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Commissioning Test Results of Variable Temperature Helium Refrigerator/Liquefier for NIFS Superconducting Magnet Test Facility

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***Abstract*—The superconducting magnet test facility in the National Institute for Fusion Science has been upgraded for excitation tests at a wide temperature range and a higher magnetic field of 13 T. As part of the upgrade, the helium refrigerator/liquefier operated for 24 years was replaced with a variable temperature helium refrigerator/liquefier. The required liquefaction rate is 250 L/h and the required refrigeration capacity is 600 W at 4.5 K as the previous one. Besides, it has a new feature that can supply helium gas of a wide temperature range. The typical design cooling capacity is 1 kW under the condition of 20 K supply/30 K return and 1.5 kW under the condition of 40 K supply/50 K return. After the replacement, a series of commissioning tests were performed under the various operational conditions. From the results, the satisfactory thermodynamic performance was confirmed. In the future, it is expected that the substantial progress will be made in the development of large scale superconducting magnets with advanced superconductors such as high temperature superconductors and MgB_2. The design of the variable temperature helium refrigerator/liquefier and the results of the commissioning tests are reported in detail.**

***Index Terms*—helium refrigerator/liquefier, commissioning test, variable temperature, superconducting magnet, test facility.**

I. Introduction

The SUPERCONDUCTING MAGNET TEST FACILITY was constructed in the National Institute for Fusion Science (NIFS) to develop large scale superconducting magnets primarily for the Large Helical Device (LHD) [1]. The facility consists of a helium cryogenic system with the cooling capacity of 600 W at 4.5 K, large experimental cryostats with the maximum bias field of 9 T, DC power supplies with the maximum current of 75 kA and a distributed control system [2], [3]. In the past, the development of the superconductors and the superconducting magnets for the helical coils (HC) and the poloidal coils (PC) of the LHD, a lot of excitation tests and various collaborative research efforts have successfully been carried out in the facility [4]–[11].

It is proposed from the standpoint of higher magnetic field and less activation that high temperature superconductors (HTS) and MgB_2 will be applied to superconducting magnets and applications for fusion reactors and accelerators in the future [12]–[14]. Therefore, the test facility with higher bias field is required and the helium cryogenic system which can supply coolant of wide temperature range is also desired because the magnets and applications have a potential to be operated above liquid helium temperature.

In Japanese Fiscal Year (JFY) of 2014, the helium cryogenic system of the NIFS superconducting magnet test facility was partially updated for excitation tests of superconductors and superconducting magnets with HTS and MgB_2. In the update, the main compressor, the helium refrigerator/liquefier and the control system, which had been operated since 1991, were replaced. The new helium refrigerator/liquefier has not only the same cooling capacity as the old one but also the function that allows supply of helium gas of variable temperature in order to investigate the characteristics of superconductors and superconducting magnets under various temperatures [11]. The new control system similar to the duplicated control system of the cryogenic system for the LHD is adopted with the object of reliability and maintainability [15]. Besides, a superconducting magnet of solenoid winding with the bore diameter of 700 mm and the maximum field of 13 T was fabricated in order to conduct excitation tests under the high magnetic field [16]. It is expected that the R & D of superconducting magnets and applications for future fusion reactors and accelerators will be promoted strongly. In this paper, the update of the cryogenic system for the NIFS superconducting magnet test facility is reported. Especially,

Fig. 1. Photograph of the new main compressor. The oil removal system is installed beyond the compressor.

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the modified design of the variable temperature helium refrigerator/liquefier is described and results of the commissioning tests are reported in detail.

II. Renewed Devices in Helium Cryogenic System

A. Main Compressor

The previous compressor of Kobe Steel, Ltd. with the discharge pressure of 1.52 MPaG and the mass flow rate of 99.2 g/s has been replaced with an oil injection type screw compressor of Kaeser Kompressoren GmbH with the discharge pressure of 0.95 MPaG and the mass flow rate of 101.7 g/s. The electric power consumption is reduced from 450 kW to 239 kW. An oil removal system in the downstream and a valve unit for adjustment of the circulating flow rate of the helium cryogenic system are equipped by Taiyo Nippon Sanso Corporation. Fig. 1 is a photograph of the main compressor in the compressor room.

The major part of the helium cryogenic system is excluded by the application of the High Pressure Gas Safety Act in Japan because the discharge pressure is less than 1 MPaG. Thus, the maintenance can be simplified and the prompt repair can be performed. As the result, the running cost will be reduced and the availability will be improved.

B. Variable Temperature Helium Refrigerator/Liquefier

An LR280 of Linde Kryotechnik AG with the same cooling capacity of 600 W at 4.5 K as the previous helium refrigerator/liquefier of Kobe Steel, Ltd. was installed in the helium cryogenic system for the NIFS superconducting magnet test facility. Fig. 2 is a photograph of the cold box in the main laboratory and Fig. 3 shows its flow diagram during a series of the commissioning tests.

It consists of two stage of expansion turbines with dynamic gas bearing, two internal absorbers (80 K and 20 K), a gas-liquid separator with a heater to control the liquid helium level, eight aluminium plate-fin heat exchangers and a lot of cryogenic valves. In the liquefaction mode, the inlet pressure of the cold box is 0.86 MPaG and the mass flow rate is 89.0 g/s. The Joule-Thomson expansion pressure is 0.83 MPaG, while the pressure in the external LHe dewar is 0.024 MPaG. The rotational speed of the first and second turbine is around 170 krpm and 110 krpm, respectively.

Fig. 2. Photograph of the variable temperature helium refrigerator/liquefier.

An external heater unit to warm helium gas returned to the suction of the main compressor and an external pump to vacuum the thermal insulation vessel are equipped. Liquid helium (LHe), supercritical helium (SHe) and variable temperature helium gas (VT-GHe) can be output. Dummy heater units were attached on the supply/return ports of supercritical helium and variable temperature helium gas to measure the cooling capacity in the commissioning tests (see the right ends of Fig. 3).

The required helium liquefaction rate is 250 L/h in pure liquefaction mode and the required cooling capacity at 4.5 K is 600 W in pure refrigeration mode. In the case of supercritical helium, the required mass flow rate without liquefaction is 50 g/s with the cooling capacity of 350 W at 4.55 K. The new refrigerator/liquefier has the function that can supply the

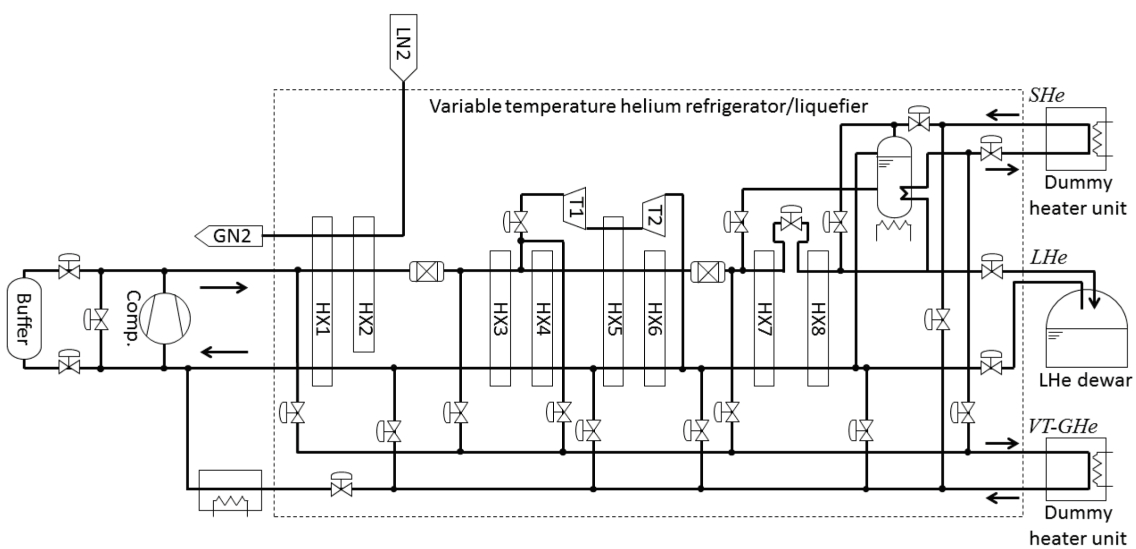

Fig. 3. Flow diagram of the variable temperature helium refrigerator/liquefier with two dummy heater units for the commissioning test.

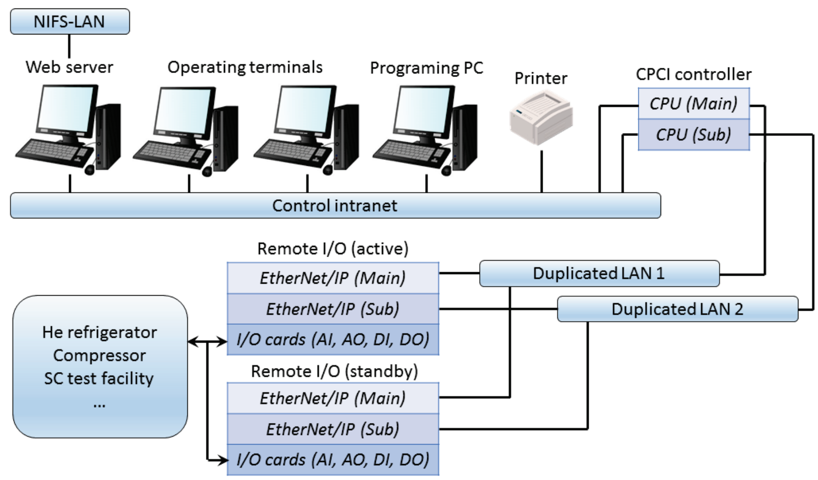

Fig. 4. Configuration of the control system of the helium cryogenic system for the NIFS superconducting magnet test facility.

helium gas at wide temperature range without liquefaction. As typical design, the cooling capacity is 1 kW when the supply temperature is 20 K and the return temperature 30 K while it is 1.5 kW when the supply temperature is 40 K and the return temperature is 50 K. In all conditions above, liquid nitrogen (LN2) are used as auxiliary cryogen.

C. Cryogenic Control System

The control system for the helium cryogenic system has also been renewed in order to simplify the system configuration and to improve the reliability and maintainability of the system. The configuration similar to the control system for the LHD cryogenic system has been adopted and is shown in Fig. 4 [15].

A controller was changed from discontinued micro-XL of Yokogawa Electric Corporation into DeMPICS of Taiyo Nippon Sanso Corporation. It is connected to remote I/O with EtherNet/IP and CPU of the controller, LAN and remote I/O are doubled, respectively. The control system has four personal computers (PC) as human interface and those are two operating terminals, a programing PC and a web server. The web server is connected to the NIFS-LAN and remote monitoring can be provided for improvement of safety and convenience.

III. Commissioning Test

A. Test Methods

After the update of the cryogenic system had been completed, the purifying operation of the helium cryogenic system had been done and then a series of the commissioning tests had been performed. The tested conditions are as follows; (1) helium liquefaction rate, (2) cooling capacity at 4.5 K, (3) cooling capacity at supply temperature of 20 K and return temperature of 30 K (at 20 K/30 K), (4) cooling capacity at supply temperature of 40 K and return temperature of 50 K (at 40 K/50 K) and (5) mass flow rate and cooling capacity of supercritical helium.

In the liquefaction test, increase of the liquid helium level in the LHe dewar of 10,000 L was measured. In the cooling capacity test at 4.5 K, electric power of the heater in the gas-liquid separator was measured when the liquid helium level in the separator was kept constant by the heater. In the cooling capacity tests at 20 K/30 K and 40 K/50 K, helium gas of 20 K or 40 K which was made by mixing helium gas after HX3 with helium gas after HX6 was supplied to the dummy heater unit of the VT-GHe port and then the return gas was returned to the low pressure line between HX4 and HX5. In the test of SHe, the dummy heater unit of the SHe port was provided with SHe at 0.79 MPaG cooled down to 4.42 K by heat exchange with saturated liquid helium in the gas-liquid separator and then the return SHe was flashed into the separator in order to be utilized for the heat exchange. In the last three tests, electric power of the dummy heaters was measured when the variable temperature helium refrigerator/liquefier was operated at steady state with constant power of the dummy heater. And also, mass flow rate was estimated by dividing heat input of the dummy heater by enthalpy difference of SHe between the inlet and outlet of the unit.

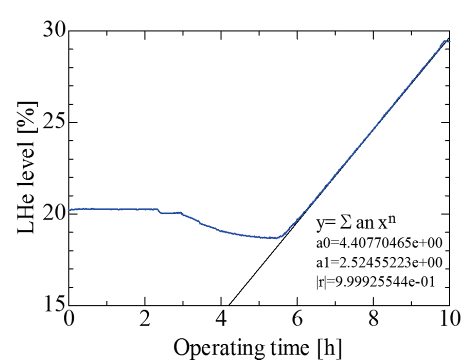

Fig. 5. Change of the liquid helium level in the LHe dewar of 10,000 L during the liquefaction test.

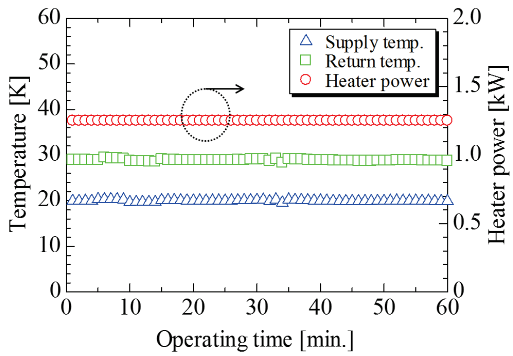

Fig. 6. Supply/return temperature of helium gas and the heat input from the dummy heater during the cooling capacity test at 20 K/30 K. Open triangles show the supply temperature, open squares return temperature and open circles the electric power of the dummy heater.

TABLE I
PERFORMANCE OF VARIABLE TEMPERATURE HELIUM REFRIGERATOR/LIQUEFIER

Tested condition	Required performance	Measured performance
Liquefaction rate	250 L/h	275.5 L/h
Cooling capacity @4 K	600 W	675 W @4.36 K
Cooling capacity @20 K/30 K	1 kW, 18 g/s @20 K/30 K	1193 W, 25 g/s @20 K/29 K
Cooling capacity @40 K/50 K	1.5 kW, 20 g/s @40 K/50 K	1603 W, 33 g/s @40 K/49.3 K
SHe	350 W, 50 g/s @4.55 K	407 W, 51.3 g/s @4.42 K

B. Test Results

As to the first tested condition above, Fig. 5 shows change of liquid helium level in the dewar. After start of the test, the level decreased once and then the level increased at a constant rate approximately. The constant increase rate was 2.52 % per hour, corresponding to 275.5 L/h, from the least-squares method. The liquefaction rate more than the required rate of 250 L/h was confirmed.

The test result of the cooling capacity at 20 K/30 K, which is the third tested condition above, was reported as the representative cooling capacity of the helium refrigerator/liquefier. The test was demonstrated by suppling helium gas at 20 K, 0.31MPaG to the dummy heater unit with constant heat input of 1,193 W from the supply port of the variable temperature helium. Fig. 6 shows the supply/return temperature of helium gas and the electric power of dummy heater. It was observed that the return temperature became constant at 29 K. As a result, the cooling capacity at 20 K/30 K is estimated to be more than 1,193 W.

With regard to the other tested conditions, the commissioning tests were similarly performed. All test results are summarized in Table I. Consequently, the specifications of the variable temperature helium refrigerator/liquefier have been satisfied and the excellent performance of the updated helium cryogenic system for the NIFS superconducting magnet test facility has been confirmed.

IV. CONCLUSION

The helium cryogenic system for the NIFS superconducting magnet test facility have been updated partially. In particular, the variable temperature helium refrigerator/liquefier with the function that can supply helium gas at wide temperature range was installed in order to conduct the excitation tests at various temperatures for applying HTS and MgB_2 to the superconducting magnets and applications. A series of the commissioning tests were conducted for five conditions and the test results were satisfactory. The large bore high magnetic field test cryostat is scheduled to be assembled in JFY 2015-2016, utilizing the 13 T superconducting magnet with the bore of 700 mm. It is expected that the development of the large scale high magnetic field superconducting magnets for fusion reactors and accelerators in future and various applied research on HTS and MgB_2 will be advanced significantly.

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