary, LMN model tends to gives us the large pressure drop than realistic in the case of two-phase flow helium. In other words, evaluating the pressure drop using the LMN model means designing the cooling pipe with a safety factor. Pipe inner diameter for the two-phase flow cooling line was determined to be 23.9 mm from the simulation introduced above. In addition, this is because the cooling system will be upgraded in the next phase (phase II), and it is desirable that the cooling piping should be applicable in this upgrade without any modification. In such conditions listed in table 3, outlet quality becomes 0.41 which is less than allowable outlet quality of 0.5.
Table 3. Summary on flow conditions of two-phase flow for COMET phase I.

| parameter                      | value                      |
|--------------------------------|----------------------------|
| mass flow rate, $m$            | 10 g/sec                   |
| total heat load, $Q_{tot}$     | 74.5 W                     |
| total cooling pipe length, $L_{tot}$ | 132 m                     |
| outlet quality, $x_{out}$      | 0.409                      |
| calculated from (11)           |                            |
| inlet pressure, $P_{in}$       | 1.3 bar                    |
| wall friction coefficient, $\lambda$ | 0.03 (in case of homogeneous model) |
|                                | $0.0054 + \frac{0.3964}{Re^{0.5}}$ (in case of LMN model) |

3.2. Structures

3.2.1. Cross section and brief structures Figure 4 shows typical cross section of transfer line for transport solenoid in addition to the conduction cooled superconducting cables which are in parallel with 4 K cooling line. Figure 5 shows the clamp structure for the superconducting cable, bending structures of the 4 K line and superconducting cables, flexible tube and its cover and cross section of the transfer line.

3.2.2. Pipe size Design pressure of each inner pipe is 2.0 MPa-abs. This pressure is determined from the flow behavior of helium such as pressure shock during magnet quench. Pipe outer diameter and thickness for the two-phase flow of helium is 27.2 mm and 1.65 mm, respectively.

Figure 4. Cross section of the transfer line for transport solenoid and conduction cooled superconducting cables and clamp structures for them.
This diameter is determined from thermo-fluid analysis introduced in subsection 3.1. Pipe outer diameter and thickness for the shield line is determined to be 34 mm and 1.65 mm, respectively by the calculation of the pressure drop for the gas single-phase flow. Outer diameter and thickness of the vacuum jacket is 267.4 mm and 3.4 mm, respectively.

3.2.3. Thermal design  

NbTi superconducting cables are laid in parallel to the 4 K cooling pipe as shown in figure 4. Thermal contraction of cooling pipe which is made from stainless steel is almost same as that of the superconducting cables. Therefore, no special compensation structures for the thermal contraction difference between cooling pipe and superconducting cable is incorporated into the transfer line. The diameter of the superconducting cable with insulation is 1.56 mm and it has flexibility. As a result, a slight difference in thermal contraction can be absorbed automatically in crank structures such as bending point. Also thermal conduction of the 4 K cooling lines can be compensated automatically in crank structures such as the bending point, too. Therefore no flexible tubes are employed in the 4 K cooling line. However we employ flexible tubes in shield cooling lines. Then flexible cover for their flexible tubes are adopted as shown in figure 4 so that the direction of deformation could be controlled in unique direction without the flexible tube contacting the jacket with 300 K. Polyimide MLI is wound around the 4 K stage and the shield with 20 and 40 layers, respectively.

3.3. Cooling structure of conduction cooled superconducting cables

Figure 6 schematically shows the cooling method of the 12 superconducting cables. It is not easy to fix the contact surface sufficiently because the diameter of the superconducting wire is as small as 1.56 mm with insulation and the surface is cylindrical. Therefore, in order to reduce the contact thermal resistance between the superconducting wire and the aluminum clamp, an indium sheet with the thickness of 0.1 mm is sandwiched between them. In addition, the distance between adjacent clamps was determined to be 13 cm by several experiments. On the contrary we also pay special attention to keep electrical insulation between them. The procedure
Figure 6. Conduction cooling structures for 12 superconducting cables.

To reduce thermal resistance and increase electrical insulation between superconducting cables and Al clamp is described below.

- **step-1:** Kapton tape is affixed to the groove on the Al clamp (see Figure 6 (A)).
- **step-2:** Pure Al sheet ($t=0.5\text{mm}$) is prepared and Kapton tape is also affixed to it (see Figure 6 (B)). Edge of the Al sheet is folded back so as not to damage the superconducting wire at the edge of the Al sheet.
- **step-3:** A superconducting cable is bundled and wrapped with an indium sheet with the thickness of 0.1 mm.
- **step-4:** Apiezon grease is applied to the grooves and Al sheet.
- **step-5:** 12 Superconducting cables are clamped simultaneously. (see Figure 6 (C)).
- **step-6:** After being tightened with bolts, Apitzon grease is spread homogeneously using heat gun.

4. Summary

Transfer line for the transport solenoid is designed and fabricated in the last fiscal year. In the design phase, cooling pipe diameters were determined from two-phase flow dynamics and several experimental results. The transfer line has 12 superconducting cables which have to be cooled down by the thermal conduction from 4 K two-phase flow line. It is cleared from the experiments that due to the small diameter of 1.56 mm and cylindrical surface shape, it is not easy to cool down all superconducting cables simultaneously and homogeneously. Therefore we employed indium sheet with the thickness of 0.1 mm and pure Al sheet to increase contact heat transfer coefficient. In addition, the distance between adjacent clamps was determined to be 13 cm by several experiments. It was clarified that all superconducting wires are cooled down to 4.6 K by the conduction cooling from 4 K two-phase flow line.

5. References

[1] Haruyama T., et al. 1988 *Advances in Cryogenic Engineering* **33** 543