≪Review Paper≫ Applied Science and Convergence Technology Vol.24 No.4, July 2015, pp.77~83
http://dx.doi.org/10.5757/ASCT.2015.24.4.77

Introduction to Helium Leak Detection Techniques for Cryogenic Systems

Heetae Kim[a]*, Yong Sik Chang[b], Wookang Kim[a], Yong Woo Jo[a], and Hyung Jin Kim[a]

[a]*Rare Isotope Science Project, Institute for Basic Science, Daejeon 305-811, Korea*
[b]*Department of e-Business, Hanshin University, Osan 447-791, Korea*

(Received July 1, 2015, Revised July 7, 2015, Accepted July 10, 2015)

Many welding processes are performed to construct cryogenic system. Leak-tight for the cryogenic system is required at low temperature environment. Helium leak detection techniques are commonly used to find leak for the cryogenic system. The helium leak detection techniques for spraying, sniffing and pressurizing techniques are introduced. High vacuum is also necessary to use helium leak detector. So, types of fluid flow, effective temperature, conductance and pumping speed are introduced for vacuum pumping. Leak test procedure is shown for pipe welding, cryomodule and low temperature test. Cryogenic seals which include copper gasket, helicoflex gasket and indium are investigated.

Keywords : Leak detection, Cryogenic system, Welding, Cryogenic seals, Conductance

I. Introduction

Helium leak test is commonly used to construct cryogenic systems. Cryogenic system has many welding processes and leak-tight is required in the environment of superfluid helium at the temperature of 2 K. Superfluid droplets were studied around 1.5 K [1-3]. Molecular gas flow through a tube was investigated [4,5] and dynamic of capillary rise was studied [6]. Ultrahigh vacuum technology was developed for a large accelerator [7]. The size effect of thermal radiation [8-10] and the effective temperature for non-uniform temperature distribution was investigated [11-13]. Thermal radiation from arbitrary dimension was studied [14]. To accomplish Rare Isotope Science Project, the construction of cryogenic system and superconducting radio frequency test facility is important.

In this paper, we introduce the helium leak detection techniques for cryogenic systems. The basic information for vacuum technology is shown. Types of flow, effective temperature, conductance and pumping speed are introduced to make high vacuum. Helium leak detection techniques are introduced for spraying test, sniffing test and pressurizing test. Leak test procedure is also shown for pipe welding and low temperature test.

II. PUMP

1. Vacuum pumps

In order to make leak test, we need to evacuate the

* [E-mail] kim_ht7@yahoo.com

chamber with pumps. Vacuum pumps consist of rotary pump, diffusion pump, turbo molecular pump (TMP), ion pump, NEG pump, cryopump, etc. For instance, a leak detector consists of rotary pump and turbo molecular pump (TMP). The atmospheric pressure can be expressed as 1 atm, 760 torr, 1.01325 bar, 1.01325×10^5 Pa and 14.696 psi. Vacuum pressure can be considered as rough vacuum (RV) (1~760 torr), medium vacuum (MV) (10^{-5}~1 torr), high vacuum (HV) (10^{-8}~10^{-5} torr) and ultrahigh vacuum (UHV) ($<10^{-8}$ torr).

2. Types of fluid flow

Types of fluid flow are viscous flow which includes turbulent flow and laminar flow depending on Reynold number, Knudsen flow (intermediate flow) and molecular flow. Mean free path of a particle is the average distance that a particle can travel between two successive collisions with other particles. The mean free path for collisions of identical particles can be expressed as

$$l = \frac{k_B T}{\sqrt{2}\pi P d_m^2}, \quad (1)$$

where d_m is the particle diameter, P is the pressure, k_B is the Boltzmann constant and T is the absolute temperature. The effective temperature can be used in Eq. (1) when the temperature is not uniform throughout the chamber. For non-uniform temperature distribution, the effective temperature becomes [10]

$$T_{eff} = [\frac{1}{V}\int_0^V T^4 dv]^{1/4}, \quad (2)$$

where V is the total volume of the system. The Knudsen number is expressed as

$$k_n = \frac{l}{d}, \quad (3)$$

where l is the mean free path and d is the diameter of flow channel. The value of the Knudsen number characterizes the types of gas flow: continuous flow or viscous flow for the low vacuum of $k_n < 0.01$, Knudsen flow for the medium vacuum of $0.01 < k_n < 1$ and molecular flow for the high vacuum and ultrahigh vacuum of $k_n > 1$. The viscous flow shows that gas molecules make frequent collisions with themselves and less frequent collisions with the wall of the chamber. That is, gas molecules make strong interactions between molecules and weak interaction with the wall of the vessel. The Reynold number can be expressed as

$$R_e = \frac{\rho v L}{\eta}, \quad (4)$$

where ρ is the density of the gas, η is the dynamic viscosity, v is the mean velocity of flow and L is the characteristic length. For a tube, L is the diameter of the tube in Eq. (4). The laminar flow occurs for $R_e < 2300$ and turbulent flow occurs for $R_e > 4000$.

Gas interaction between gas molecules can be negligible in the molecular flow. The molecular flow occurs in high vacuum and ultrahigh vacuum. Molecules interact mainly with the wall of the vessel.

3. Conductance

Let us image the simple vacuum system, a straight tube with constant cross-section connecting two large volumes. The throughput is defined as

$$Q = \frac{PdV}{dt}, \quad (5)$$

where P is the pressure and V is the volume. The throughput is the power carried by a gas flowing in or out of the volume V at a rate of *dv/dt*. The *dv/dt* represents volumetric flow rate, which is also called pumping speed. The throughput can also be expressed as

$$Q = PS, \quad (6)$$

where S is the pumping speed and P is the pressure. Suppose we have a pipe connecting two volumes with different pressure, the conductance of the pipe can be expressed as

$$C = \frac{Q}{\Delta P}, \quad (7)$$

where ΔP is the pressure difference. The higher the conductance the more current runs through the pipe. For laminar flow, the conductance for a long round pipe becomes

$$C_{pipe,lam} = \frac{\pi d^4 \overline{P}}{128\eta L}, \quad (8)$$

where η is the dynamic viscosity, L is the length of the pipe, d is the diameter of the pipe and $\overline{P}$ is the average pressure. The conductance of a pipe for laminar flow is proportional to the diameter to the fourth power, proportional to the mean pressure and inversely proportional to the length of the pipe. For molecular flow, the conductance for a long round pipe is

$$C_{pipe,mol} = \frac{\pi v d^3}{12L}, \quad (9)$$

where L is the length of the pipe, v is the average velocity at the given temperature and d is the diameter of the pipe. The conductance for molecular flow does not depend on pressure. The conductance for molecular flow is increased linearly with the average velocity, is proportional to the diameter to the third power and is inversely proportional to the length of the pipe.

4. Pumping speed

For a typical pump, the amount of gas pumping out is proportional to pressure, so pimping speed S (liter/second) is defined as

$$S = \frac{V}{P}\frac{dP}{dt}, \quad (10)$$

where P is the pressure and V is the volume. From Eq. (10), the pressure is decreased as

$$P = P_0 \exp(-\frac{St}{V}), \quad (11)$$

where t is the evacuation time, V is the enclosed evacuation volume, S is the pumping speed, P_o is the initial pressure and P is the pressure at the time of t. In reality, pressure decreases slowly due to outgassing from the surface of the chamber. When the conductance of vacuum system is considered, Eq. (11) is modified to

$$P = P_0 \exp(-\frac{S_{eff}t}{V}), \quad (12)$$

where S_{eff} represents the effective pumping speed. The effective pumping speed of S_{eff} can be expressed as

$$\frac{1}{S_{eff}} = \frac{1}{S} + \frac{1}{C}, \quad (13)$$

where C is the conductance of the system. So, the conductance of the system plays an important role in achievable pumping speed.

III. Helium Leak Detection

1. Leak detection methods

It will be great to reduce risk before operate cryogenic system. As far as we know, helium leak test is the best method for risk management in cryogenic system. Leak detection guarantees at test temperature. Leak–tight can be guaranteed at room temperature if leak is tested at room temperature. Leak–tight can be guaranteed at 77 K if leak is tested at liquid nitrogen temperature. Generally, leak–tight probably works at 4.2 K if leak is tested at the liquid nitrogen temperature of 77 K. Most of materials such as stainless steel make most of thermal contraction from 300 K to 77 K, so extra thermal contraction is very small from 77 K to 4 K. With our best knowledge and experience, there is no leak test at 2 K in superfluid helium environment without cooling down to 2 K. Superfluid helium having negligible viscosity can go through very narrow channels. It will be very challenging to make leak–tight around 2 K environments.

Helium is the best atom for leak test. Helium can flow well through narrow channels due to small collision cross section and non-interacting property. Helium leak detector measures the leakage rate of helium gas flow. Leakage rate is expressed as

$$Q_L = \frac{\Delta PV}{\Delta t}, \qquad (14)$$

where ΔP is the pressure change during measurement time, V is the volume and is Δt the measurement time. Helium leak detection increases as the volume of test body increases. As pressure decreases, helium leak detection level decreases. That is, the sensitivity of leak detection is increased by reducing the pressure of the chamber. So, it is important to do leak test in high vacuum.

2. Spraying test

Spraying test is most widely used for helium leak test in order to prepare cryogenic system which requires cool-down with liquid helium. Fig. 1 shows the schematic drawing for spraying test. The spraying test is the most sensitive helium leak detection method. Test body is being pumped with the leak detector. Helium gas is sprayed on the suspected areas of the test body and then observes the helium detection level. If helium detection level is not increased, the test body has leak-tight. Background helium leak detection level requires below 5.0×10^{-8} mbar l/s. Spraying test can be performed at room temperature and liquid nitrogen temperature for cryogenic system. The thermal cycle test from 300 K to 77 K can be performed about three times to make sure leak-tight at liquid helium temperature.

3. Sniffing test

Sniffing test detects the escaping helium gas through a long distance sniffer probe from the part which the tested body is pressurized with helium gas. Fig. 2 shows the schematic drawing for sniffing test. The sniffer probe can be moved over potential leak areas and the leak can be located while the leak detector is not supposed to move due to turbo molecular pump in leak detector. When the leak is small, we can measure the total leak by collecting all the escaping helium gas with vinyl wrapping from all the potential leak area for about 5 minutes. The leak sensitivity is increased by collecting helium gas. Insert the sniffer into the vinyl wrapping to test leak after collecting the escaping helium gas for 5 minutes. It is better to reduce the collecting volume in order to increases sensitivity. Reference for sniffing test is air around the test area. Background reference is 5 ppm helium in air. There is no leak with sniffing test if leak detection is not observed. Ventilation is important to reduce background helium in air for sniffing test. When helium gas is released around the test area, the sensitivity of sniffing test becomes very low because the helium concentration of surrounding air is increased by the released helium gas.

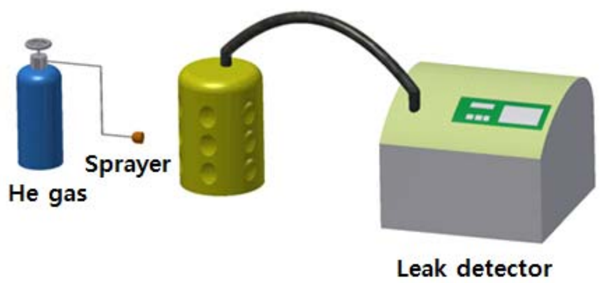

Figure 1. Schematic drawing for spraying test.

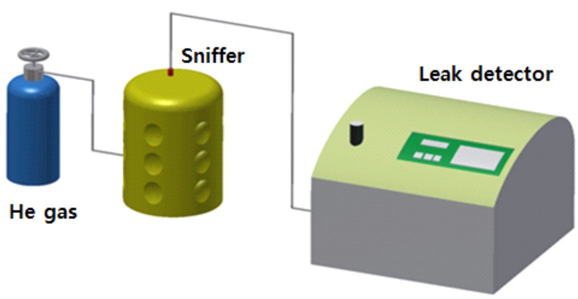

Figure 2. Schematic drawing for sniffing test.

4. Pressurizing test

Fig. 3 shows the schematic drawing for pressurizing test. The pressurizing test fills the test part with helium gas, placing it in a test chamber connected to the leak detector. The leak detector measures the flow of helium escaping from the part through all the leaks at the end of the test cycle. The leak cannot be located, which is integral leak test. Applied pressure range is from 1 to 25 bars.

5. Leak test procedure for pipe welding

Stainless steel (STS) 316L is commonly used material for cryostat and Stainless steel (STS) 304 is mainly used for helium gas pipe. Tungsten Inert Gas (TIG) welding techniques can be applied for the welding of STS 316L and STS 304. Welding stick rod should be the same material as the welding body because the same material shows same thermal contraction at low temperature. Leak can be caused by non-uniform thermal contraction during cooling process. Leak should be tested after Tungsten Inert Gas (TIG) welding. Leak test procedure for pipe welding is follows. First, radiographic test needs to be performed for welding inspection. Second, helium gas needs to be pressurized for test container. Here, the mixed gas of nitrogen and helium can be used for the pressurizing gas. Third, watch the pressure change for about 2 hours. If the pressure is not changed, we can process next step. Vinyl wrapping process can be performed around welding area and then do sniffing test. Leak-tight can be guaranteed if sniffing test is passed.

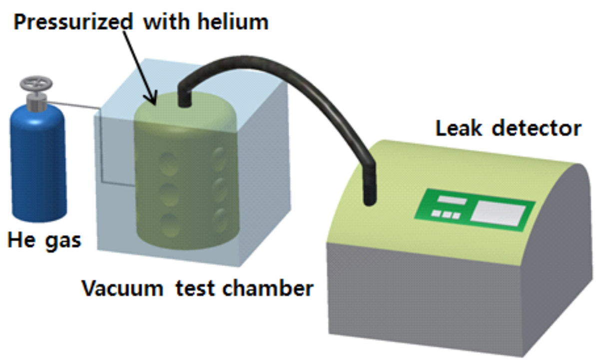

Figure 3. Schematic drawing for pressurizing test.

6. Leak test procedure for cryomodule

In order to do helium leak test, we need to pump the cryogenic system such as cryomodule. Fig. 4 shows the photographs of the inside and outside of

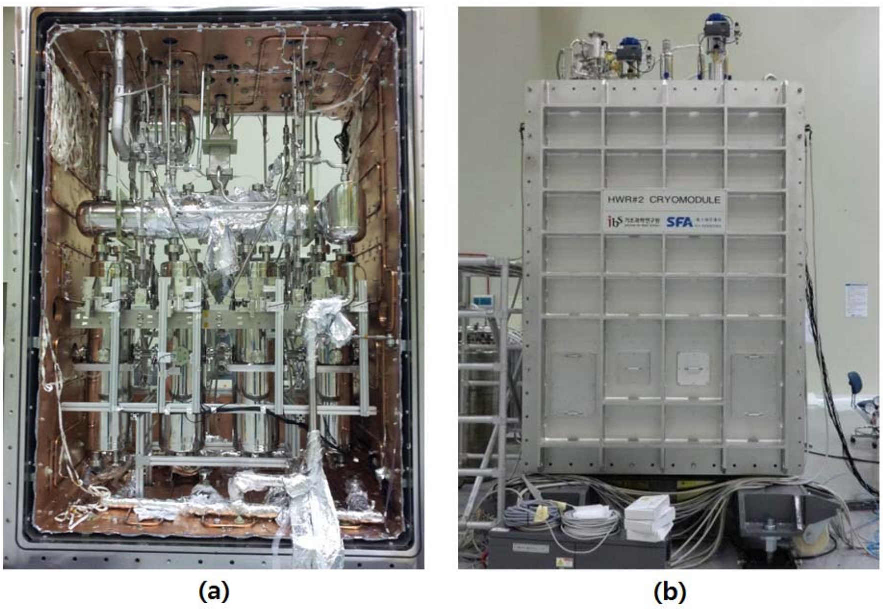

Figure 4. Photographs of the inside (a) and outside (b) of Half-Wave Resonator Type II (HWR2) cryomodule.

Half-Wave Resonator Type II (HWR2) cryomodule. The HWR2 cryomodule consists of 4 cavities. Pumping with helium leak detector is not enough to pump efficiently, so auxillary pump is required to pump the cryomodule. Once the pressure is low enough for leak test, we can spray helium gas to find leak. Spray helium gas to all suspected area to find out leak. It is better to find all possible leaks first before you fix the leak. Once all leaks are found, fix the leaks one by one. If leak is not found by local leak test, we need to perform global leak test. Helium gas can be sprayed in confined volume to make global leak test in which helium can flow into the all suspected leak place at the same time. Global leak test is much effective than local leak test. However, we can not locate the leak place with the global leak test.

7. Leak test procedure for low temperature test

Low temperatures for helium leak test can be 77 K, 4.2 K and 2.172 K. We can do leak test with liquid nitrogen at 77 K after leak test is performed at room temperature. If the cryogenic system is leak-tight at 77 K, the leak-tight can be possible with liquid helium at 4.2 K because thermal contraction between 77 K and 4.2 K is low. However, the leak-tight below the superfluid transition of 2.172 K is not guaranteed even if there is no leak at 4.2 K because the superfluid helium can flow through very narrow channels having micron-sized diameter hole. It causes superleak when the temperature becomes just below at 2.172 K. When there is superleak, we need to keep pumping the vacuum area and increase the temperature of liquid helium above 2.172 K by stop pumping the liquid helium.

8. Cryogenic seals

Copper gasket, helicoflex gasket and indium wire can be used for cryogenic seals at 2 K. It causes leak when helicoflex gaskets are used more than three times in our experience. We may use ten times if you do not overtighten helicoflex gaskets. Helicoflex gaskets can be generally used for large size, but they are very expensive. Copper gaskets are cheap and used for small size. Cooper gasket shows leak-tight at 2 K, which is applied to HWR cryomodule. Indium wire is medium-priced and requires some experience. Use high purity indium wire. Procedure to use indium wire is follows. First, clean seal surface and indium wire with alcohol. Second, apply small amount of vacuum grease to the indium wire. It is very hard to remove the indium wire from the seal surface if vacuum grease is not applied. Use heat gun to remove indium since the melting temperature of indium is only 430 K. Third, fit the indium wire to seal and pre-compress the crossover region. Fourth, screw the flanges together with bolts tightened in opposition. Another way, we can tight bolts in clockwise slowly. Fifth, retighten bolts every 10 minutes for an hour. Now, you are ready to cool-down. After you finish your low temperature experiment, it will be good to retighten the indium once again, which makes very good sealing in next low temperature experiment.

IV. Conclusions

We have shown helium leak detection methods for cryogenic systems. Types of gas flow were introduced, which includes viscous flow, Knudsen flow and molecular flow according to Knudsen number. Conductance of a long round pipe was shown for laminar flow and molecular flow. Helium leak detection methods such as spraying test, sniffing test and pressurizing test were introduced. Leak test procedure was shown for pipe welding, cryomodule and low temperature test. Cryogenic seals which include copper gasket, helicoflex gasket and indium were investigated.

Acknowledgements

This work was supported by the Rare Isotope Science Project of Institute for Basic Science funded by the Ministry of Science, ICT and Future Planning (MSIP) and the National Research Foundation (NRF) of the Republic of Korea under Contract 2013M7A1A1075764. This work was also supported by Hanshin University Research Grant.

References

[1] H. Kim, K. Seo, B. Tabbert, and G.A. Williams, Journal of Low Temperature Physics **121**, 621-626 (2000).

[2] H. Kim, K. Seo, B. Tabbert, and G.A. Williams, Europhysics Letters **58**, 395-400 (2002).

[3] H. Kim, P. A. Lemieux, D. J. Durian, and G.A. Williams, Phys. Rev. E **69**, 0614081-0614084 (2004).

[4] W. Steckelmacher and M.W. Lucas, J. Phys. D: Appl. Phys., **16**, 1453-1460 (1983).

[5] L. Fustoss and G Toth, Vacuum, **40**, 43-46 (1990).

[6] B.V. Zhmud, F. Tiberg and K. Hallstensson, Journal of Colloid and Interface Science, **228**, 263-269 (2000).

[7] G.Y. Hsiung, C.C. Chang, Y.C. Yang, C.H. Chang, H.P. Hsueh, S.N. Hsu and J.R. Chen, Applied Science and Convergence Technology, **23**, 309-316 (2014).

[8] S. J.Yu, S. J. Youn, and H. Kim, Physica B **405**, 638-641 (2010).

[9] H. Kim, S. C. Lim, and Y. H. Lee, Physics Letters A **375**, 2661-2664 (2011).

[10] H. Kim, S. J. Youn, and S. J. Yu, Journal of the Korean Physical Society **56**, 554-557(2010).

[11] H. Kim, M.S. Han, D. Perello, and M. Yun, Infrared Physics & Technology **60**, 7-9 (2013).

[12] H. Kim, C.S. Park, and M.S. Han, Optics Communications **325**, 68-70 (2014).

[13] H. Kim, W. K. Kim, G.T. Park, C. S. Park, and H. D. Cho, Infrared Physics &Technology **67**, 49-51(2014).

[14] H. Kim, W. K. Kim, G.T. Park, I. Shin, S. Choi and D. O. Jeon, Infrared Physics & Technology **67**, 600-603 (2014).