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Experiment of Low Heat Loss Liquid Helium Transfer line for NSRRC Cryogenic System

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Abstract. X-ray photon sources are used in research. During the past decade, the technology of the X-ray photon source has grown rapidly. To fulfil demands for an X-ray photon source in Taiwan, the Taiwan Photon Source (TPS), an electron accelerator with the energy of 3 GeV has been constructed with high brilliance and flux. To let the Superconducting radio frequency (SRF) system and cryogenic undulators in TPS to be under stable operation, the cryogenic system is therefore very important. Refrigerant of the TPS cryogenic system is liquid helium , to maintain LHe in its state, temperature has to be maintained below 4.5 K; however to evaporate 1 gram of liquid helium, only 20 Joule is needed. Therefore, the Multi-Channel Line (MCL) has been developed to prevent liquid helium vaporizing. Several mechanical parts have been designed to reduce heat loss and strengthen structure stability. In this paper, assembly of the transfer line and experimental results are discussed.

1. Introduction

During the past decade, the technology of X-ray photon source is getting more and more advanced, more and more countries are now striving to build the biggest synchrotron facility to meet their needs. In Taiwan, the Taiwan Photon Source (TPS) project proposes an electron accelerator with a beam current of 500 mA at 3 GeV and a low emittance of 1.6 nm·rad. The circumference of storage ring and booster ring is 518.4 m and 496.8 m, respectively. In the TPS project, the installation of two 500 MHz single-cell superconducting cavities and multiple insertion magnets is planned.

The refrigerant of the TPS Cryogenic System is liquid helium, for liquid helium to maintain its state, the temperature of liquid helium has to be maintained below 4.5 K; however, 20 Joules is enough for 1 gram of liquid helium to change phase. Therefore, the Multi-Channel Transfer Line is developed in our system to prevent ambient temperature affecting the inner pipelines due to heat transfer. The total length of liquid helium transfer lines is 178 m. One switch-valve box and four control-valve boxes are required to distribute the liquid helium from the Dewar to up to four SRF cavities [1] [2]. The estimated heat load of 130 m helium transfer lines is 43 W, and that of the valve boxes is 63 W. The total heat load of eight

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12 m branched transfer-lines that connects to the SRF cavities to the Multi-Channel Transfer Line is 96 W. The cryogenic system must thus supply a refrigeration power of 562 W and support a liquefaction rate of 21 L/h. The equivalent refrigeration capability is 642 W during the operation of the two superconducting cavities. To increase the efficiency of helium used in National Synchrotron Radiation Research Center (NSRRC), the new Multi-Channel Transfer Line that has minor heat loss has been developed to meet its need. The Multi-Channel Transfer Line has thermal shielding at 77 K by using liquid nitrogen. The vacuum pipe of the Multi-Channel Transfer Line has a diameter of 273.05 mm. Inside the vacuum pipe are a line for liquid helium of diameter 26.67 mm, a line for liquid nitrogen of diameter 21.34 mm, and a return line for helium gas of diameter 42.16 mm as shown in Figure 1.

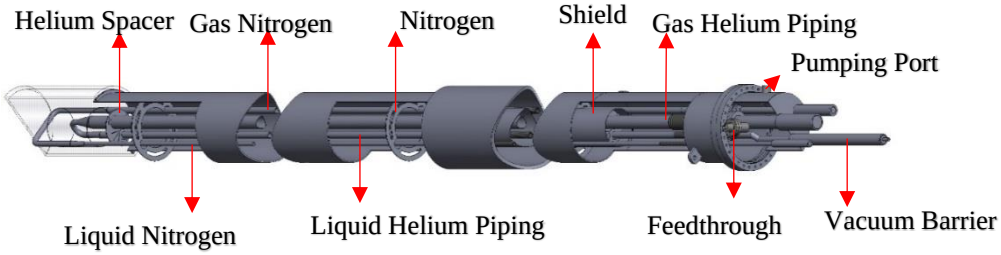

Figure 1. Multi-Channel Transfer Lines installed for TPS.

2. Heat load experiment of Multi-Channel Transfer Line

2.1 Experiment Setup

During the experiment, the Multi-Channel Transfer Line is connected to the Distribution Valve Box of the NSRRC cryogenic system, a 1000 L test dewar and an evaporator with three vacuum pipes, as shown in figure 2; Determining correct heat load for all the other parts is difficult, Therefore, measuring entire heat load of the system and subtracting the heat load of parts connected to the Multi-Channel Transfer Line is not considered. The experiment on the Multi-Channel Transfer Line is divided into two sections, a whole section which is 14 m (7 m LHe+7 m GHe) and a half section which is 7 m (3.5 m LHe+3.5 m GHe). To measure the heat loss, the whole section of the Multi-Channel Transfer Line connected with the entire system is measured first and is done with six different openings of the valve which will give six different flow rates, as shown in Figure 3. After measuring the whole section, the half section of the Multi-Channel Transfer Line connected with the entire system is then measured with the same six openings, as shown in Figure 3. By subtracting heat loss of the whole section by half section, 7 m of heat loss can be determined, by dividing the heat loss by the length, heat loss per meter will then be determined.

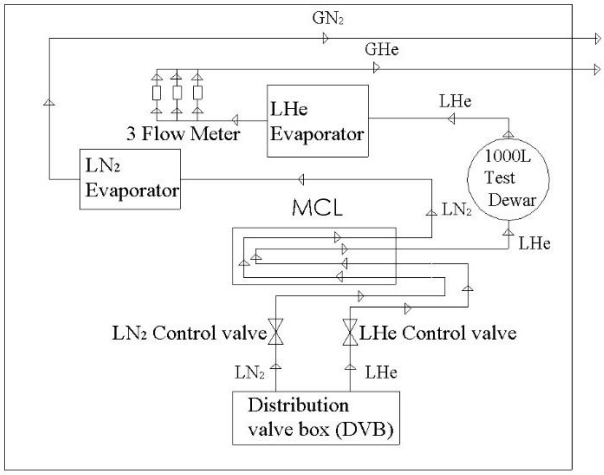

Figure 2. P&ID diagram of Multi-Channel Transfer Line.

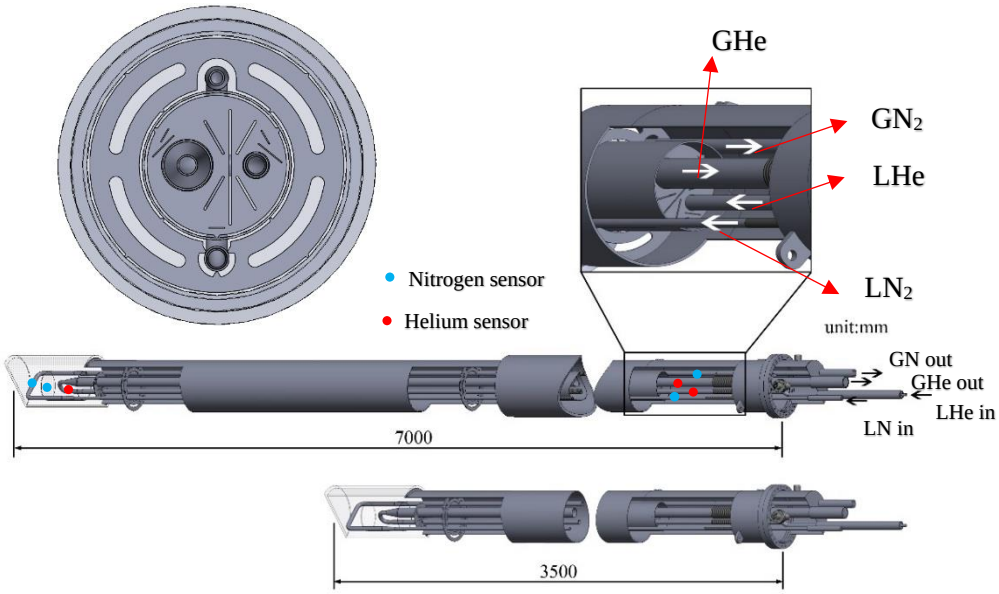

Figure 3. Sectional view, whole section and half section of Multi-Channel Transfer Line (mm).

2.2 Heat Load Measurement

The flow rates of the whole and half section are shown in Figures 4 and 5, respectively. The flow rate is kept under stable condition for more than one hour, three flow meters are used and are parallel connected.

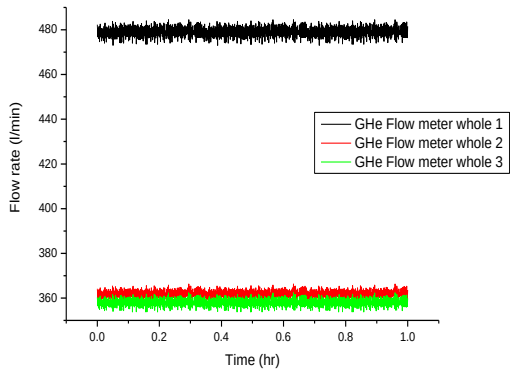

Figure 4. Flow rate of whole section of Multi-Channel Transfer Line.

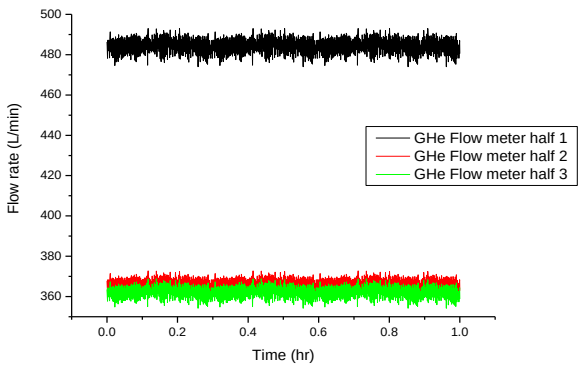

Figure 5. Flow rate of half section of Multi-Channel Transfer Line.

Note that the data measured from the flow meter is measured at the end of the evaporator, thus it is the flow rate of GHe. To calculate the heat loss of the Multi-Channel Transfer Line per unit length is given by

$$Q = \frac{(m_{whole}/He_{exp} \times Q_L) - (m_{half}/He_{exp} \times Q_L)}{L} \quad (1)$$

Where m_{whole} is Flow rate for the whole section of Multi-Channel Transfer Line, l/sec; m_{half} is the Flow rate for half section of Multi-Channel Transfer Line, l/sec; He_{exp} is Expansion ratio for helium which would be 757, L is length of half the Multi-Channel transfer line. Q_L is the amount of energy released or absorbed during the change of phase of the substance which would be 0.71 W for liquid helium and Q is the Heat loss of Multi-Channel Transfer Line per meter.

$$Q_L = mh_{fg} \tag{2}$$

Where m is the mass of the substance and h_{fg} the specific latent heat for a particular substance. Flow velocity of the mass elements are calculated by using mass flow rate formula given by

$$\dot{m} = \rho v A \tag{3}$$

$$\rightarrow v = \frac{\dot{m}}{\rho \times A} \tag{4}$$

The results of six opening are shown in Figure 6 and is compared with the simulation analysis solution, average heat load on the experiment and simulation analysis is 0.045 W/m and 0.035 W/m [3], respectively. The trend of the Multi-Channel Transfer Line for simulation and experiment are a match. The difference between simulation and experiment data's might be caused by the surface finish of some components or by the heat transfer mechanisms. The fluctuation is caused by momentum transfer due to velocity fluctuations and turbulent heat fluxes caused by heat transfer resulting from velocity and temperature fluctuations in turbulent flows.

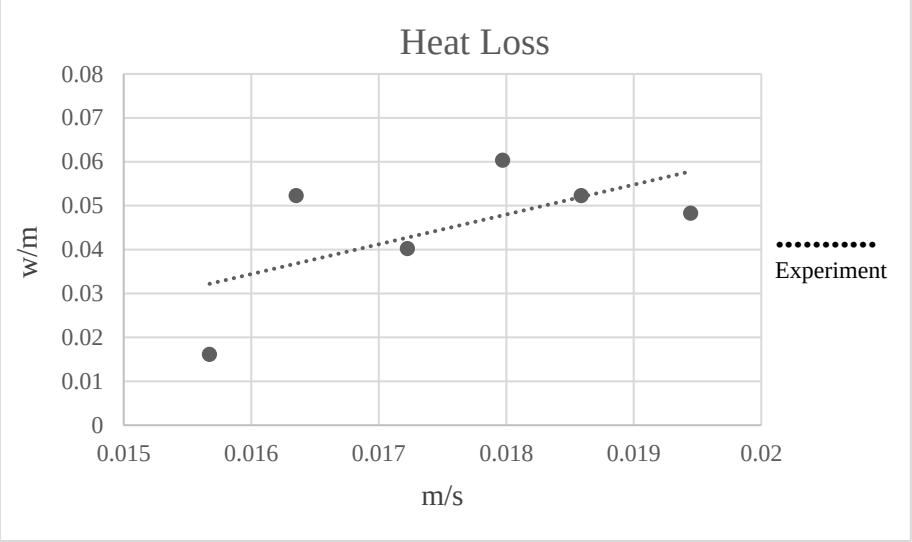

Figure 6 Heat loss per meter of Multi-Channel Transfer Line (experiment).

Figure 7 illustrates the mass flow rate of six different openings, indicating that for every opening of the experiment, there will be a different mass flow rate.

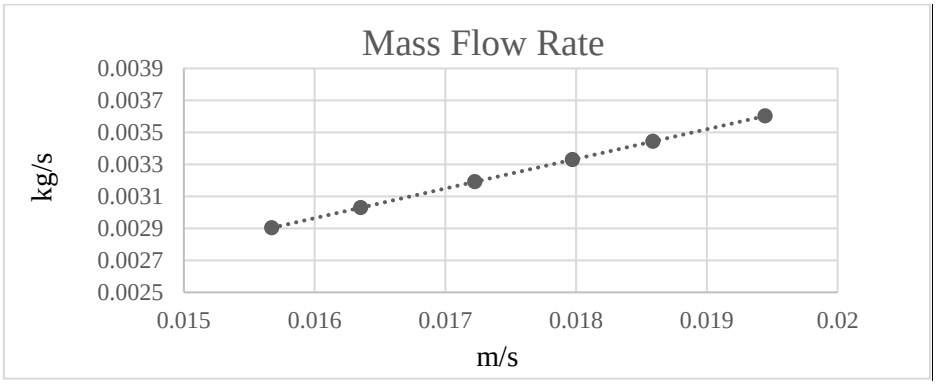

Figure 7 Mass flow rate of MCL with different openings.

In the experiment, liquid helium is continuously heated, due to constant specific heat and temperature, by the definition of mean heat transfer rate given below, heat transfer rate will increase when flow rate increases. This result has the same trend as experiment and simulation.

$$\dot{q} = \dot{m}Cp\Delta T \tag{5}$$

According to energy conservation equation, $E = Q_{heat} + Q_{load} - Q_c + U$ (Internal Energy), Internal Energy will increase when helium pressure increases, since Internal Energy is not considered in this study, the Heat Flux will increase when flow rate increases. The flow inside the helium pipelines is turbulent flow. Minor temperature, velocity, and other properties changes continuously in time at every point of a turbulent flow. These changes are irregular fluctuations, the fluctuation of the data shown in figure 6 may be the cause of momentum transfer due to velocity fluctuations and turbulent heat fluxes caused by heat transfer resulting from velocity and temperature fluctuations [4].

Conclusion

The experiment of the test section of the Multi-Channel Transfer Line leads to the result of 0.045W of average heat loss per meter for helium pipeline. According to energy conservation equation, $E = Q_{heat} + Q_{load} - Q_c + U$ (Internal Energy) in a closed system, Internal Energy will increase when helium pressure increases (According to the property table of the helium), since Internal Energy is not considered in this study, the Heat Flux will increase when flow rate increases. The fluctuation is caused by momentum transfer due to velocity fluctuations and turbulent heat fluxes caused by heat transfer resulting from velocity and temperature fluctuations in turbulent flows.

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Acknowledgments

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