Appl. Sci. Converg. Technol. 25(3): 47-50 (2016)
http://dx.doi.org/10.5757/ASCT.2016.25.3.47

Research Paper

Low Temperature Test of HWR Cryomodule

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Received May 25, 2016; revised May 30, 2016; accepted May 30, 2016

Abstract Low temperature test for half-wave resonator (HWR) cryomodule is performed at the superfluid helium temperature of 2 K. The effective temperature is defined for non-uniform temperature distribution. Helium leak detection techniques are introduced for cryogenic system. Experimental set up is shown to make the low temperature test for the HWR cryomodule. The cooldown procedure of the HWR cryomodule is shown from room temperature to 2 K. The cryomodules is precooled with liquid nitrogen and then liquid helium is supplied to the helium reservoirs and cavities. The pressure of cavity and chamber are monitored as a function of time. The vacuum pressure of the cryomodule is not increased at 2 K, which shows leak-tight in the superfluid helium environment. Static heat load is also measured for the cryomodule at 2.5 K.

Keywords: Cryomodule, Linear accelerator, Low temperature test, Effective temperature, Vacuum pump

I. Introduction

RAON, heavy-ion accelerator facility in Korea was designed for nuclear physics, material science and medical research [1]. The RAON cryomodule design is optimized to provide various high-intensity stable ion beams for domestic and international users. The driver accelerator accelerates various ion beams ranging from proton to uranium beams, delivering more than a 400 kW beam power. The driver linear accelerator consists of a low-energy superconducting linac (SCL1), a high-energy superconducting linac (SCL2) and a low-energy superconducting linac (SCL3). Cryomodule types of RAON are quarter-wave resonator (QWR), half-wave resonator (HWR) and single-spoke resonator (SSR). The prototypes of all the cryomodule were fabricated. Operation temperature for QWR cryomodule is 4.3 K and that of HWR and SSR cryomodule is 2.1 K. Temperature of a body can be measured with blackbody radiation in all range of temperature. Blackbody radiation is changed when its size becomes small. The size effect of blackbody radiation was investigated [2-4]. Thermal radiation from arbitrary dimension was studied [5]. The effective temperature was defined for non-uniform temperature distribution [6-8]. Helium leak detection techniques were introduced to construct cryogenic systems [9]. Molecular gas flow through a tube was investigated [10,11] and vacuum test of cavity was performed with liquid nitrogen [12].

In this paper, we show the low temperature test of HWR cryomodule. Effective temperature, pumping speed and properties of superfluid helium are introduced. Experimental set up is shown to make low temperature experiment for HWR cryomodule at 2 K. The cooldown procedure of HWR cryomodule is shown and the leak test is performed at 2 K. Heat load is also measured for the cryomodule by keeping constant vapor pressure at 2.5 K.

II. Theory

In order to understand the low temperature test of HWR cryomodule, effective temperature, pumping speed, helium leak detection method and properties of superfluid helium are useful. The effective temperature is defined for the non-uniform temperature distribution. Pumping speed is useful information to make high vacuum when pumps are used. Helium leak detection techniques are briefly introduced for cryogenic system. Properties of superfluid helium are introduced to understand the effect of low temperature test below 2.172 K.

1. Effective temperature for non-uniform temperature distribution

Effective temperature is useful when the temperature of a system is not uniform. The effective temperature for two-different temperature distribution in three-dimension can be expressed as [6]

$$T_{eff} = \left[\left(\frac{V_1}{V}\right){T_1}^4 + \left(\frac{V_2}{V}\right){T_1}^4\right]^{1/4} \tag{1}$$

where V is the total volume, V_1 is the volume of temperature T_1 and V_2 is the volume of temperature T_2. For n segments of different temperature distribution, the

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effective temperature of the body can be generalized as [6]

$$T_{eff} = \left[\frac{1}{V}\sum_{i=1}^{n} V_i T_i^4\right]^{1/4} \tag{2}$$

where V is the total volume of the body. The effective temperature for two-dimension can be expressed as [7]

$$T_{eff} = \left[\frac{1}{A}\sum_{i=1}^{n} A_i T_i^3\right]^{1/3} \tag{3}$$

where A the total area of the surface. The effective temperature for one-dimension is [8]

$$T_{eff} = \left[\frac{1}{L}\sum_{i=1}^{n} L_i T_i^2\right]^{1/2} \tag{4}$$

where L is the total length. The effective temperature is higher than the average temperature.

2. Pumping Speed

Knudsen number characterizes the types of gas flow. Knudsen number is defined as $k_n = \frac{l}{d}$ where d is the diameter of flow channel and l is the mean free path of molecules. Gas flow is viscous flow for the low vacuum of (kn<0.01), Knudsen flow for the medium vacuum of (0.01 <kn<1) and molecular flow for the high and ultrahigh vacuum of (kn>1). Reynold number determines either laminar flow or turbulent flow. Reynold number is defined as $R_e = \frac{\rho v L}{\eta}$ 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. The laminar flow occurs for Re< 2300 and turbulent flow occurs for Re>4000. Reynold number represents the ratio of the kinetic energy of the gas to the potential energy of the gas. The flow becomes turbulent flow when its kinetic energy become big compared to potential energy. The flow becomes laminar flow when its potential energy becomes big compared to kinetic energy.

Pumping speed which is proportional to pressure is defined as

$$S = \frac{V}{P}\frac{dP}{dt} \tag{5}$$

where P is the pressure, t is the time and V is the volume. It is important to get high pumping speed at the target pressure. When the conductance of vacuum system is considered, the pressure is expressed as [9]

$$P = P_0 exp\left(-\frac{S_{eff}t}{V}\right) \tag{6}$$

where S_{eff} is the effective pumping speed, t is the evacuation time and V is the enclosed evacuation volume. The effective pumping speed can be expressed as

$$\frac{1}{S_{eff}} = \frac{1}{S} + \frac{1}{C_{tot}} \tag{7}$$

where S is the pumping speed and C_{tot} is the total conductance of the system. In order to make effective pumping, the optimization of pipe design is important to make high conductance. It is also important to reduce outgassing to achieve high vacuum.

3. Helium leak test

Helium leak detection consists of spraying test, sniffing test and pressurizing test [9]. The spraying test is follows: Test body is being pumped with leak detector. Helium gas is sprayed on the suspected area of the test body and then the helium detection level is monitored. The sniffing test is follows: 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. The pressurizing test is follows: The pressurizing test fills the test part with helium gas, placing it in a test vessel connected to 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.

In the preparation of cryogenic system, it is necessary to do leak test with spraying test because it has the highest sensitivity. It is also useful to do leak test with liquid nitrogen before cooldown of the cryogenic system with liquid helium.

4. Properties of superfluid helium

Liquid helium above 2.172 K is normal fluid, which is the same as classical fluid. Liquid helium below 2.172 K becomes superfluid. Superfluid helium has negligible viscosity. So, the flow of superfluid keeps for the age of universe. Superfluid can flow through a narrow channel, which causes superleak when the temperature becomes below 2.172 K. Stokes drag for hard sphere is

$$F_{normal} = -6\pi\eta R v \tag{8}$$

where η is the viscosity of vapor, R is the radius of the sphere and v is the velocity. Stokes drag of Eq. (8) can be used when a water drop moves in air or gas environment. But, Stokes drag for superfluid droplets can be expressed as [13,14]

$$F_{\mathrm{sup}rl} = -4\pi\eta R v \tag{9}$$

Compared to hard sphere, the Stokes drag of superfluid droplet is reduced by the flow of the superfluid on the surface of helium droplet. Another important property of superfluid helium is that the thermal conductivity of superfluid is the highest among known-materials, so the temperature of superfluid helium is almost the same. It does not generate any bubble as long as superfluid helium stays. There are bubbles in normal liquid helium. The 30-nm thin film of superfluid helium covers all surfaces as long as the temperature is below 2.172 K.

III. Experiment

Fig. 1 shows the piping and instrumentation diagram

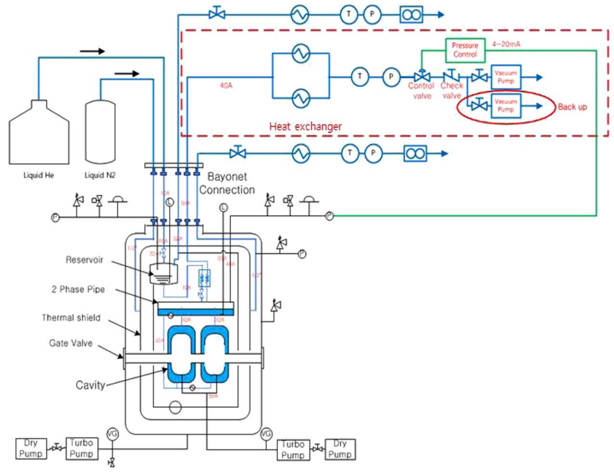

Figure 1. P&ID for HWR cryomodule test.

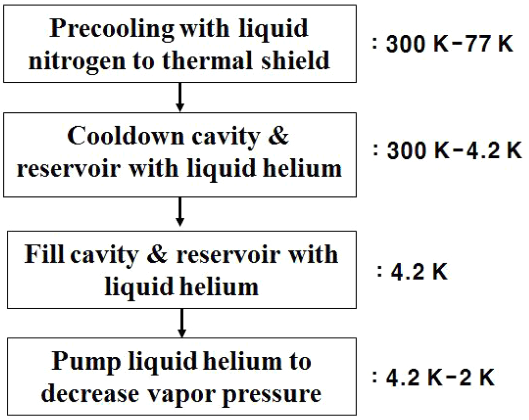

Figure 2. Cool-down procedure for HWR cryomodule.

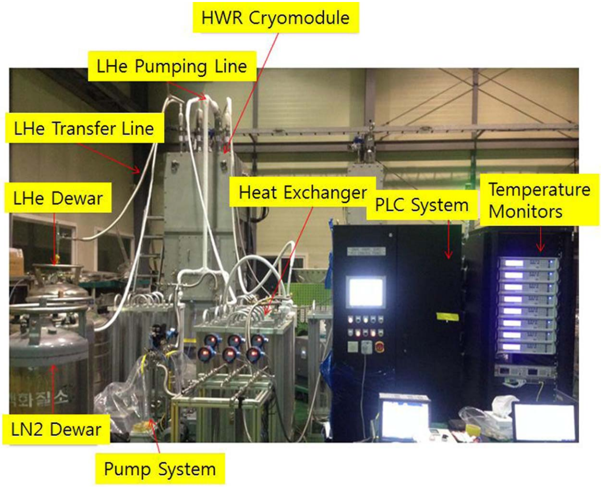

Figure 3. Experimental apparatus for cryomodule test.

(P&ID) for HWR cryomodule test. Dry pump and turbo molecular pump (TMP) are used to make chamber and cavity vacuum, respectively. Liquid nitrogen is supplied to the thermal shield and liquid helium is supplied to the helium reservoirs and cavities. Vacuum pumps are used to make 2 K in the helium reservoir and cavity.

Fig. 2 shows the cool-down procedure. The cryomodule is precooled with liquid nitrogen. After that, the cooldown of the cryomodule begins with liquid helium. The helium reservoir and cavity can be filled with liquid helium once temperature becomes 4.2 K. Liquid helium is pumped to reduce the vapor pressure of the liquid helium in the helium reservoir and cavity in order to make 2 K.

Fig. 3 shows the experimental apparatus for cryomodule test. Liquid helium dewar having 500 l is used to transfer the liquid helium to the cryomodule. Liquid nitrogen dewar having 180 l is used to supply the liquid nitrogen to thermal shield. Heat exchangers installed outside of the cryomodule are used to increase the temperature of helium and nitrogen coming out of the cryomodule.

Programmable logic controller (PLC) is used to control cryogenic valves, heaters, safety valves and pumps. PLC also monitors pressure, temperature and pumping speed. Temperatures are measured from LakeShore temperature monitor. Pressurized air is supplied to the control system of cryogenic valves.

Three pumps are used to make the temperature of 2 K for the HWR cryomodule. Pumping speeds of the three pumps are 2000 l/min, 2000 l/min and 5000 l/min, respectively. The three pumps are fully operated to reduce the vapor pressure of liquid helium, so it can reach the temperature of 2 K in 2 hours. Fig. 4 shows the vapor pressure and temperature around 2 K. The vacuum pressure of cavity and chamber is not increased even if the temperature is below 2.172 K. The partial helium pressure from residual gas analyzer (RGA) is not increased. Fig. 5 shows the vacuum pressure of cavity and chamber as a function of time. The vacuum pressure of cavity is not increased and the vacuum pressure of chamber is not increased as well during cryomodule experiment. So, leak is not found in the cavity and chamber of the cryomodule. The partial pressure of helium gas in the chamber is also constant with residual gas analyzer (RGA). So, helium leak is not found through RGA measurement in chamber. Therefore, HWR crymodule is shown to be leak-tight at 2 K. Superleak is not found in the cryomodule.

Vapor pressure is controlled at 100 mbar using pressure control valve. The vapor pressure of 100 mbar in liquid helium corresponds to the temperature of 2.5 K. Fig. 6 shows the liquid helium level as a function of time at 2.5 K. Heat load can be expressed as

$$\frac{\partial Q}{\partial t} = L\frac{\partial m}{\partial t} \tag{10}$$

where L is the latent heat of liquid helium and m is the mass of liquid helium. Heat load can be calculated from Eq. (10) by measuring the liquid helium level as a function of time. Cavities are secured by a strong-back holder. For the first heat load measurement, the temperature of strong back is 37.2 K and the heat load measurement shows 5.7 W. For the second heat load measurement, the temperature of the strong-back holder is 36.2 K and the heat load measurement shows 5.5 W. The

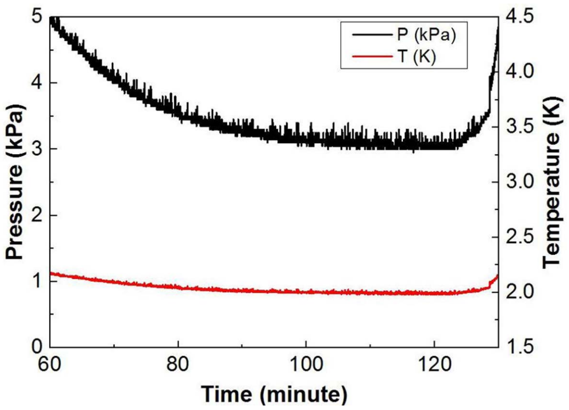

Figure 4. Vapor pressure and temperature versus pumping time around 2 K.

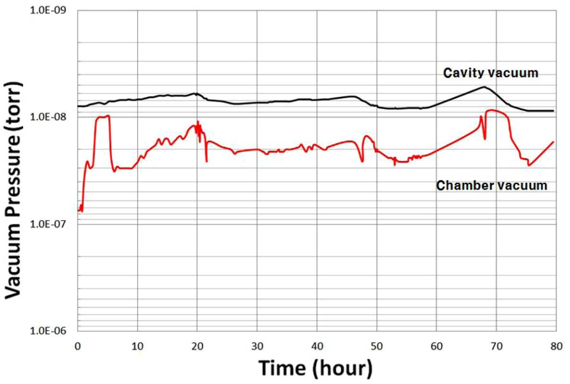

Figure 5. Vacuum pressure of cavity and chamber versus time.

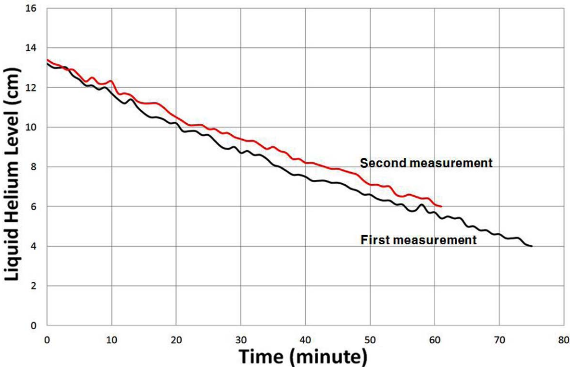

Figure 6. Liquid helium level versus time at 2.5 K.

heat load can be reduced by decreasing the temperature of the strong-back holder.

IV. Conclusions

We have shown the low temperature test of HWR cryomodule. Types of fluid flow and effective pumping speed were studied. Helium leak detection techniques were introduced to test cryogenic system. Properties of superfluid helium were briefly introduced. Experimental set up for HWR cryomodule was shown and cooldown procedure was shown from 300 K to 2 K. Leak test for the cryomodule at 2 K was performed. The cryomodule showed leak-tight because the vacuum pressure of cavity and chamber was not increased and the partial helium pressure from RGA was constant as a function of time. Heat load was measured for the cryomodule at 2.5 K.

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.

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