Design and commissioning of the exhaust detritiation system for the Large Helical Device

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The Large Helical Device (LHD) is the largest helical fusion test device with superconducting magnets. During deuterium plasma experiments using the LHD, tritium and neutrons are produced by the deuterium-deuterium reaction. Thus, an exhaust detritiation system (EDS) using conventional oxidation–adsorption tritium removal was designed and installed to ensure safe tritium handling and public acceptance. The EDS consisted of a vacuum exhaust gas processing system for deuterium plasma experiments and a maintenance purge gas processing system for LHD maintenance. The vacuum exhaust gas processing system used molecular sieves as the dryer unit, whereas the maintenance purge gas processing system used a polymer permeable membrane. The key technique for receiving the complex exhaust gas stream from the LHD was feedback control of the pressure in the piping line to keep the process flow constant. To validate the recovery performance and feedback control system for the EDS prior to using deuterium gas, we used hydrogen gas to simulate tritium gas and actual exhaust gas stream from the LHD. The specified hydrogen recovery rate of more than 95% was satisfied and the actual complex exhaust gas stream was received by the

proposed feedback control system in the EDS.

Keywords; Large Helical Device; Deuterium plasma experiment; Exhaust detritiation system; Molecular sieves; Polymer permeable membrane

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1. Introduction

As part of the nuclear fusion research program at the National Institute for Fusion Science (NIFS) in Japan, deuterium plasma experiments will be conducted to investigate high-temperature plasma physics and the hydrogen isotope effect. In the deuterium plasma experiments, tritium and neutrons will be produced by the deuterium–deuterium reaction. The NIFS has a deuterium plasma experiment schedule using the Large Helical Device (LHD), which is the largest helical fusion test device with superconducting magnets [1]. Although the production rate of tritium in the LHD will be low, tritium is a radioactive material. Thus, careful tritium handling is required to reduce tritium release into the environment in order to ensure public acceptance and conform to regulatory limits on environmental release. The oxidation–adsorption process is an atmospheric detritiation technique that combines an oxidation unit for converting all tritium species to HTO and a dryer unit for HTO adsorption [2]. This candidate system has been tested and used as an atmospheric detritiation system, a glove box gas purification system, an exhaust detritiation system (EDS), and an air clean-up system in tritium handling facilities worldwide and at the Joint European Torus (JET) and Tokamak Fusion Test Reactor (TFTR) fusion test facilities, which have performed deuterium–tritium plasma experiments [2-11]. The EDS in the JET facility consists of a two-stage catalytic recombiner for converting tritium and its compounds to tritiated water vapor, and three molecular sieve driers to recover the tritiated water vapor [3, 4]. The system provides a constant air stream to the JET torus vacuum vessel and tritium handling system openings for ventilation during maintenance and detritiates the exhaust gases during an accident [7].

At NIFS, tritium is generated in the LHD vacuum vessel during deuterium plasma experiments and released from the vacuum pumping system; thus, the EDS is installed downstream of the pumping system. The vacuum exhaust gas during plasma experiments has high hydrogen isotope concentrations, is oxygen free, is dry with a dew point of less than -20 °C, and can have a flow rate of several normal cubic meters per hour to more than 10 Nm^3/h during the cryosorption pump regeneration in neutral beam injection (NBI) [12]. Therefore, the EDS for the LHD must be designed to handle various gas stream conditions with a safety processing system for hydrogen oxidation. After plasma experiments, the experimental facilities are inspected, and maintenance and improvements for new research are carried out. During these operations, people enter the vacuum vessels, which retain tritium in the walls. To prevent oxygen deficiency and reduce the internal radiation exposure from tritium, the working environment is purged with air at a flow rate of 300 Nm^3/h. The air that is released from the vacuum vessel contains a small amount of tritium and must be treated by the EDS to reduce the tritium release from the stack.

The EDS is a key device for conducting deuterium plasma experiments with the LHD because the EDS ensures safe tritium management and public acceptance. In this paper, we describe the design of an EDS based on the gas stream from the LHD vacuum exhaust system,

the construction procedure and commissioning test results using hydrogen gas, and the complex exhaust gas stream from the LHD and NBIs.

2. Design of EDS

2.1. LHD vacuum pumping system and requirements specification in the EDS

A schematic of the LHD vacuum pumping system and the exhaust gas line is shown in Fig. 1. The LHD is equipped with various components of the plasma heating system, such as NBI and electron cyclotron resonance heating, an ice hydrogen pellet injection system, a gas puff system, and plasma diagnostics. These components are installed with various independent vacuum pumping systems that are operated continuously or when needed. The main vacuum pump system is the cryosorption pumps for the LHD closed helical divertor and the LHD/NBI vacuum vessels [13-16]. Because these cryosorption pumps are regenerated at certain intervals, the EDS must handle a variable gas flow.

The EDS specifications for LHD are summarized in Table 1. The EDS must treat gas flows from several normal cubic meters per hour containing a high concentration of hydrogen isotope gas to 300 Nm^3/h with no hydrogen isotope gas, depending on the LHD operation mode. Thus, to receive the complex exhaust gas stream (Fig. 1), the EDS requires a vacuum exhaust gas processing (MS) system and a maintenance purge gas processing (PM) system for ventilating the vacuum vessel and other related facilities. The MS system is only operated during the plasma experiments. The operating time is estimated to be about 4000 h. The maximum process gas flow rate is 20 Nm^3/h because dry air is added to dilute hydrogen gas in the exhaust gas and to add oxygen to oxidize hydrogen. However, the PM system operates all year, because the related facilities, which are the greenhouse for maintaining contaminated apparatus and the analytical apparatus for researching plasma-facing materials in the maintenance room, are operated continuously. The flow rate of 300 Nm^3/h is determined from the viewpoints of working environment. The number of workers in the LHD vacuum vessel, the maintenance room and greenhouse during the maintenance period is estimated to be about 24. The amount of ventilation per one person considering the CO_2 concentration is calculated to be 12.5 Nm^3/h [17]. Thus a maximum process gas flow rate of 300 Nm^3/h is required.

The maximum amount of tritium produced by the deuterium plasma experiments in the LHD is assumed to be 55.5 GBq annually [18, 19]. The tritium gas is released from the vacuum vessel with deuterium gas as the main operation gas, and the gasses are passed through the EDS. Then, the gas treated by the EDS is released into the environment via the stack after the room air ventilation gas is diluted. Tritium concentration in the stack is monitored by the active tritium sampler, which has a detection limit of less than 10^{-8} Bq/cm^3 [20], and the real time tritium monitor using an ionization chamber. The annual amount of tritium release from the stack must be less than 3.7 GBq under the agreement with local governments. Thus, the detritiation factor of the EDS must be more than 20, corresponding to a tritium recovery rate of more than 95%.

2.2. Process gas flow control method

The process gas flow control method is essential to maintaining the process conditions and the tritium removal performance in EDS. Observations of the exhaust gas stream from the LHD during an 18-cycle plasma experiment [12] showed that the exhaust gas flow rate varied with the operation modes, which are rough pumping in the LHD and NBI vacuum vessel, regenerating the cryosorption pumps, hydrogen or helium glow discharge cleaning, and injecting ice pellets into the plasma, and the exhaust operation during plasma experiments. Thus, in the EDS, various kinds of control method are used to treat complex exhaust gas. The control methods used in the EDS are shown in Fig. 2. The basic principle is controlling the pressure gradient in the pipeline by providing the negative pressure in the EDS. The pressure gradient from the outlet of the LHD vacuum pumping system to the receiving buffer tank in the EDS is created by the pressure control units, such as the blower and scroll pump, the air supply, and the process gas circulation (Figs. 2(a)–(c)).

The flow rate and hydrogen concentration of the regeneration gas from the cryosorption pump of the NBIs is too high to treat during operation. The maximum volume of regeneration gas is estimated to be 42.5 Nm^3 for several hours' operation [12]. Thus, the process gas must be stored temporarily under pressure in a buffer tank, and then the gas is supplied to the main process line for tritium removal (Fig. 2(d)). This method eliminates the flow rate and hydrogen concentration of the regeneration gas. To store the process gas by applying pressure, a circulation loop equipped with a compressor, pressure control valve, and receiving buffer tank is used. Before the regeneration gas is supplied to the EDS, the compressor is started and the process gas is circulated in the loop at a constant flow rate. When the regeneration gas flow increases and the process gas is introduced to the receiving buffer tank, the pressure in the receiving buffer tank increases, and then the downstream control valve is opened to maintain the pressure in the receiving buffer tank. After regeneration, the storage gas in the buffer tank is introduced to the main process line. The hydrogen concertation in the storage buffer tank is increased by repeating the storage operation. Thus, the flow rate of the supply gas from the storage buffer tank is controlled by the regulating valve to keep the hydrogen concentration in the main process line below 1%.

2.3. MS system

The process flow diagram for the vacuum exhaust gas processing system is shown in Fig. 3. It consists of the buffer tank for receiving exhaust gas, two catalytic reactors for oxidizing hydrogen and hydrocarbons, two water adsorption towers packed with molecular sieves, the gas storage system, and the molecular sieve regeneration system. The operation modes are the main process mode, gas storage mode, regeneration mode, and emergency mode. The inlet of MS system is connected to the inlet of PM system as shown in Fig. 1. When the malfunction appears in MS system, the process line of MS system is switched to PM system.

2.3.1. Main process mode

The main process mode is the once-through mode at less than 10 Nm^3/h. The process flow is controlled by the pressure in the buffer tank, air supply, and a scroll pump (Fig. 2(b)). The scroll pump is one of the components of the exhaust fan system. The controlled pressure in the buffer tank is set to -2 kPa(G).

Because the vacuum exhaust gas from the LHD is oxygen free, dehydrated compressed air is supplied to the main process to add oxygen gas after the buffer tank. The main process flow rate after adding dry air is kept at 20 Nm^3/h. The process fluid is designed to be air containing hydrogen (0–1%) and tracer hydrocarbons. The tracer hydrocarbons are produced by the plasma surface interaction such as chemical sputtering because the divertor tile of LHD is made of carbon. The hydrogen and hydrocarbons are oxidized to water vapor by two catalytic reactors. The first reactor oxidizes hydrogen gas and is packed with a platinum catalyst (DASH-520, N.E. CHEMCAT Corporation; grain size, ϕ2–4 mm). The reactor is a column with a diameter of 200 mm and a height of 400 mm. The packing volume of the catalyst is designed to be 13 L with design margin and the catalyst weight is 10 kg, according to basic data and the volume estimation of catalytic reactor by Uda, et al. [21]. The temperature of the reactor is normally kept at 200 °C. The pressure drop in the reactor column is designed to be 1 kPa at 200 °C. The hydrogen conversion rate is designed to be more than 99% in the process flow diagram. The second reactor oxidizes the hydrocarbons. The reactor is packed with a palladium catalyst (DASH-520D, N.E. CHEMCAT Corporation; grain size, ϕ2–4 mm). The palladium catalyst is superior to the platinum catalyst for hydrocarbon oxidation. The shape of the reactor and the volume of the catalyst are designed to be the same as the first reactor, according to the results of Uda et al. [21]. The temperature of reactor is controlled at 450 °C. The pressure drop in the reactor column is designed to be 1.5 kPa at 450 °C. The hot gas is cooled to below 20 °C by a heat exchanger, and then supplied to the adsorption tower.

After the hydrogen and hydrocarbons are passed through the reactor, the resulting water vapor is recovered by the adsorption tower. The adsorption tower is packed with molecular sieves (Union Showa K.K.; 5 Å, 1/16 in.). The recovered water weight is estimated to be about 21 kg per week according to the observation results [12]. When the water absorption capacity of molecular sieves at 25ºC is 0.12 kg/kg, the weight of molecular sieves is required more than 175 kg. Thus the packing volume of molecular sieves is 650 L and the weight of molecular sieves is designed to be 416 kg considering the design margin. The tower is a column 800 mm in diameter and 1300 mm in height. The tower is normally operated at room temperature. The pressure drop in the tower is designed to be 0.3 kPa at 20 °C. The adsorption tower consists of two columns, one in operational mode and the other in standby mode. Before the adsorption capacity is exceeded, the operational tower is switched to allow continuous operation and regenerate the molecular sieves. The regeneration temperature of the molecular sieves is 350 °C. The pressure drop is estimated to be 1.5 kPa at 350 °C. The water recovery rate is designed to be more than 99.5% in the process flow diagram. Thus the

total recovery rate is designed to be more than 98.5%.

2.3.2. Gas storage mode for cryosorption pump regeneration

The cryosorption pumps for the NBIs are regenerated once a week. The maximum flow rate exceeds 10 Nm^3/h and the hydrogen concentration is above 50%. The higher flow rate and hydrogen concentration cannot be handled by the main process mode. Thus, the main process mode is switched to the gas storage mode, and the exhaust gas is stored temporarily in the buffer tank. The flow rate during regeneration changes greatly depending on the temperature of the cryosorption panel. To receive a large and varying flow rate, the circulation system and pressure control are used (Fig. 2(d)). Because the regeneration gas for the cryosorption pump contains high concentrations of hydrogen and tritium, the compressor must be leak-proof. Therefore, we use an oil-free two-stage metal diaphragm compressor (PDC-4-50-100, PDC Machines Inc.). The maximum flow rate is designed to be 40 Nm^3/h according to the observation results [12]. The maximum compression pressure is required to be 0.67 MPa(G). When the pressure in buffer tank 3 is in the range of 0.1 to 0.67 MPa(G), the volume of buffer tank 3, which consists of two tanks, must be 14 m^3 to store the maximum gas volume of 42.5 Nm^3 within the operation pressure

After regeneration gas storage, the storage gas in buffer tank 3 is supplied to the main process line at a flow rate. Because the final hydrogen concentration in buffer tank 3 is estimated to be more than 40%, the supply flow rate is regulated so that the hydrogen concentration is less than 0.8% before the first oxidation reactor. These process operations can mitigate the heat of combustion from hydrogen oxidation during the cryosorption pump regeneration.

2.3.3. Regeneration mode for molecular sieves

Because the molecular sieves have a limited water adsorption capacity, they must be regenerated by desorbing water at regular intervals. The regeneration interval is designed to be once a week. The desorbed water contains tritium, and thus the regeneration system must have a leak-proof closed loop. The circulation pump has a seal-less oil-free magnetic coupling roots blower (FLB-NO.2 [PZ1YL140], Yotsuba Air Machine Manufacturing Co., Ltd.). The circulation flow rate is designed to be 90 Nm^3/h when the molecular sieves are regenerated within 3 days. The rotation rate of the blower is controlled by the variable voltage variable frequency (VVVF) inverter system to maintain a constant flow rate. The molecular sieves are heated to 350 °C for 6 h to desorb the tritiated water. The desorbed tritiated water is condensed in the heat exchanger at below 10 °C and recovered to the waste water tank. Then, the molecular sieves are cooled to room temperature over 2 days. The recovered tritiated water is delivered to the Japan Radioisotope Association at regular intervals.

During regeneration, the inline pressure increases and decreases according to the temperature. To keep the pressure between -10 and 10 kPa(G), circulation process gas is supplied to the main process line when the pressure reaches 10 kPa(G) and dry air is supplied

to the circulation line when the pressure is less than -10 kPa(G). The regeneration mode operates in parallel with the main process mode.

2.3.4. Emergency mode

The hydrogen recovery rate is continuously monitored by a hydrogen sensor and dew point hygrometer at the inlet and outlet of the MS system. When the recovery rate drops below 95%, the MS system may not be operating normally, and the operation mode is switched to the emergency mode to prevent tritium release from the stack. The operation of LHD and all of vacuum pumping system is stopped immediately via an interlock system. Then, the operation gas is stored in the LHD vacuum vessel.

In the emergency mode, the scroll pump in MS system is started, the valves of the MS system inlet and air supply are closed, and the scroll pump in the exhaust fan system is stopped. Then, the process gas is circulated in the MS system until the recovery rate is above 95%.

2.4. PM system

The process flow required for the PM system is 300 Nm^3/h, which is 15 times higher than that for the MS system. A large amount of molecular sieves would be necessary to treat the large gas flow using the conventional method. A system of this size would not fit the space available and the initial and running costs of the molecular sieves would be enormous. Thus, a polymer permeable membrane was proposed [22-26], which has the advantages of allowing continuous separation and being compact, low cost, and maintenance free.

The process flow diagram for the PM system is shown in Fig. 4. The system consists of the buffer tank for receiving the purge gas, a catalyst reactor for oxidizing hydrogen, a blower, an oil-free screw compressor, a dryer as an aftercooler, polymer membrane modules, and the adsorption tower packed with molecular sieves for the roughing pump exhaust gas. The operation modes are the main process mode, and temporary process mode for roughing pumping.

2.4.1. Main process mode

The main process mode in the PM system is the once-through mode at 300 Nm^3/h. The process flow is controlled by the pressure in the buffer tank, circulating current, and a blower (Fig. 2(c)). The controlled pressure in the buffer tank is set to -5 kPa(G). A magnetic coupling high-pressure seal-less vortex blower (U2V-1100-01, Showa Denki Co., Ltd.) is used. The normal flow rate is designed to be 300 Nm^3/h. The rotation rate of the blower is controlled by a VVVF inverter system to maintain a constant flow rate or pressure in buffer tank 1.

Although the maintenance purge gas is wet air without hydrogen gas, an oxidation reactor packed with a platinum catalyst (DASH-520, N.E. CHEMCAT Corporation; grain size, ϕ2–4 mm) oxidizes trace hydrogen gas. The reactor is a column 700 mm in diameter and 400

mm in height. According to basic data and the volume estimation of catalytic reactor by Uda, et al. [21], the packing volume of the catalyst is designed to be 154 L and the catalyst weight is 119 kg. The temperature of the reactor is normally kept at 200 °C. The hydrogen conversion rate is designed to be more than 99% in the process flow diagram. The pressure drop in the reactor column is designed to be 1.5 kPa at 200 °C. After passing through the reactor, the hot gas is cooled to below 20 °C by a heat exchanger. Some of the moisture in the process gas is condensed by a heat exchanger and recovered as tritiated water.

Most of the moisture in the process gas is recovered by the polymer permeable membrane system. The driving force for the gas separation membrane is the differential pressure between the feed side and the permeate side of the polymer membrane. Thus, a compression system consisting of an oil-free two-stage screw compressor (ZR75VSD-10.4, Atlas Copco) and aftercooler is necessary to drive gas permeation. The flow rate at the compressor inlet is designed to be constant at 400 Nm^3/h because the permeate side of membrane modules is purged with some of the dry product gas to increase the differential partial pressure of the moisture. The purge flow rate is designed to be 100 Nm^3/h, corresponding to a ratio of feed gas flow rate to purge gas flow rate of 0.25. Moisture in the process gas is separated by the membrane module and returned with the purge gas at the compressor inlet. The moisture is condensed by the aftercooler and recovered as tritiated water. The water recovery rate is designed to be more than 99.8% in the process flow diagram. Thus the total recovery rate is designed to be more than 98.8%.

The compressor system is not airtight and the compressed process gas leaks through the gap between the rotor shaft and the seal. To prevent the leakage of process gas containing tritium, tritium blocking gas is supplied by another compressor system to the rotor shaft (Figs. 4 and 5). The blocking gas passes through the gap and is mixed with the leakage air containing tritium. The gas mixture is released from the rotor shaft and returned to the compressor inlet, ensuring a tritium leak-proof compression system.

2.4.2. Temporary process mode for the vacuum vessel roughing pump

Before beginning plasma experiments in the LHD, the vacuum vessel must be evacuated from atmospheric pressure to ultra-high vacuum conditions. The exhaust gas flow rate is huge at the start of evacuation and decreases with the decrease in vacuum pressure [12]. To follow the change in the exhaust gas flow, the rotational frequency of the blower is controlled by the pressure in the buffer tank (Fig. 2(a)). The polymer permeable membrane system cannot function when the flow rate changes quickly. Thus, the adsorption tower is used to recover moisture to bypass the membrane system. The specifications for the adsorption tower are the same as that of the MS system and the MS regeneration system is shared.

3. Procedure for installing and constructing the EDS

The outline of the procedure for installing and constructing the EDS is shown in Fig. 6.

First, the EDS process flow diagram (see Section 2) was created according to the specifications and the exhaust gas observation results. Then, the piping and instrumentation diagram was designed based on the process flow diagram.

The EDS installation space was limited; thus, the construction was planned considering the layout of towers, tanks, and machines. Before installation, 3D field measurements of the EDS room were carried out to provide a 3D plan of the EDS. The layout of the components also considered ease of maintenance. The installation positions were marked according to the plan. After marking and placing the chemical anchor bolts, the larger tanks were installed first. Next, the frame for the components, medium size tanks and towers, the heater, and the heavy parts of the rotating machines were installed. Finally, the pipe and instrumentation components were installed. After wiring the electrical cables, operational checks were performed on the rotating machines. The integration tests were conducted to tune the feedback control parameters, including those for process flow and heater temperature. Finally, the commissioning test was conducted using hydrogen gas and the vacuum exhaust gas during operation to evaluate the recovery performance of the EDS. The design, construction, and commissioning tests took 18 months to complete.

4. Commissioning test results for EDS

4.1. Performance test using hydrogen gas

To validate the performance of tritium recovery, hydrogen gas was used to simulate tritium gas. In these performance tests, the hydrogen gas concentration at the inlet and the outlet of EDS were measured by a catalytic combustion sensor (D58 series, Riken Keiki Co., Ltd.; range, 0–4%) and an electrochemical sensor (Xgard, Crowcon Detection Instruments; range, 0–2000 ppm, detection limit < 1 ppm), respectively. The moisture was measured by a capacitance dew point transmitter (TE-460, Tekhne Co., Ltd.; range, -40 to +60 °C at the inlet, -60 to +20 °C at the outlet). The recovery rate of hydrogen and water vapor, R, is defined as

$$R = \left[1 - \frac{\left(C_{out}^{H_2} + C_{out}^{H_2O} \right) \times F_{out}}{\left(C_{in}^{H_2} + C_{in}^{H_2O} \right) \times F_{in}} \right], \quad (1)$$

where $C_{in}^{H_2}$ and $C_{in}^{H_2O}$ are hydrogen concentration and water vapor concentration at the inlet, $C_{out}^{H_2}$ and $C_{out}^{H_2O}$ are hydrogen concentration and water vapor concentration at the outlet, and F_{in} and F_{out} are the flow rate at the inlet and the outlet, respectively. In these performance tests, F_{in} and F_{out} were the same.

The vacuum exhaust gas from the LHD and NBIs was not received during the hydrogen performance test. For the MS system performance test, the hydrogen gas from a gas cylinder was supplied to the main process line after adding dry air. The hydrogen concentration at the inlet of the oxidation reactor was diluted from 1 to 0.2 %. The flow rate after adding dry air was kept constant at 20 Nm^3/h and the dew point was less than -40 °C.

The results of the performance test are shown in Fig. 7. Hydrogen gas was not observed at the outlet of the MS system and the concentration was under the instrument detection limit. Because the dew point at the outlet of MS system was less than -60 °C, the recovery rate of hydrogen was calculated to be more than 95% irrespective of the inlet hydrogen concentration.

Similar to the MS system performance test, the PM system test was performed using hydrogen gas. In the performance test, the room air containing moisture was introduced to the main process line. Then, hydrogen gas was added to the main process gas upstream of the oxidation reactor. The hydrogen concentration was 0.3% and the moisture content was 0.57%, corresponding to a dew point of -1 °C. The feed flow rate was kept at 300 Nm^3/h. The results of the performance test are shown in Fig. 8. Hydrogen gas was not observed at the outlet of the PM system. Because the dew point at the outlet of the PM system was less than -52 °C, the recovery rate of hydrogen was calculated to be more than 95%. These results indicate that the required decontamination factor of 20 was achieved using hydrogen gas simulated tritium gas.

4.2. Operation tests with LHD roughing pumping gas and regeneration gas from the NBI cryosorption pump

The operation tests for validating the proposed flow control method were conducted using the actual exhaust gas flow. The tests used the roughing pump gas from the LHD vacuum vessel in the PM system or the regeneration gas from the cryosorption pump for the NBIs in the MS system.

The LHD has two high-throughput vacuum pumps for the vacuum vessel roughing pumping, which produce the roughing pump exhaust gas. If two vacuum pumps are operated at the same time, the exhaust gas flow rate exceeds the capacity of the EDS. Thus, the pumps are started at different times. Figure 9 shows the operation results for the roughing pump exhaust gas. When one of the pumps started, the pressure in buffer tank 1 surged to -1.4 kPa(G), and the exhaust gas flow rate exceeded 150 Nm^3/h. The blower control signal increased sharply to 50%, and then decreased slowly under PID control to remain at -5 kPa(G). After the first pump started, the second pump started after 10 min, and the exhaust gas flow rate reached 296 Nm^3/h. The pressure in buffer tank 1 surged to –0.9 kPa(G) again, and then the blower control signal reached 82%. Because the blower control signal did not exceed 100% at peak flow rate, the flow control system in Fig 2(a) was validated under actual operation conditions. In this operation mode, the moisture in the exhaust gas was recovered by the adsorption tower packed with molecular sieves (Fig. 4). The recovery rate was more than 95%.

In the second test, the regeneration gas from the cryosorption pumps for five NBIs was received by the gas storage mode in the MS system. The operation results for the regeneration gas are shown in Fig. 10. The hydrogen concentration at the inlet of the MS system was measured by an optical interferometric sensor (FI-800, Riken Keiki Co., Ltd.;

range, 0–100%). The gas storage system was filled with nitrogen gas. Before starting the cryosorption pump regeneration, the rough pumps for NBIs were warmed up for 45 min. Following the gas storage in the MS system, the regeneration operation of the cryosorption pumps of five NBIs was started at the same time. The feed flow rate exceeded 10 Nm^3/h and the valve was opened under PID control to maintain the pressure at -5 kPa(G) in buffer tank 2. The maximum degree of valve opening was 45.6%. Under the storage operation, the pressure in buffer tank 3 increased with time. In this test, the pressure reached 0.22 MPa(G). Because the degree of valve opening was less than 100% and the pressure in buffer tank 3 was below 0.67 MPa(G), the gas storage control system (Fig. 2(d)) was validated under actual operation conditions.

The variation in hydrogen concentration is shown in Fig. 10(d). The hydrogen concentration in the regeneration gas increased to 55.5%, which could not be treated in the once-through mode by the MS system. The hydrogen gas volume and total storage gas volume were estimated to be 5.4 and 44 Nm^3, respectively. The hydrogen concentration in the buffer tank 3 was estimated to be 12%. After the storage operation, the storage gas in the buffer tanks 3 was introduced to the main process line to dilute the hydrogen gas. The hydrogen concentration in the main process line was kept below 0.8% by controlling the flow rate from buffer tank 3. When the pressure in buffer tank 3 decreased to 0.1 MPa(G), the feed gas flow from buffer tank 3 was stopped. This storage system could be used to average and treat large flow rates and high hydrogen concentrations safely.

5. Conclusion

Based on the results of the exhaust gas stream and the specifications, the EDS for LHD was designed and installed downstream of the vacuum pumping system. The EDS consists of the MS system, which comprises two types of catalyst reactor and dual adsorbent beds for the vacuum exhaust gas processing, and the PM system, which comprises an oxidation catalyst reactor and the polymer permeable membrane module separator for maintenance purge gas processing. The key component in the design of these systems is the control of pressure gradient in the pipeline to receive the complex exhaust gas stream, and then to maintain a constant pressure at the EDS inlet.

To validate the process control method and the recovery rate, we conducted commissioning tests using the vacuum exhaust gas during the actual operation and hydrogen gas was used to simulate tritium gas. The required recovery rate was achieved and the complex exhaust gas stream was received by the feedback control of the process pressure at the EDS inlet.

Acknowledgements

The authors wish to thank Mr. Z. Aoki and K. Inai, JGC CORPORATION, for their technical support in constructing and commissioning the system. We would also like to express our gratitude to our colleagues Drs. T. Saze, N. Akata, G. Motojima, K. Ikeda, H.

Nakano, T. Kobuchi, Mr. H. Sekiguchi, M. Sato, and T. Nisimura, NIFS, for their operational support.

This work was supported by the NIFS budget ULGG801 and 802, and partially by JSPS KAKENHI Grant Number 17K06998.

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Table 1. Specifications of the EDS for the LHD.

Systems	EDS	
	MS system	PM system
Process gas	Vacuum exhaust gas from LHD, NBI, and other experimental apparatus	Purge gas from LHD and NBI vacuum vessel and maintenance room
Max. process flow rate [Nm^3/h]	20	300
Gas composition in process flow	Q_2, Q_2O, C_xQ_y, He, Ne, Ar, N_2 (Q = H, D, T)	Wet air
Detritiation factor (tritium recovery rate)	>20 (>95%)	
Annual operating hours [h]	~4300 (24 h × 180 days)	~8400 (24 h × 350 days)

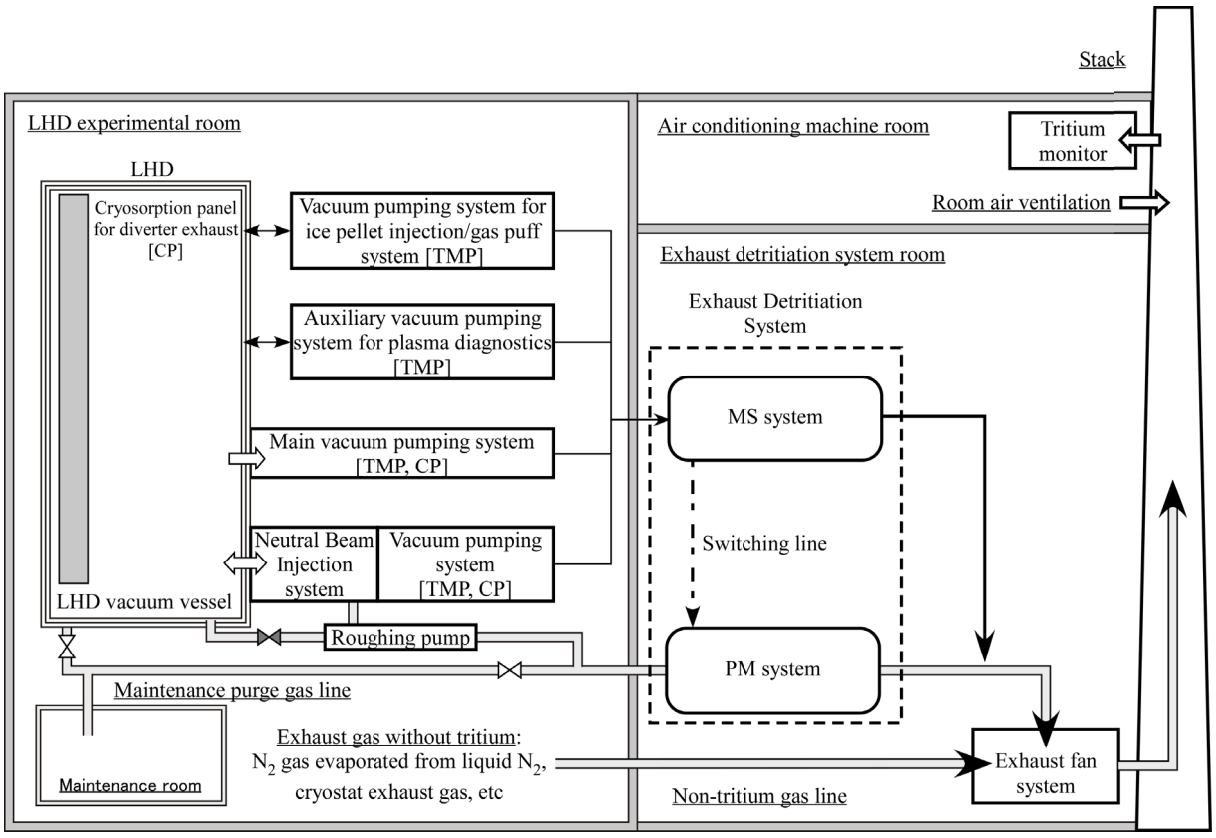

Fig. 1 Schematic of the LHD vacuum pumping system and the EDS. TMP: turbo molecular pump. CP: cryosorption pump.

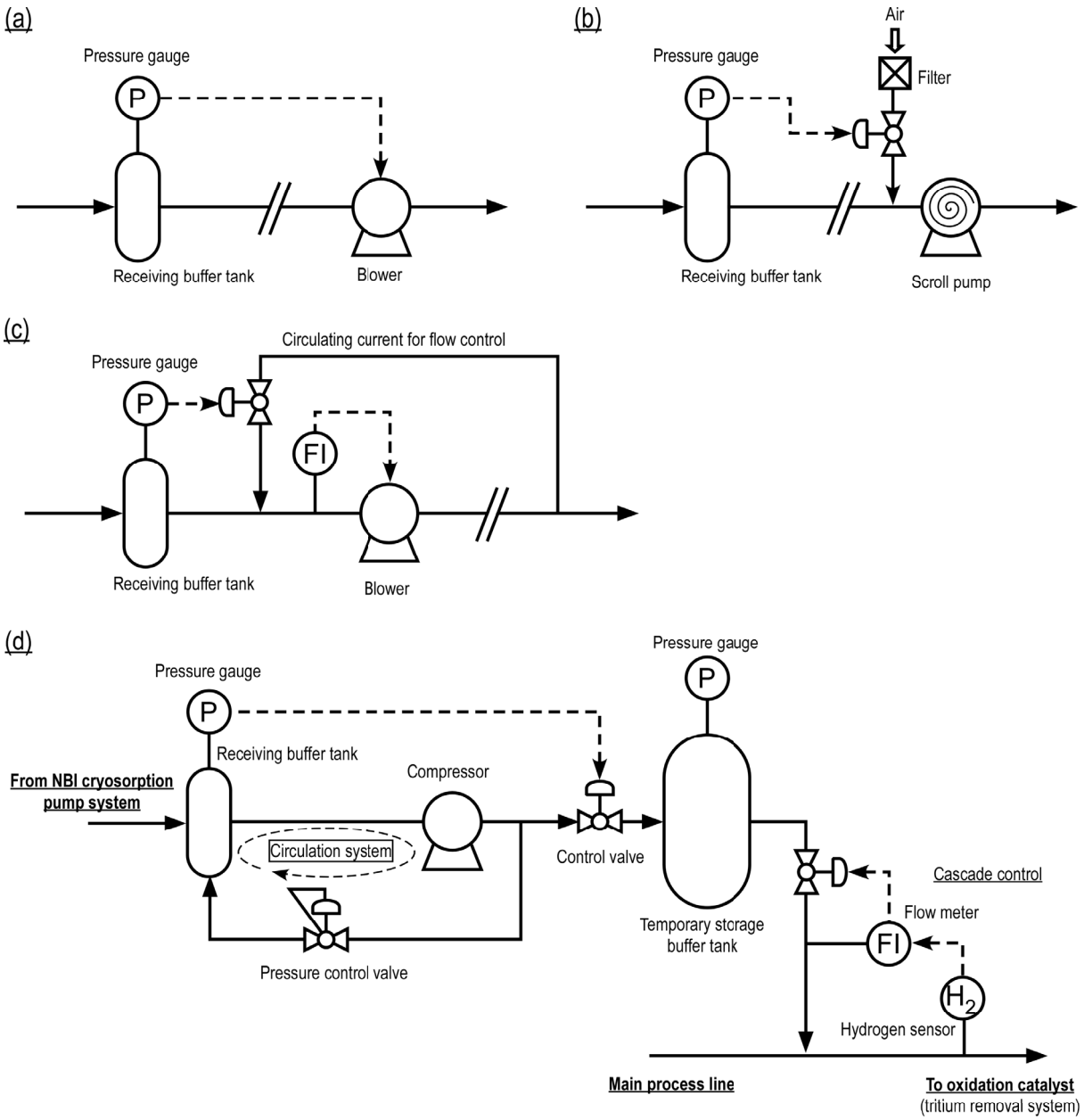

Fig. 2 Feedback control methods used in the EDS.

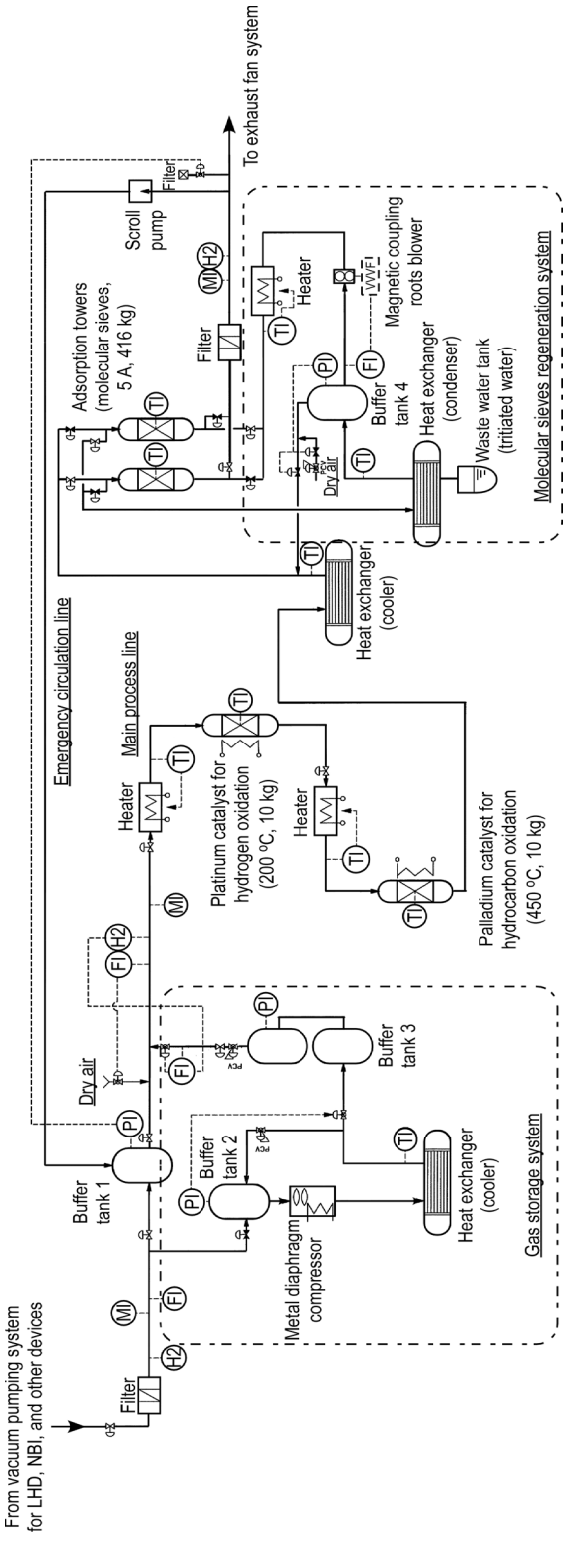

Fig. 3 Process flow diagram for the MS system. TI: temperature indicator. PI: pressure indicator. FI: flow indicator. H2: hydrogen concentration indicator. MI: moisture indicator. PCV: pressure control valve. VVVF: variable voltage variable frequency (inverter).

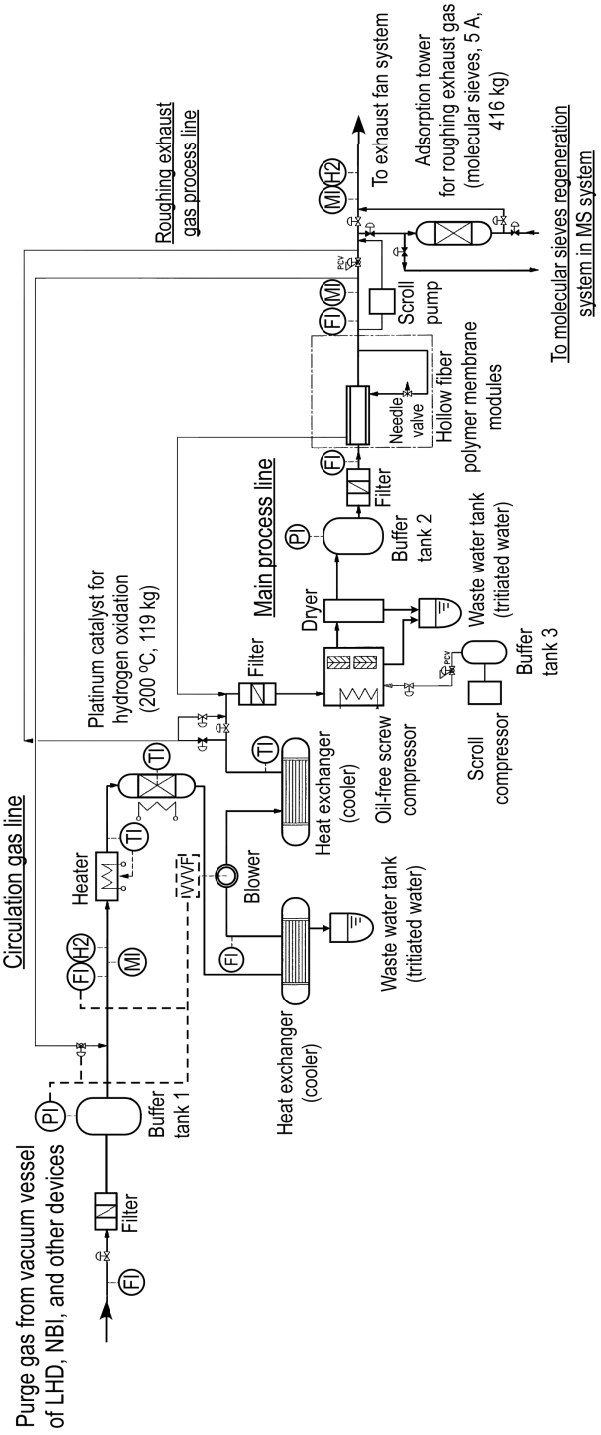

Fig. 4 Process flow diagram for the PM system. TI: temperature indicator. PI: pressure indicator. FI: flow indicator. H2: hydrogen concentration indicator. MI: moisture indicator. PCV: pressure control valve. VVVF: variable voltage variable frequency (inverter)

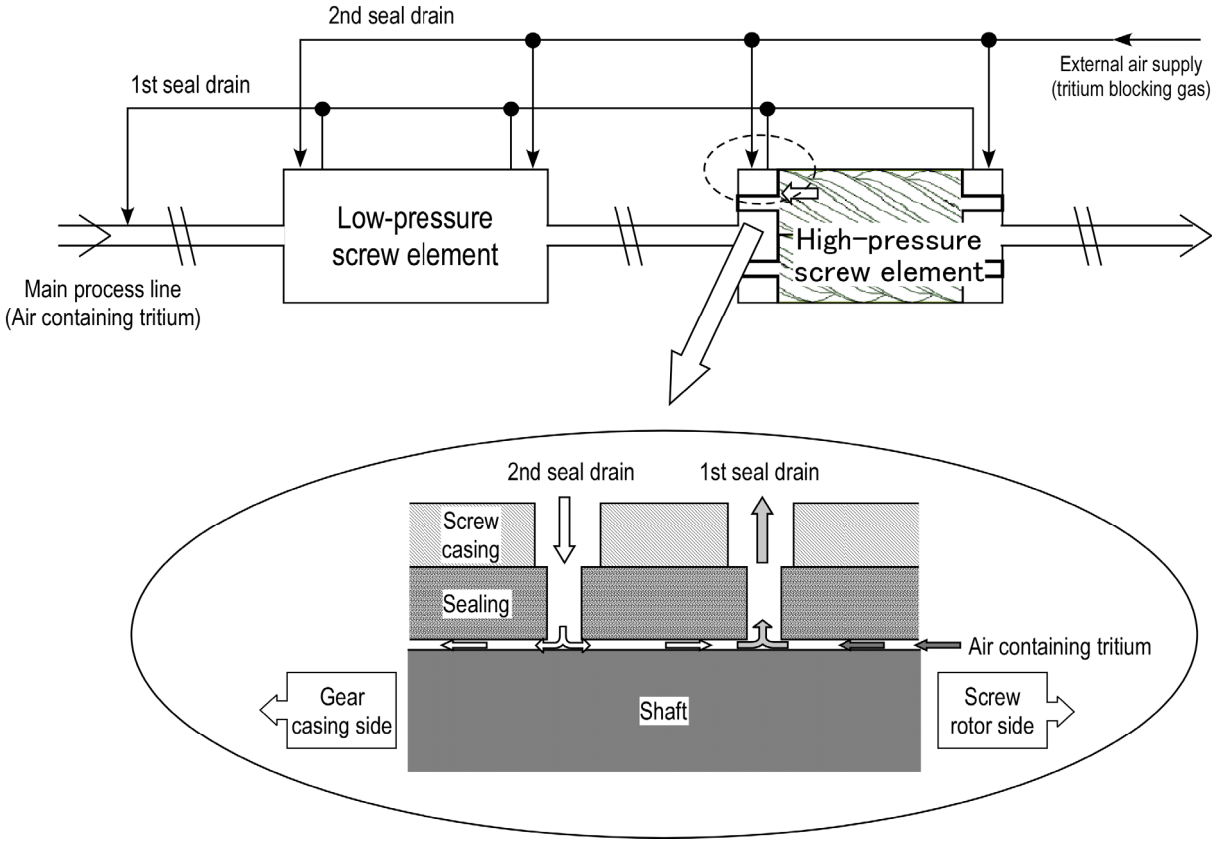

Fig. 5 Schematic of tritium blocking gas system for the screw compressor.

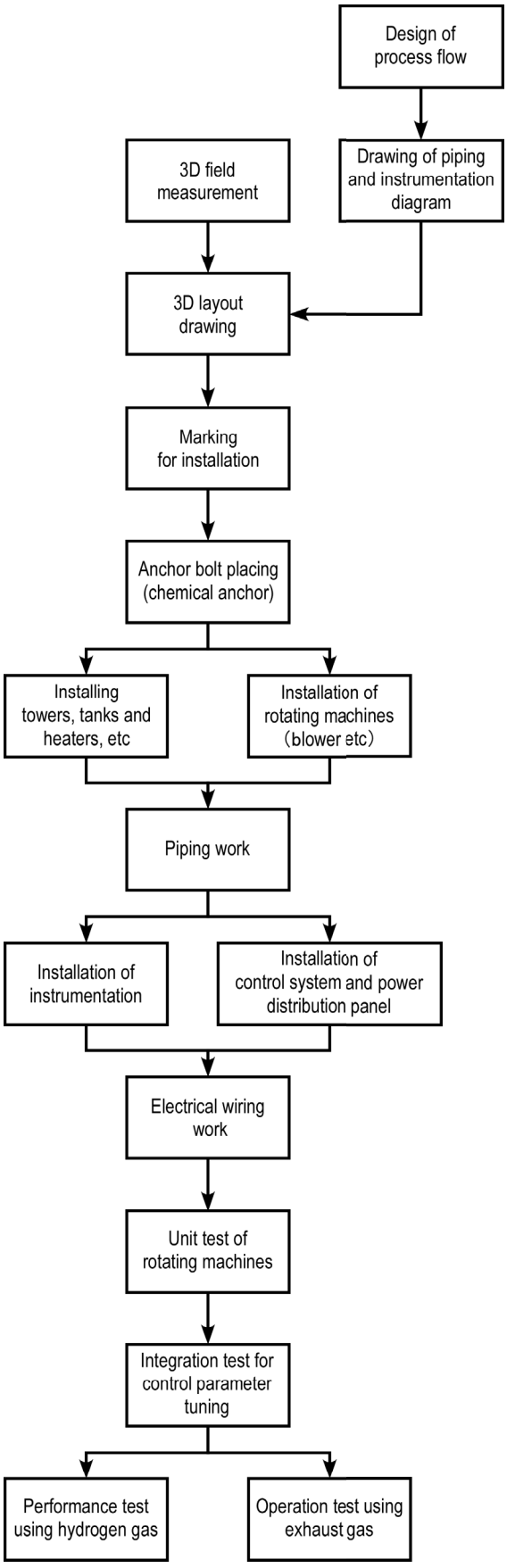

Fig. 6 Outline of the procedure for installing and constructing the EDS.

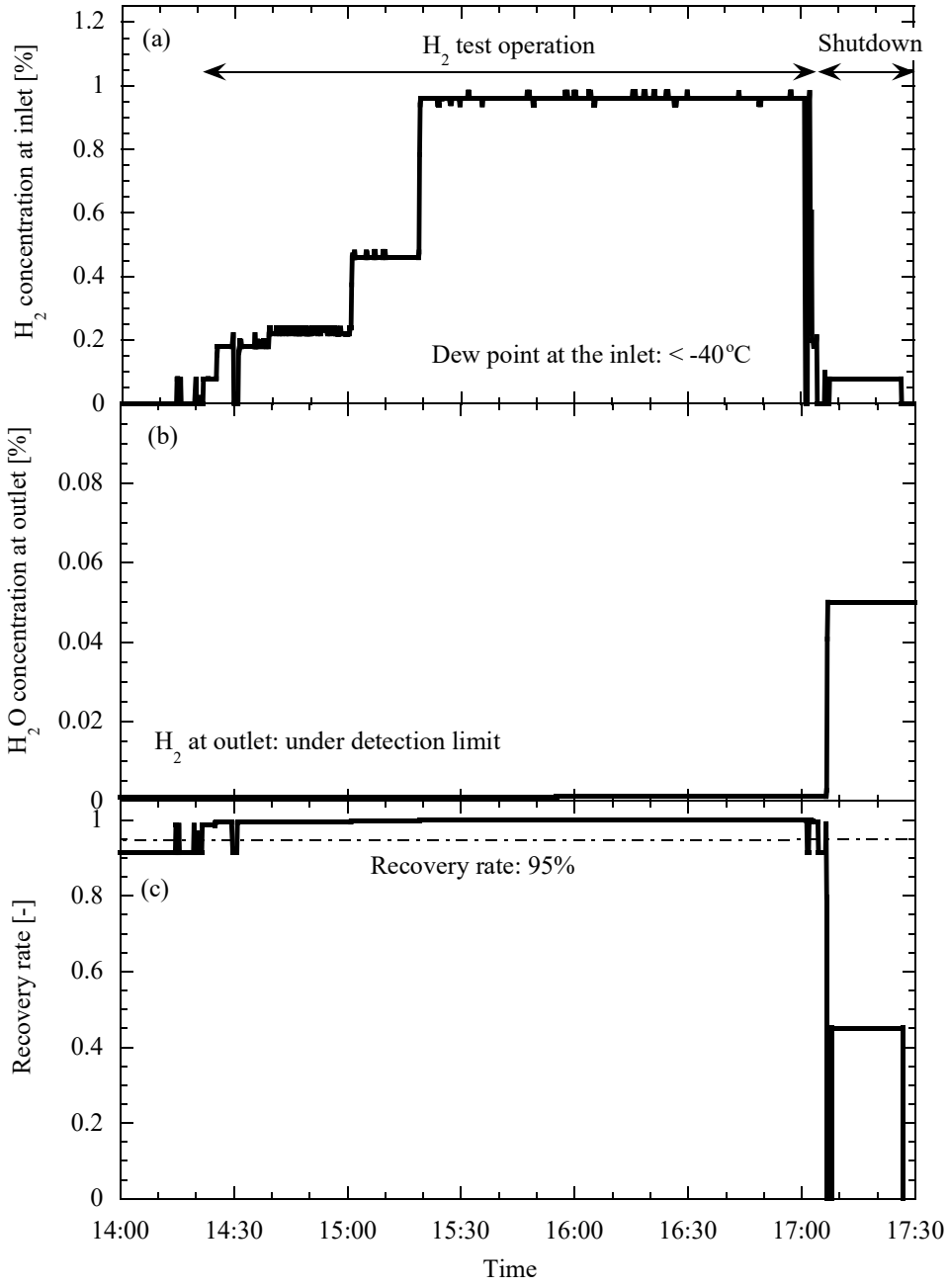

Fig. 7 Performance test results of the MS system using hydrogen gas: (a) hydrogen concentration at the inlet, (b) water vapor concentration at the outlet, and (c) hydrogen recovery rate.

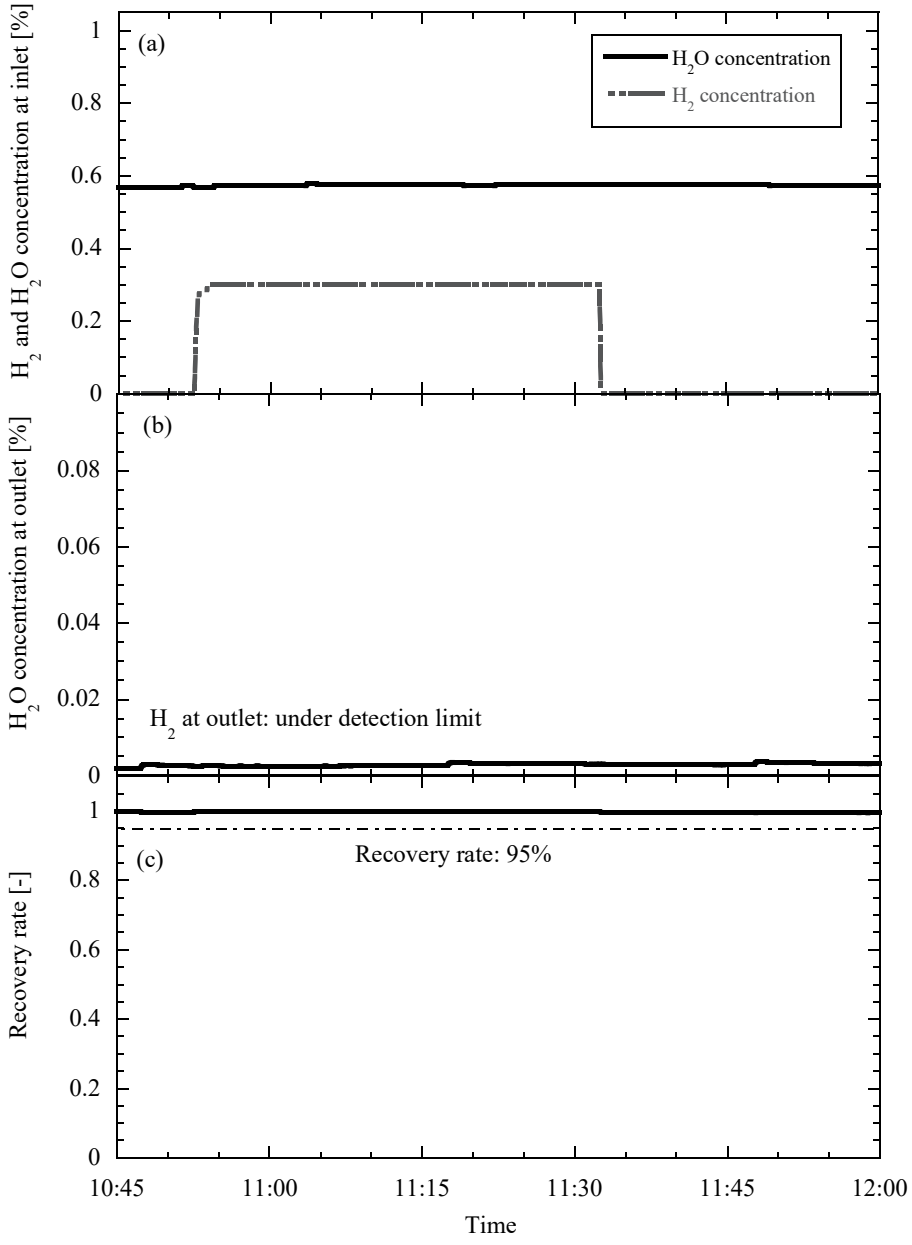

Fig. 8 Performance test results of the PM system using hydrogen gas: (a) hydrogen and water vapor concentrations at the inlet, (b) water vapor concentration at the outlet, and (c) hydrogen recovery rate.

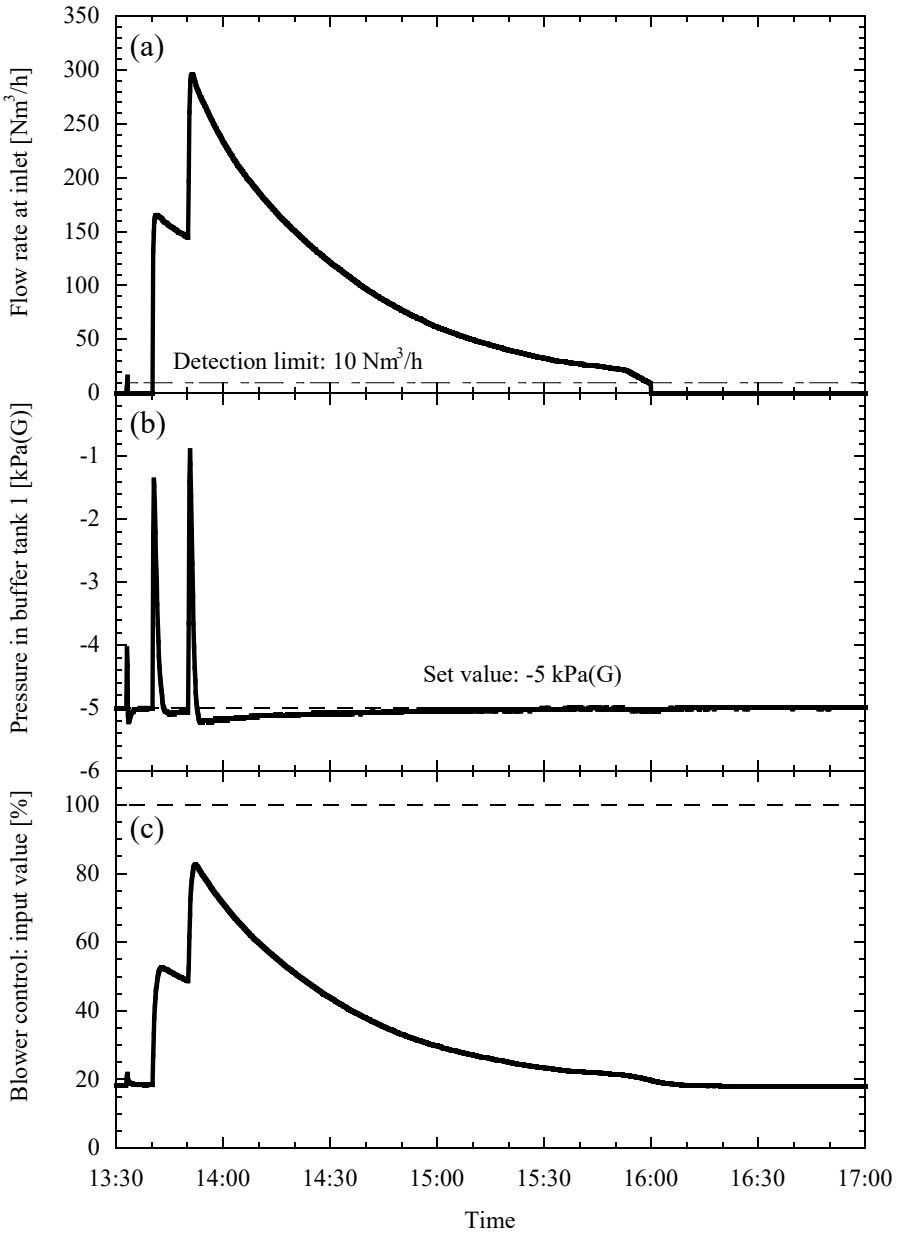

Fig. 9 Operation results of roughing pump exhaust gas from the LHD: (a) flow rate at the inlet, (b) pressure in buffer tank 1, and (c) blower control value.

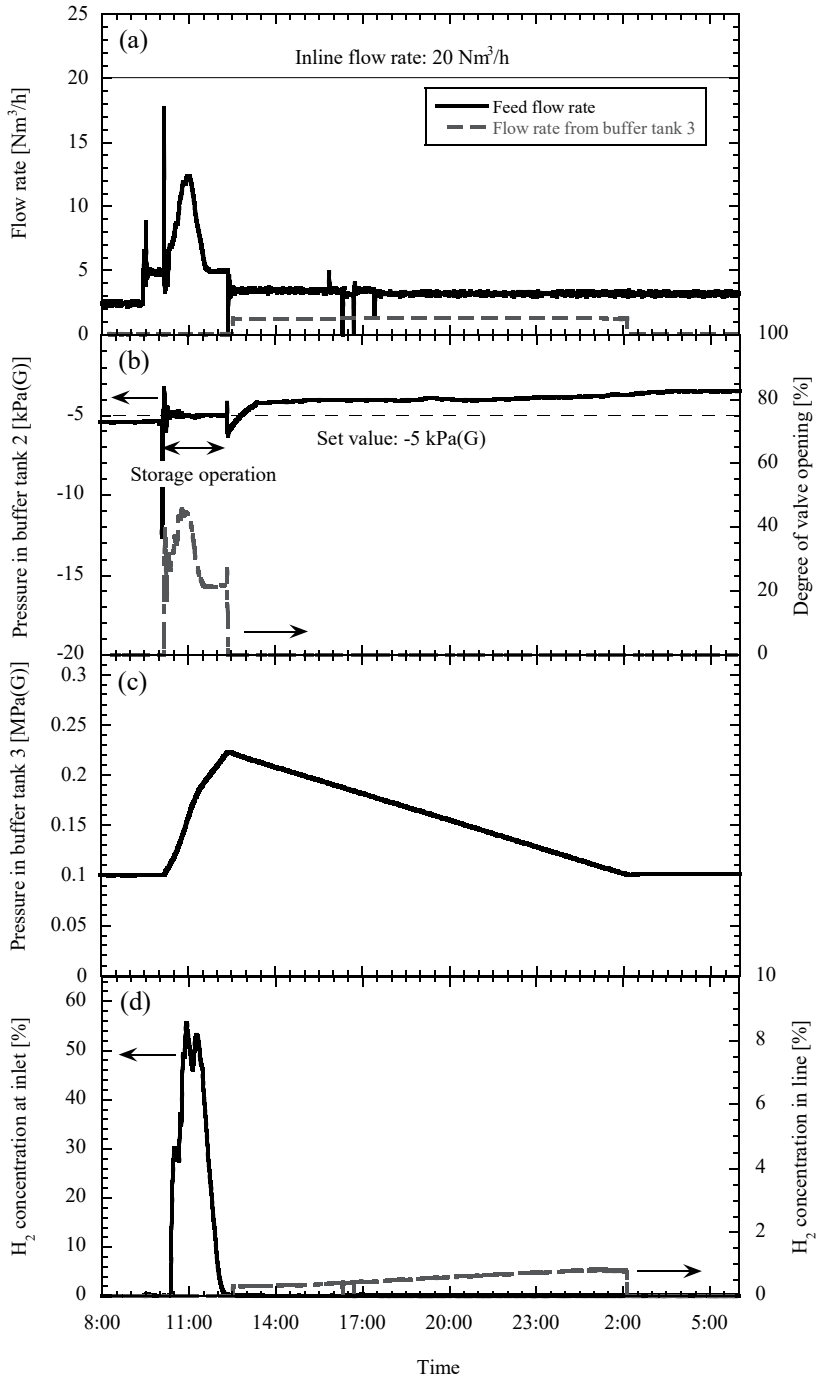

Fig. 10 Storage operation results of regeneration gas from NBI cryosorption pumps: (a) flow rate at the inlet and from buffer tank 3, (b) pressure in buffer tank 2 and degree of valve opening at the inlet of the buffer tank 3, (c) pressure in buffer tank 3, and (d) hydrogen concentrations at the inlet and in the main process line.