Introduction of the liquid nitrogen transfer line for TPS beamline endstation

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Abstract. At Taiwan Photon Source (TPS), the main liquid-nitrogen (LN$_2$) transfer line of length 600 m for beamline endstations was installed in 2015. It formerly supplied LN$_2$ to maximum 24 beamline endstations. Beamline endstation 13A, of which the aim is advanced and general studies of biological structures and structural kinetics in solution or condensed forms under environmental simulations, from atomic to micrometre scale and time resolution from microsecond to minute, was installed during 2018 and 2019. We designed and self-manufactured one LN$_2$ transfer line according to the requirement of beamline endstation 13A, to supply LN$_2$ into the double-crystal monochromator (DCM), to solve the problem of thermal deformation of the crystal. Otherwise the keep-full device was designed to replace the phase separator of the chiller. In this paper we present the pipeline design, performance testing, keep-full device, pressure reducer, noise reduction and heat-load measurement.

1. Introduction
The installation and commissioning of one LN$_2$-transfer system for the Taiwan Photon Source (TPS) project was completed in 2015 [1]. This system included two transfer lines (length 600 m), eight keep-full devices and 24 cryogenic control valves for 24 straight sections of beamlines. The consumption of LN$_2$ required for each beamline is 20 L/h. We studied the LN$_2$ consumption of the beamline for TPS Project [2]. The LN$_2$ supply from one storage tank (60 m$^3$) was refilled every 2-3 days from a LN$_2$ truck. Another transfer line of length more than 300 m that supplied users of Taiwan Light Source (TLS) was installed in 2003. The configuration of the LN$_2$-transfer system in TLS and TPS is shown in Figure 1. During years 2015 to 2018, four LN$_2$ branch lines were installed for TPS beamline endstations (05A, 09A, 23A, 25A), enabled and used LN$_2$ to cool the beamline equipment for the double-crystal monochromator (DCM). The reason is that highly intense X-rays cause a large thermal load on the DCM at the beamline endstation. To remove this large thermal load and to diminish its thermal effects, a LN$_2$ cooling system used to minimize the thermal deformation of the crystals is a solution better than a water-cooling system. Some unexpected problems appeared on these four LN$_2$ branch lines, such as that the separator filling process is too noisy, frozen ice or water formed due to cold nitrogen gas exhaust, pressure downstream of the pressure-reducing valve that activates the safety valve was excessive, and heat loss caused by the non-vacuum design of the pressure-reducing device was excessive. In 2019, we designed, self-manufactured, installed and commissioned one vacuum-shielded LN$_2$ branch line for the endstation of beamline 13A.
2. Design and development of the LN\textsubscript{2} cooling device for a beamline endstation

2.1. Design goal of the LN\textsubscript{2} cooling device
Based on long-term operation in an early beamline LN\textsubscript{2} branch, some problems should be considered and avoided in this self-manufactured LN\textsubscript{2} branch line, such as a diminished heat load, diminished sound, decreased two-phase flow, improved pressure stabilization and avoidance of the frozen ice and water phenomenon. For these purposes we designed three devices built in the branch line – a pressure-regulator device, a keep-full device and a sound-suppression device with a heater. The goal of the pressure-regulation device is to maintain a set pressure at the outlet of the device, independent of any variation of pressure at the inlet of the device. In our case, the set pressure is about 1.5 barg; the variation of pressure is about 2 to 4.5 barg. The keep-full device was designed to replace the original equipment that was called a LN\textsubscript{2} phase separator mounted before the DCM of the beamline endstation. The goal of the keep-full device is to decrease the two-phase flow inside the branch line. To decrease the heat load, these two devices are manufactured as vacuum-shielded and insulation-layer-shielded types. Non-continuous noise and frozen water or ice appeared during cold N\textsubscript{2} gas flowing from the keep-full device; one sound suppressor device with an electrical heater was designed to avoid these problems. In the following section we present details to describe the design contracts of these devices.

2.2. Pressure-regulating device
An unavoidable pressure fluctuation in a LN\textsubscript{2} transfer line appears when a large quantity of liquid flows or is shut off by LN\textsubscript{2} users. A significant pressure fluctuation appears during the period of refilling of the 60 m\textsuperscript{3} LN\textsubscript{2} tank from the LN\textsubscript{2} truck; the pressure fluctuation peak to peak was more than 2.2 bar compared with normal fluctuation 0.5 bar. Some extreme cases actuated the safety relief valve of the LN\textsubscript{2} equipment. The best way is to install a mechanical device as pressure regulator before the equipment. Figure 2 shows the structure of a pressure-regulator device. One pressure-regulator valve connects with a LN\textsubscript{2} pipe located in a chamber for gaseous nitrogen. For the
maintenance, the top and bottom caps of the chamber can be opened. We can open the caps and adjust the pressure of the pressure-regulator valve during cold conditions while pure gaseous nitrogen flows into the chamber. We installed a check valve in the chamber to avoid the worst case according to which the pressure-regulator valve leaks after thermal cycles. Two pressure transducers were installed at the downstream side and the GN$_2$ chamber. Vacuum-shielded and super-insulation-shielded types decreased the heat load of this device. G10 material provides support inside the pipe.

![Figure 2. Pressure-regulating device](image)

2.3. *Keep-full device*

At TPS beamline endstations 05A, 09A, 23A and 25A, one phase separator connects between the branch line and a chiller to provide pure liquid fluid to its equipment. One simple keep-full device built between the branch line and the equipment can also provide pure liquid fluid as a phase separator. The structure of the keep-full device is shown in Figure 3. This keep-full device is also of the vacuum-shielded and super-insulator-shielded type. One mechanical ball-float valve is built inside a buffer. At the beginning of the two-phase flow of nitrogen flowing through the entrance of the buffer, the GN$_2$ is exhausted away with the ball-float valve. Until the LN$_2$ fills the buffer, the ball blocks the exhaust port inside the ball-float valve. Because of heat ingress, there is two-phase flow of fluids, and liquid nitrogen vaporizes to nitrogen gas in the branch line. Especially with low or no flow, this condition can lead to an accumulation of gaseous nitrogen in the pipeline. The emerged gas is exhausted through the keep-full device. The branch line itself stays filled with liquid nitrogen, fully mechanically and automatically.

![Figure 3. Keep-full device](image)
2.4. Sound-suppression device with electric heater

In the TPS LN\textsubscript{2} transfer line and branch line, an annoying noise appeared when a keep-full device emitted nitrogen, because, when the high-speed exhaust jet left the nozzle, the momentum was transmitted to the atmosphere, and the impact of the high-speed air stream generated sound waves. A sound-suppression device was hence designed to diminish the noise by altering the flow velocity and the audio structure. The structure of this sound-suppression device, shown in Figure 4, which uses the porous characteristics to diminish the air vibration so as to decrease the noise, mainly refers to a common exhaust muffler for motor vehicles. This muffler is classified as a resistance muffler, also known as an acoustic filter. The simplest type of expansion chamber is a thick tube with a large cross section connected to the airflow channel tube, but the end is a thin tube. Adjusting the length of the cross-section buckle of the expansion chamber (large tube) changes the reflection and interference performance of the sound wave. No sound-absorbing material was placed therein. This sound-suppression device is located at the exhaust port of the keep-full device. The condensation or icing occurs because of gaseous nitrogen at low temperature. We wound an electrical heating wire around the surface to bring the exhaust to room temperature.

![Sound-suppressor device](image)

**Figure 4.** Sound-suppressor device

3. Results and discussion

3.1. Pressure-stabilization test

The length of the vacuum-shielded branch pipe is about 6 m. Figure 5 shows the pressure fluctuations of a tank, the upstream pressure and the downstream pressure of the pressure-regulating device. The pressure of the tank fluctuated from 2.6 to 2.7 bar gauge (barg) when the 60 m\textsuperscript{3} LN\textsubscript{2} tank was refilled from the LN\textsubscript{2} truck; the pressure rose briefly to 2.9 barg, but the pressure upstream of the pressure-regulating device was greatly shaken for a period about 24 h; the pressure fluctuation range was 2 ~ 4.2 barg, which was a large fluctuation compared with the normal operation situation 2-2.6 barg. Because of the long-distance transfer and the random use of LN\textsubscript{2}, pressure fluctuations were unavoidable. The mechanical pressure-regulating device stabilized the downstream pressure fluctuations and diminished the impact on the cryogenic equipment of the beamline. The downstream pressure of the pressure-regulating device is about 1.48 to 2.1 barg.

![Pressure of the LN\textsubscript{2} tank, upstream and downstream of the pressure-regulating device](image)

**Figure 5.** Pressure of the LN\textsubscript{2} tank, upstream and downstream of the pressure-regulating device
3.2. Noise measurement and temperature control

Two tests were performed for a sound-suppression device -- noise measurement and temperature control. The noise arose from the exhaust gas of the keep-full device. A larger exhaust gas caused a greater sound level. The method of sound measurement was based on the standard of IEC61672-1 class 1. The measurement results showed that the maximum flow rate of the nitrogen exhaust was 100 L/min. The sound measured for the keep-full device only was 82 dB, for the keep-full device connected with a 0.7-barg check valve 65 dB, and for the keep-full device connected with the 0.7-barg check valve and the sound suppressor 57 dB, compared with the ambient sound measurement about 53 dB. The performance of the sound suppressor was satisfactory. According to the specification of the ball-float valve in the keep-full device, the exhaust flow rate was 100 L/min at 3 barg pressure, so this test was satisfactory in all various operational situations. This sound measurement is shown in Figure 6(a). The function of the keep-full device was to keep the pipeline as pure liquid nitrogen. The cold nitrogen gas was exhausted through the sound suppressor, which would cause condensed water or even frozen ice. We wrapped a heating tape on the outer layer of the sound-suppression device to maintain the overall temperature of that device above 30 °C. Figure 6(b) shows the overall temperature of the actual muffler equipment. The temperature is controlled between 30 °C and 37 °C.

![Figure 6](image_url)

(a) GN₂ Exhaust Sound
(b) GN₂ Exhaust temperature control

**Figure 6.** Noise measurement and temperature control for the sound suppressor

3.3. Measurement of the total heat load

The static heat loss is an important quality indicator for the vacuum–shielded pipeline. This section describes the measurement of the heat load of this branch line. Pure saturated liquid nitrogen flowed through the LN₂ branch line. The static heat load along the entire path \( q_r \) vaporized the liquid and thus delivered the gas to the keep-full device. The total rate of mass flow, \( m_r \), was measured after warming the cold gas through a passive heater. \( m_r \) is the vaporized LN₂ from the static heat load as the supply of the LN₂ was stopped during the measurement. The calculation of the heat load was based on the following equation,

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m_r \times h_{fg} = q_r
\]

in which \( h_{fg} \) is the enthalpy of LN₂. This branch line contains a pipeline of length 6 m, a reserve pipeline of length 1 m, a pressure-regulating valve and a keep-full device. Before the test, liquid nitrogen should flow into the branch line and nitrogen gas flow out of the keep-full device. One flow
meter (FT2) recorded the rate of gas flow of the nitrogen exhaust. As the pipeline cooled, the liquid nitrogen filled the pipeline; the keep-full device stopped discharging because the float valve closed the exhaust port. At this time, the LN$_2$ supply valve was closed to stop the liquid-nitrogen supply; at this moment the pressure in the pipe was about 2 barg, the same as the supply pressure. After the liquid nitrogen evaporated, the exhaust port was opened again because the liquid level decreased. The pressure in the pipe decreased rapidly, and the rate of gas flow was large, caused by the pressure drop between the pipe and the atmosphere. After the pressure was discharged to about atmospheric pressure, the flow in 30 min is shown in Figure 7. The exhaust flow rate at this time was only the vapor from liquid nitrogen. We recorded the data from 30 to 58 minutes. The average flow rate was about 1.5 L/min. Using Equation 1, we obtained the total heat load to be 5.68 W.

![Figure 7. Exhaust gas of the keep-full device](image)

4. Results and discussion

4.1. Liquid-nitrogen filling
The procedure of liquid-nitrogen filling was undertaken in four steps. Step one was manually to open CV1 to fill liquid nitrogen until the liquid level LT1 of the 300-L heat-exchange buffer (sub-cooler) reached the set point of the LN$_2$ level about 53 % (LT1). Step two was manually to open FV2 and FV3 to fill the 15-L inner vessel to reach its set point of the LN$_2$ level about 32 % (LT2). Step three was manually to start the LN$_2$ pump to circulate and to cool the internal pipeline of the DCM; at this time, the liquid-nitrogen level of the 15-L vessel was consumed through flow into the internal pipeline; valve FV2 opened and refilled LT2 up to 32 %. Step four was that, when the internal pipeline of the DCM was full of liquid nitrogen, the control mode switched to automatic mode, to keep LT1 at 53 % and LT2 at 32 % with the PLC controller. The pressure of the 15-L inner vessel remained 2 barg with the LN$_2$ pump. Figure 8 is the configuration of the LN2 cooling system for beamline 13A.

4.2. 72-h commissioning of the beamline cryogenic modules
Figure 9 shows the test results of 72-h commissioning of the beamline cryogenic module. Several operating modes and processes were performed. The first stage (during 0–32 h) was the manual operation: the DCM module operated with beam power on; in the second stage (during 32–72 h) the DCM operated with beam power off, and in the third stage (during 56–61 h) the level of LT1 decreased from 53 % to 35 % and then rapidly filled to 53 %. Figure 9(a) shows the increase of inlet temperature TT1 and outlet temperature TT2 of the DCM. At pressure 2 barg, the temperature change was the sensible heat change of the pure liquid phase. With beam power, the temperature rose from 77.04 K to 78.15 K, an increase 1.11 K. Without the beam power, the temperature increased from
76.92 K to 77.8 K, an increase about 0.88 K. We obtained the heat load to be 109 W and 86 W respectively. Figure 9(b) shows the pressure fluctuation of the LN$_2$ tank, the pressure of the regulator upstream PT3, and the pressure of the regulator downstream PT4. The pressure fluctuations are discussed in the previous section 3.1. The difference was that at 57 h we assumed that the CV213 LN$_2$ supply valve must be closed for 2 h. The branch line had no liquid nitrogen and was refilled with liquid nitrogen after 2 h. Figure 9(c) shows the pressure stability control; PT1 was the pressure of the 15-L vessel, for which the pressure was controlled at 1.9965 ± 1 mbar; the DCM inlet pressure was 1.997 ± 3 mbar. For any light source equipment, the vibration requirement was extremely sensitive; so the pressure fluctuation was stable enough to ensure almost no vibration of the pipeline. Figure 9(d) shows that the automatic liquid-level control worked well before hour 56. Control valve CV1 maintained a small opening and kept the liquid level of 300 L stably at 52 % ± 2 %. At 56 h, we stopped the automatic level-control function and closed valve CV1. The liquid level began to decrease until the level reached 35 %, turning on the automatic level-control refill of LN$_2$ to 52 % within 10 min. From the perspective of other pressures and temperatures, the short and large filling of the sub-cooler would not cause a worse stability of operation. The result shows no effect on the beamline cryogenic equipment.

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**Figure 8.** Configuration of the LN$_2$-cooling system for beamline 13A. CV213: LN$_2$ supply valve, PT1 LN$_2$ pressure of the inner vessel; PI2: LN$_2$ pressure of the DCM; PT3: LN$_2$ supply pressure, PT4 pressure of the pressure reducer outlet; LT1: LN$_2$ level of the sub-cooler; LT2: LN$_2$ level of the inner vessel; TT1: temperature in the inlet of DCM; TT2: temperature transducer at the inlet of DCM; TT3: exhaust gas temperature; FT1: LN$_2$ flow rate of DCM; FT2: exhaust gas for heat-load measurement; FV1–FV5: LN$_2$ flow valve; CV1: LN$_2$ supply valve of the sub-cooler.
5. Conclusion
Some issues commonly appear in pipelines for the transmission of liquid nitrogen, such as two-phase flow, pressure fluctuations, condensation of water or ice and noise in exhaust devices. Although these are not big issues to affect the equipment performance of the light source, they sometimes cause operational instability. The branch line designed and commissioned by the cryogenic team took these issues into consideration and eliminated them. The pressure-regulating device suppressed the pressure-fluctuation problem. The keep-full device improved the pure liquid fluid in the branch line, which replaced the separator originally installed before the beamline cryogenic equipment. Sound suppression and the temperature controller diminished noise and avoided condensation. The overall heat load of the branch line (length 6 m) is about 5.6 W at 77 K. The commissioning with the beamline DCM device also had excellent test results. The design, fabrication and assembly by the cryogenic team in NSRRC decreased not only the budget but also time. The design of more complicated cryogenic piping for TPS is under planning in the near future.

6. Reference
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