Operations of the Helium Subcooling System for the LHD Helical Coils during Ten Plasma Experimental Campaigns*)

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The Large Helical Device has a helium subcooling system with two cold compressors for helical coils to enhance the magnetic fields and improve the cryogenic stability of the coils by lowering the coil temperature. The system was installed in 2006 and then it has stably supplied 3.2 K subcooled helium at the nominal mass flow rate of 50 g/s to the coils during ten plasma experimental campaigns. The running time of the cold compressors exceeds 30,000 hours and the total time of subcooling operations exceeds 20,000 hours. In the system, the supplied helium is subcooled in a heat exchanger of a saturated helium bath. The bath pressure and temperature are reduced by a series of two centrifugal cold compressors with gas foil bearing. In the steady state subcooling operation, the bath temperature is stabilized within range of 0.02 K with automatic flow control of helium gas through the cold compressors by a heater in the bath. The control method is also useful to protect the system by mitigating large disturbance of the pressure and the mass flow rate. In the present study, the thermal hydraulic behavior of the system and the operational performance during ten plasma experimental campaigns are reported.

Keywords: cold compressor, subcooled helium, superconducting coil, cooling system, automatic control

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1. Introduction

The Large Helical Device (LHD) is an experimental device for fusion plasmas and the LHD helical coils are large scale superconducting coils to provide heliotron magnetic field [1,2]. In 2006, a helium subcooling system was installed to the helical valve box in the cooling system of the LHD helical coils in order to enhance the magnetic fields and improve the cryogenic stability of the coils by lowering the operating temperature of the coils [3–6]. Figure 1 is a photograph of the LHD and the helical valve box with the helium subcooling system. In the system, liquid helium of 120 kPa is subcooled to 3.0 K in a heat exchanger of a saturated helium bath and is supplied to the coils at the mass flow rate of 50 g/s. The bath pressure and temperature are reduced by a series of two centrifugal cold compressors with gas foil bearing [7]. After the installation, the maximum operating current of 11.833 kA was achieved due to improvement of the cryogenic stability [8, 9]. Also, the system has been operated stably, while the running time of the cold compressors exceeds 30,000 hours and the total time of subcooling operations exceeds 20,000 hours.

In the subcooling operation, the temperature of supplied helium should be kept constant for stable excitations of the coils. Also, centrifugal compressors should be operated within each appropriate operational range of the mass flow rate and the pressure ratio in order to avoid the surge and the choke for mechanical soundness and stable operation. Therefore, it is important to understand the performance of the cold compressors for the reliable operation of the cooling system, especially the transient characteristics against large disturbance due to heat load generated in superconducting coils [10–13]. In the present study, the thermal hydraulic behavior of the helium subcooling system and the operational performance during ten plasma experimental campaigns are reported. It is also discussed how to prevent the cold compressors from the surge and choke due to the large disturbance of the pressure and mass flow rate

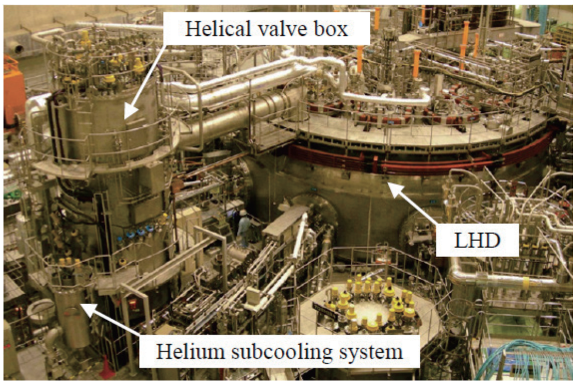

Fig. 1 Photograph of the Large Helical Device (LHD), which is an experimental device for heliotron type fusion plasmas, and the helical valve box with the helium subcooling system.

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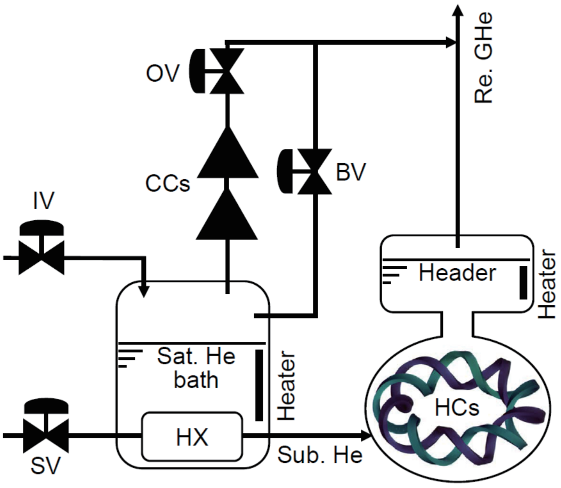

Fig. 2 Schematics of the helium subcooling system with a series of the cold compressors. The subcooled helium is generated in the heat exchanger (HX) and then supplied to the LHD helical coils (HCs).

after a quick discharge of the LHD helical coils for quench protection.

2. Helium Subcooling System and Steady State Subcooling Operation

Figure 2 is the schematics of the helium subcooling system for the LHD helical coils. In the system, liquid helium of 120 kPa is subcooled to 3.0 K at the heat exchanger (HX) in the saturated helium bath and is supplied to the helical coils [4, 7]. The mass flow rate of the supplied helium is regulated by a supply valve of the helical coils (SV) to be 50 g/s. In a header of the helical coils (HCs), the excess helium is exhausted by a heater. The bath pressure and temperature are reduced by a series of the two centrifugal cold compressors with gas foil bearing. In the steady state subcooling operation, an outlet valve of the cold compressors (OV) keeps fully open. A bypass valve (BV) is slightly opened because of both adjustment of the pressure ratio of the cold compressors and preparation for emergency situation. The liquid helium level in the bath is automatically controlled to be 70 % by an inlet valve of the bath (IV). The set value of the rotational speed of the cold compressors is 95 %, corresponding to the rated rotational speed of approximately 90,000 rpm. The helium mass flow rate of cold compressors is automatically controlled to be 16 g/s by the heater in the saturated helium bath in order to operate the cold compressors at the rated operating point [13, 14].

Figure 3 shows the bath temperature and the inlet temperature of the coils with the mass flow rate of the cold compressors. The main heat load of the bath consists of the heat from the heat exchanger, the radiation heat and the heat input from the heater. The total heat load is kept constant because the evaporation rate of saturated helium in the bath is kept to be 16 g/s by the heater. That is the reason why the bath becomes stabilized thermally and the bath temperature is regulated within range of 0.02 K (peak-to-peak).

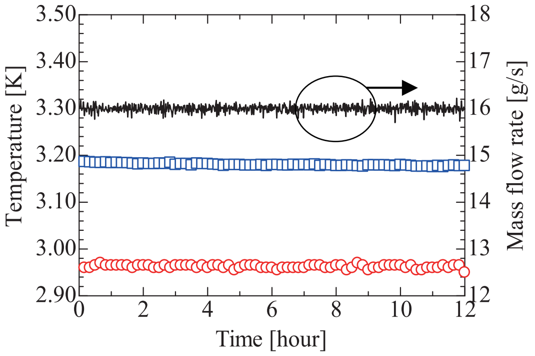

Fig. 3 Helium mass flow rate of the cold compressors (solid line) and temperature stabilized with the automatic flow control of the cold compressors by the heater in the bath. Open circles show the temperature of the saturated helium in the bath and open squares that of the supplied helium at the inlet of the helical coils, respectively.

3. Thermal Hydraulic Behavior of Helium Subcooling System after Quick Discharge

3.1 Temperature and pressure

Figure 4 shows time variations of both the temperature and the pressure at the inlet and the outlet of the cold compressors with the pressure of the header above the helical coils after the quick discharge of the LHD superconducting magnet system. Here, the quick discharge is a discharge for quench protection in emergency situations and the time constant is 30 seconds. While a solid line and a dashed line show the inlet and the outlet pressure of the cold compressors, open circles and open squares the inlet and the outlet temperature of those, respectively. Pluses also display the pressure of the helical coil header.

The inlet temperature and the inlet pressure changed scarcely, after the temperature and the pressure in the cases of the helical coils increased due to the heat load generated by the AC loss of the helical coils. On the other hand, the outlet temperature and the outlet pressure increased up to 7.8 K and 135 kPa with the buildup of the back pressure due to the increase of the pressure of the helical coil header up to 140 kPa, which was a little higher than the set pressure of recovery valves. That is because the outlet of the cold compressors was connected to the outlet of the helical coils at the return line of the cold helium gas. Here, the subcooled helium of the coolant for the helical coils worked as a thermal buffer and moderated the pressure increase at the helical coil header, because the generated heat in the helical coils was consumed as sensible heat as well as latent heat. Consequently, the pressure ratio of the cold compressors increased by approximately 17 % but the tran-

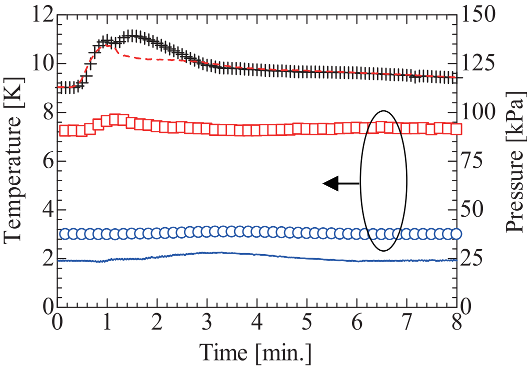

Fig. 4 Temperature and pressure variations at the inlet and the outlet of the cold compressors with the pressure of the helical coil header (+) after the quick discharge. A solid line shows the inlet pressure of the cold compressors, a dashed line the outlet pressure, open circles the inlet temperature and open squares the outlet temperature, respectively.

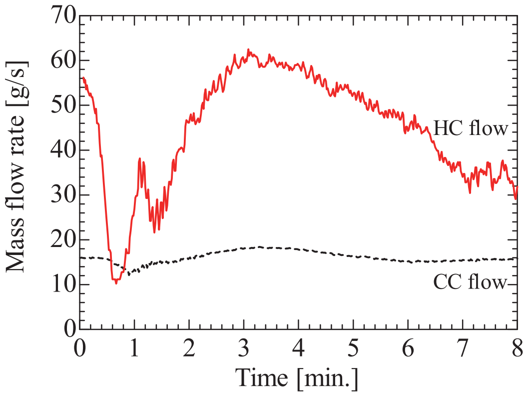

Fig. 5 Time variations of the measured mass flow rate of both the liquid helium supplied to the helical coils (solid line) and the helium gas through the cold compressors (dashed line) after the quick discharge.

sient increment was acceptable for our helium subcooling system.

3.2 Mass flow rate

Figure 5 shows time variations of the measured mass flow rate of both the subcooled helium supplied to the helical coils and the helium gas through the cold compressors after the quick discharge. A solid line shows the measured mass flow rate of the liquid helium supplied to the helical coils and a dashed line that of the helium gas through the cold compressors, respectively. The measured mass flow rate of the supplied helium decreased to approximately 10 g/s drastically, because the pressure in the helical coil cases increased and the flow was stagnated. As the result, the measured mass flow rate of the cold compressors decreased a little later to approximately 12 g/s, because the evaporation rate of the saturated helium by the heat exchange with the supplied helium was significantly reduced.

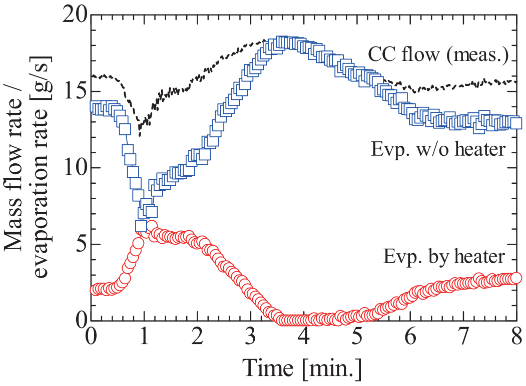

Fig. 6 Measured mass flow rate of the cold compressors (dashed line) and calculated evaporation rate by the heater in the saturated helium bath (open circles) with the difference between the measured mass flow rate and the calculated evaporation rate (open squares).

Here, the measured mass flow rate of the cold compressors includes the evaporation rate of the saturated helium not only by the heat exchange with the supplied helium to the helical coils but also by the heater in the saturated helium bath, because the automatic helium flow control of the cold compressors by the heater was working during the quick discharge. The evaporation rate of the saturated helium calculated from the heater power in the bath is shown with the difference between the measured mass flow rate of the cold compressors and the evaporation rate by the heater in Fig. 6. Dashed line is the measured mass flow rate of the cold compressors. Open circles are also the calculated evaporation rate by the heater. The difference between the both is expressed as open squares.

It was found that the minimum mass flow rate of the cold compressors without the automatic helium flow control was estimated to be approximately 6 g/s. The estimated mass flow rate of the cold compressors was considerably smaller than the allowable limit of our helium subcooling system, which is about 10 g/s from previous performance tests. At that time, the evaporation of the saturated helium of 6 g/s was added to the deficient mass flow rate of the cold compressors thanks to the automatic helium flow control by the heater. Therefore, the helium mass flow rate necessary for the stable operation was maintained. It was considered that is why the surge of the cold compressors was able to be avoided. Consequently, it was found that the automatic helium flow control of the cold compressors by the heater, which was adopted in the steady state subcooling operation, was useful in the mitigation of the large disturbance such as the dynamic variation of the pressure and the mass flow rate in the helium subcooling system for the LHD helical coils.

4. Conclusion

During ten plasma experimental campaigns after the installation of the subcooling system, ten long-term operations were carried out successfully and subcooled helium of nominal temperature and mass flow rate has been supplied to the LHD helical coils stably thanks to optimized subcooling operation and various appropriate maintenance. The running time of the cold compressors exceeds 30,000 hours and the total time of subcooling operations exceeds 20,000 hours. The automatic flow control of helium gas through the cold compressors by the heater in the saturated helium bath was applied in order to improve the stability and the reliability of the helium subcooling system. The bath temperature has been stabilized excellently within range of 0.02 K due to the automatic flow control by the heater. Furthermore, the drastic reduction of the mass flow rate of the cold compressors was mitigated by the automatic flow control and the cold compressors could be protected from surge.

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