Design and Operation of the Sub-Cooled Helium Test Facility for the LHD Helical Coils

Y. Hishinuma, S. Imagawa, N. Yanagi, T. Mito, A. Nishimura, S. Yamada, K. Takahata, H. Chikaraishi, H. Tamura, A. Iwamoto, S. Hamaguchi, K. Seo, T. Honda, T. Shinba, S. Yoshinaga, M. Satoh, H. Kakui, and O. Motojima

***Abstract*—In order to increase the cooling stability of the helical coils, an upgrade of the cooling scheme is planned from 4.4 K pool-boiling to 3.0 K sub-cooled helium of flow rate of about 50 g/sec. We have designed and constructed a R&D coil made of the same superconductor as that used for the helical coils and a sub-cooled helium test facility on the assumption of the application for actual Large Helical Device (LHD). This facility is composed of decompression tank for the sub-cooled helium generation, the R&D coil, a current lead storage tank, etc., installed in a cryostat with a liquid nitrogen shield. Two stage cryogenic compressors are installed in the top flange, and sub-cooled helium is generated by decompressing of saturated liquid helium from 0.12 MPa to 24 kPa. Liquid helium of 4.4 K and 0.12 MPa is heat exchanged by the sub-cooled helium in the decompression tank and supplied to the R&D coil from the bottom. The sub-cooling R&D experiment has been carried out.**

As the results of experiment, we found that the saturated liquid helium could be cooled from 4.4 K to 3.0 K in 8 hours and maintained at 3.0 K. The rotation speed of the first and second stage cryogenic compressors were about 87,000 and 88,000 rpm, respectively. These values agreed well with the designed values of the two-stage cryogenic compressors. Finally, this facility operated stably during 8 days of the two sub-cooling R&D experiment campaigns.

***Index Terms*—Cryogenic compressor, helical coils, LHD, sub-cooled liquid helium, test facility.**

I. Introduction

The Large Helical Device (LHD) is the largest stellarator, which has been in operation from 1998 to present, for the study of fusion plasma to a fusion reactor region [1]. The coil system of LHD is composed of the helical and poloidal coils. The helical coils of LHD are a pair of two pool-cooled superconducting magnets to produce a twisted toroidal magnetic field. Their major and minor radii are 3.9 and 0.975 m, respectively. A conductor of helical coils consists of Nb-Ti/Cu strand, a high pure aluminum stabilizer, and a copper sheath for the high cryogenic stability and mechanical strength.

The operating current of helical coils is, however, restricted below the design current of 13 kA due to the observation of a dynamically propagated normal-zone [2]. The propagation of normal-zone and recovery in the helical coils was observed several times from the first excitation up to 11.25 kA, which was 87% of the design current of 13 kA [2]. We guessed that the propagation of normal-zone and recovery in the helical coils were caused by the mechanical disturbance which arises in the helical coil winding and the deterioration of cooling characteristics by the peculiar retention of the helium gas bubble in the helical shape. In order to increase the cooling stability of the helical coils, an upgrade of the cooling scheme is planned from 4.4 K pool-boiling to 3.0 K sub-cooled helium with flow rate of about 50 g/sec. We designed and constructed the R&D coil of the same superconductor as that used for the helical coils and a sub-cooled helium test facility on the assumption of the application for actual LHD. Two sub-cooling R&D experiment campaigns were carried out from 15 to 20, December 2002 and from 30, September to 3, October 2003.

In this paper, we described the design of the components of the sub-cooled helium test facility and cooling scenario. The features and specifications of cryogenic compressor as the core of test facility are also introduced.

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Y. Hishinuma is with Fusion Engineering Research Center, National Institute for Fusion Science, Gifu 509-5292, Japan (e-mail: hishinuma@nifs.ac.jp).

S. Imagawa, N. Yanagi, T. Mito, S. Yamada, K. Takahata, H. Chikaraishi, H. Tamura, A. Iwamoto, S. Hamaguchi, and K. Seo are with Device Engineering Division, National Institute for Fusion Science.

A. Nishimura is with Fusion Engineering Research Center, National Institute for Fusion Science.

T. Honda, T. Shinba, S. Yoshinaga, M. Satoh, and H. Kakui are with Ishikawajima-Harima Heavy Industries Co., Ltd., 3-2-16, Toyosu, Koto-ku, Tokyo 135-8733, Japan.

O. Motojima is with the National Institute for Fusion Science.

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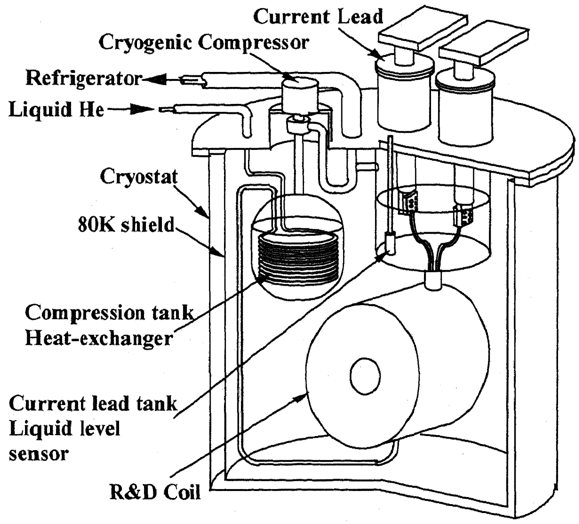

Fig. 1. The design configuration of the sub-cooled helium test facility.

II. The Component of the Sub-Cooled Helium Test Facility

A. Sub-Cooled Helium Test Facility

Fig. 1 shows that the configuration of sub-cooled helium test facility. This facility is composed of decompression tank for

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TABLE I
THE DESIGN OF THE TWO STAGE CRYOGENIC COMPRESSOR

	1st stage	2nd stage
Type	Two steps series centrifugal type (centrifugal compressor)	
Inlet Condition	23.0 kPa, 3.0 K	64.4 kPa, 5.13 K
Outlet Condition	64.4 kPa, 5.13 K	120.0 kPa, 7.39 K
Flow Rate	15.9 g/s	15.9 g/s
Adiabatic efficiency	over 65%	over 60%
Refrigeration load	below 168 W	below 179 W

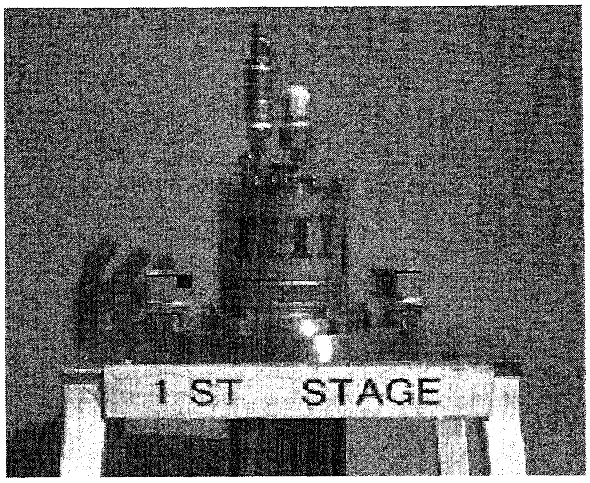

Fig. 2. The photograph of the cryogenic compressor installed sub-cooled helium test facility (First stage).

the sub-cooled helium generation, the R&D coil, a current lead storage tank, and two cryogenic compressors etc., installed in a cryostat with a liquid nitrogen shield. The dimension of the cryostat is 1,900 mm of inner diameter, 2,250 mm of outer diameter and 3,600 mm of height. The two stage cryogenic compressors are installed on the top flange.

Sub-cooled helium is generated by decompressing of saturated liquid helium from 0.12 MPa to 24 kPa. Liquid helium of 4.4 K and 0.12 MPa is heat exchanged by the sub-cooled helium of 3.0 K in the decompression tank and supplied to the R&D coil from the bottom with 5.0 g/sec of flow rate. Sub-cooled helium which cooled the coil is recovered for the current lead storage tank. The specifications of R&D coil are presented in the paper 4B-p07 of this conference [3].

B. The Features and Specifications of Cryogenic Compressor

During sub-cooling R&D experiments, sub-cooled helium is generated by decompressing of saturated liquid helium from 0.12 MPa to 24 kPa at decompression tank. In this R&D experiment, the decompressing of saturated liquid helium in the tank uses two cryogenic compressors, which are connected in two-step series. Table I indicates the design of the two stage cryogenic compressors installed sub-cooled helium test facility. The photograph and the cross-sectional drawing of the cryogenic compressor installed sub-cooled helium test facility are shown to Figs. 2 and 3, respectively. This is designed on the assumption of actual LHD upgrade. The design and production of cryogenic compressor is done by Ishikawajima-Harima Heavy Industries Co. Ltd.

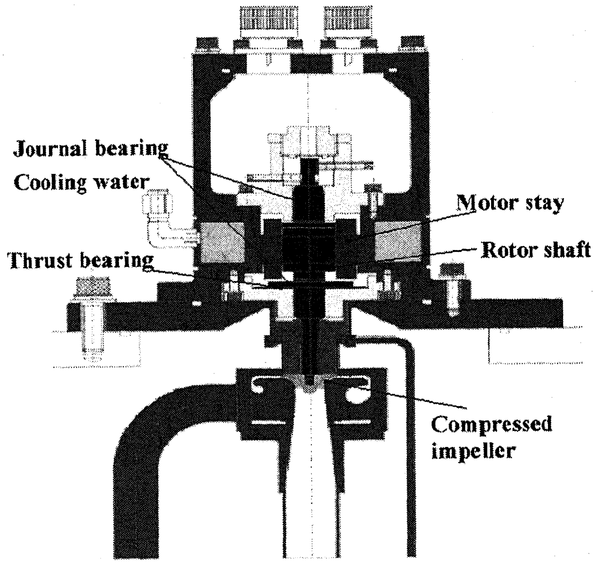

Fig. 3. The cross-sectional drawing of the cryogenic compressor installed sub-cooled helium test facility.

The cryogenic compressor adopts the centrifugal compressor, and the impeller is rotated to about 90 000 rpm of designed rotation speed. The impeller installed at the rotor shaft (the impeller + electric motor + bearing) tip is driven using the induction motor. The disconnection of cryogenic compressor from the test facility is possible without breaking the vacuum of the cold-box because the impeller and drive division (bearing and motor) are placed separately into low temperature region and ordinary temperature region, respectively. The additional feature of cryogenic compressor installed test facility is to adopt foil style dynamic pressure gas shaft which is the perfect oil-free bearing supporting the rotor shaft. In order to reduce the lowering of efficiency of the cryogenic compressor by the heat conduction from the ordinary temperature, we adopt a heat intercept structure of liquid nitrogen which absorbs the heat from the room temperature to casing at low temperature. As the results, it is possible to limit the designed heat conduction to about 4.0 W.

III. THE COOLING SCENARIO OF THE SUB-COOLED HELIUM TEST FACILITY

A. The Cooling Down of Sub-Cooled Helium Test Facility to 4.4 K

We started to cool down of the sub-cooled test facility since 15, December, 2002 as the first cooling down. The flow diagram and the cooling curves of sub-cooled helium test facility are shown to Figs. 4 and 5. The cooling curves in Fig. 5 show a plot of the change of the values of cernox thermometers, installed at outlet of heat exchanger and outlet of 2nd cryogenic compressor.

The cooling of 80 K shield and filling liquid nitrogen into external tank of cryostat was started at first. At the same time, the two stage cryogenic compressors were started up 30 000 rpm (minimum rotation speed) to prevent the freezing of cooling water of cryogenic compressor. The cooling down of sub-cooled helium test facility was carried out slowly by the low temperature helium gas for two days to prevent breaking down of com-

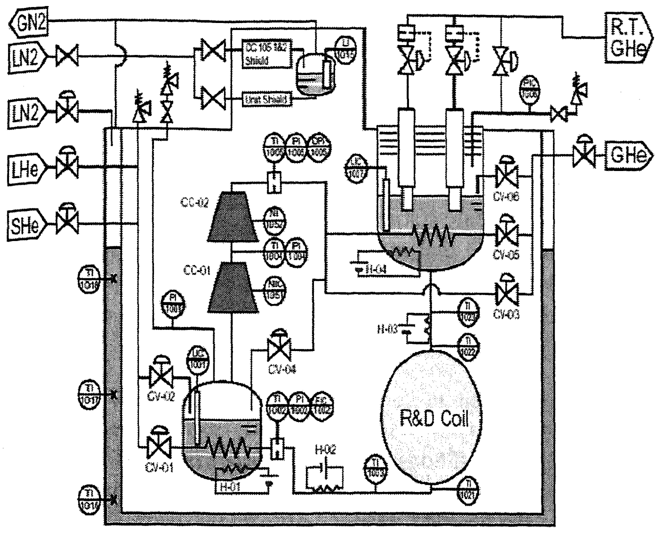

Fig. 4. The flow diagram of sub-cooled helium test facility.

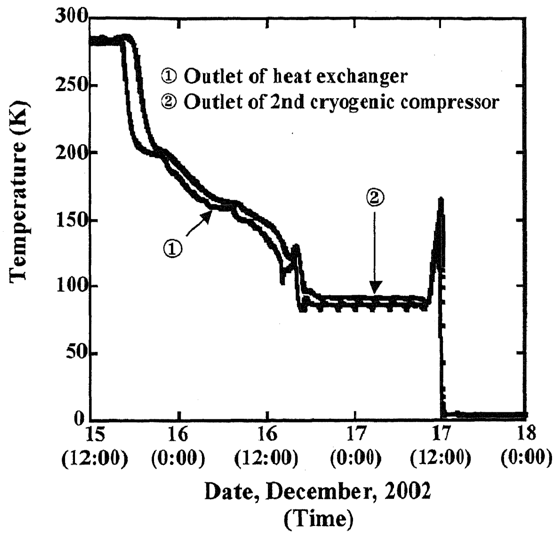

Fig. 5. The cooling curves to 4.4 K of the sub-cooled helium test facility.

ponent into test facility by thermal contraction. After that, the coolant was switched from the low temperature helium gas to the liquid helium, the cooling down to 4.4 K was carried out with the storage of liquid helium to decompression tank for the sub-cooled helium generation, the R&D coil and a current lead storage tank. The cooling down to 4.4 K was finished completely after 3 days from the start of cooling down. The conditions when sub-cooled test facility cool down to 4.4 K were as follows; 9.58 g/sec of the flow rate on outlet of heat exchanger, 30 000 rpm of rotation speed on the 1st and 2nd cryogenic compressors, 4.65 K of the temperature on the middle stage between the 1st and 2nd cryogenic compressors and 4.65 K of the temperature on the outlet of 2nd cryogenic compressor. The cryogenic stability of the R&D coil was examined at 4.4 K and 0.12 MPa, temperature was kept constant at 4.4 K during the cryogenic stability test. The results of cryogenic stability of the R&D coil at saturated helium are presented in detail in this conference, 4B-p07, 4B-p06 and 2D-p10 [3]–[5].

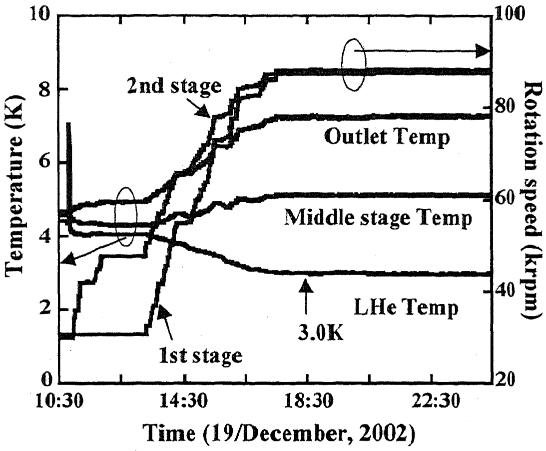

Fig. 6. The cooling curves from 4.4 K to 3.0 K on the sub-cooled helium test facility.

B. The Cooling Down From 4.4 K to 3.0 K by Sub-Cooled Helium

After the cryogenic stability test at 4.4 K and 0.12 MPa, we started to supply sub-cooled liquid helium (3.0 K, 0.12 MPa) into R&D coil. Fig. 6 shows the cooling curves of sub-cooled helium test facility and the change of the rotation speed of cryogenic compressor when it was cooled down from 4.4 K to 3.0 K. Sub-cooled helium is generated by decompression of saturated liquid helium from 0.12 MPa to 24 kPa using cryogenic compressor. The rotation speed of the 2nd cryogenic compressor was raised gradually at first in order to prevent the counter-flow of the outlet helium gas from 2nd cryogenic compressor, and then that of 1st cryogenic compressor was raised, too. The temperature of outlet of heat exchanger was decreased with raising rotation speed of 1st cryogenic compressor. After the operation of cooling down to 3.0 K, we found that liquid helium supplied into R&D coil could be cooled down to 3.0 K in 8 hours and stably kept at 3.0 K. The conditions when sub-cooled helium test facility supplied 3.0 K of sub-cooled liquid helium into R&D coil were as follows; 9.58 g/sec of the flow rate on outlet of heat exchanger, 87 550 and 88 190 rpm of rotation speed on the 1st and 2nd cryogenic compressors, 5.04 K of the temperature on the middle stage between the 1st and 2nd cryogenic compressors and 7.03 K of the temperature on the outlet of 2nd cryogenic compressor. We found that these values agreed well with the designed values of the cryogenic compressor system shown in Table I. We confirmed that this test facility was able to supply stably not only 3.0 K but also 3.5 K of sub-cooled helium into R&D coil by adjustment of rotation speed of cryogenic compressor.

Fig. 7 shows the typical relationship between pressure ratio and corrected mass flow on the 1st cryogenic compressor. The corrected mass flow is the value converted flow rate, and it becomes a function of the inlet temperature and the pressure of cryogenic compressor. The corrected speed is the value converted peripheral speed, and it is dependent on the temperature. The nought-and-cross marks shown in Fig. 7 indicate rated and operation rotation speed value of the cryogenic compressor. The compressor can be run between surge and choke region, the abnormal vibration called the surging is generated because there

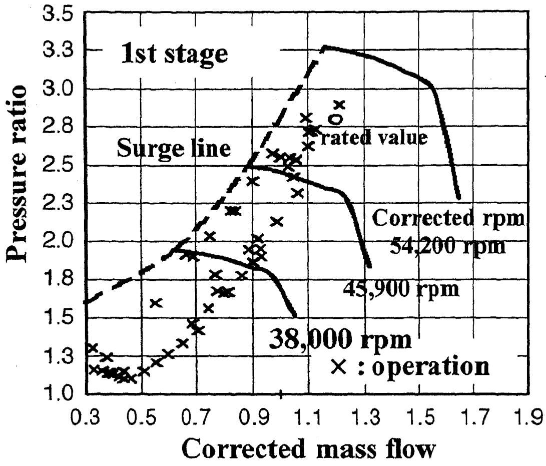

Fig. 7. The typical characteristics curve of the 1st cryogenic compressor.

TABLE II
THE DIFFERENCE OF ADIABATIC EFFICIENCY ON THE TWO STAGE CRYOGENIC COMPRESSOR (3.0 K RATED OPERATION)

3.0 K rated operation	1st stage	2nd stage
Rotation speed (krpm)	87.55	88.19
Adiabatic efficiency(Design)	> 65.0%	> 60.0%
Adiabatic efficiency(Measurement)	62.4%	61.2%

are small flow rate on the surge for the rotation. In this operation, we confirmed that the 1st cryogenic compressor was able to run safely to the rated operation range. Furthermore, we confirmed about the 2nd cryogenic compressor as well as 1st cryogenic compressor. We summarized about the difference of adiabatic efficiency on the two stage cryogenic compressor (3.0 K rated operation) in Table II. We found that there was the difference of adiabatic efficiency between two stage cryogenic compressors. The adiabatic efficiency of 2nd cryogenic compressor exceeded 60% of designed value. Though the adiabatic efficiency of 1st cryogenic compressor was lowered from 65% of designed value, we thought that there is no problem about sub-cooled helium test facility to confirm the supply at 3.0 K of sub-cooled helium into R&D coil. The cryogenic stability of the R&D coil was examined at 3.0 K, temperature was stably kept at 3.0 K during the cryogenic stability test. The results of cryogenic stability of the R&D coil at sub-cooled helium are presented in detail on this conference, 4B-p07, 4B-p06 and 2D-p10 [3]–[5]. Finally, this facility operated stably during total 8 days of the two sub-cooling R&D experiment campaigns.

IV. CONCLUSION

We designed and constructed the sub-cooled helium test facility on the assumption of the application for actual LHD in order to verify increase of the cooling stability of the helical coils by 3.0 K sub-cooled helium, and the sub-cooling R&D experiment was carried out. As the results, we confirmed that sub-cooled helium test facility could supply 3.0 K and 3.5 K of sub-cooled helium into R&D coil which was operated stably during total 8 days of the sub-cooling R&D experiment.

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