Observations of the Gas Stream from the Large Helical Device for the Design of an Exhaust Detritiation System*)

Masahiro TANAKA, Naoyuki SUZUKI, Hiromi KATO, Tomoki KONDO
and the LHD Upgrade Team

National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan

(Received 30 November 2015 / Accepted 9 March 2016)

A small amount of tritium is produced by deuterium–deuterium reactions in the core plasma during deuterium plasma experiments conducted in the Large Helical Device (LHD). From the viewpoints of tritium safety handling and public acceptance, any waste gas streams arising from the vacuum vessel of the LHD and Neutral Beam Injection (NBI) system will be treated by an exhaust detritiation system (EDS). The exhaust gas stream produced during the 18th cycle of LHD plasma experiments was observed to design the EDS. The rough pumping gas streams from the LHD and NBIs produced a high flow rate of 300 Nm^3/h. The vacuum exhaust gas stream from the LHD had a high hydrogen concentration more than 7% and a flow rate of less than 5 Nm^3/h during plasma experiments. The regeneration gas stream of the cryopump systems had a flow rate of more than 5 Nm^3/h. Based on these observations, the proposed EDS utilizes two types of tritium recovery system. One comprises two types of catalyst and dual absorbent beds. Other comprises an oxidation catalyst and polymer membrane system.

Keywords: tritium recovery, vacuum exhaust gas, exhaust gas flow rate, large fusion test device, exhaust detritiation system, tritium safety handling

DOI: 10.1585/pfr.11.2405055

1. Introduction

The development of nuclear fusion devices has remarkably progressed in recent years. Due to advances in performance when using plasma, deuterium and tritium are used as the operating gases in the fusion test device. To comply with radiation protection and safety assessments, exhausted tritium from the fusion facility will be recovered by an exhaust detritiation system (EDS) to minimize tritium release into the environment. A similar EDS has been utilized in the JET Active Gas Handling System (AGHS) [1–4]. The EDS comprises a two-stage catalytic recombiner for the oxidation of tritiated compounds such as tritiated hydrogen and tritiated hydrocarbons and three molecular sieve driers in parallel for the recovery of water vapor [1, 2]. The role of the EDS is to provide air flow into the torus vacuum vessel and AGHS openings during maintenance and to detritiate the exhaust gases in the case of an accident [4].

In the Large Helical Device (LHD), a small amount of tritium is produced by deuterium–deuterium reactions in the core plasma. A portion of this tritium is exhausted from the vacuum vessel and the rest is retained in the first wall and the diverter tiles. Although the exhausted tritium is a comparatively small amount, any waste gas streams arising from the vacuum vessel and the auxiliary equipment must be treated by the EDS to comply with safety requirements. To design the EDS for a large fusion test device, the behavior of the exhaust gas stream has to be understood quantitatively under the various operation modes. This entails measuring variables such as the flow rate, fluctuations in the flow, and gas compositions. The exhaust gas streams originate from (1) the plasma discharge operation, (2) regeneration by cryopumps and ice pellet injection systems, (3) rough pumping of the vacuum vessels of both the fusion test device and the Neutral Beam Injection (NBI) system, (4) a purge gas used in the vacuum vessel during maintenance.

In this study, the exhaust gas stream from LHD [5], which is the largest helical type fusion test device, was observed under various operating conditions, such as plasma discharges, regeneration utilizing the cryopump system, and the rough pumping of the vacuum vessels. The design of the proposed EDS has enough capacity to treat all these gas streams.

2. Monitoring the Gas Stream and Hydrogen Concentration

The deuterium plasma experiments in the LHD will be conducted during the 19th cycle of LHD plasma experiments. In preparation for these experiments, some of the exhaust gas lines were rearranged and combined for the observation of the gas stream before the 18th cycle of LHD experiments.

To observe the gas stream from the LHD, a gas stream monitoring system was installed in the exhaust

author's e-mail: tanaka.masahiro@nifs.ac.jp

*) This article is based on the presentation at the 25th International Toki Conference (ITC25).

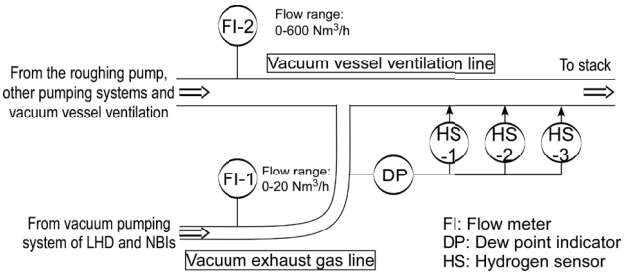

Fig. 1 Gas stream monitoring system in the gas lines from LHD and NBI.

gas line as shown in Fig. 1. The exhaust gas line comprises the vacuum exhaust gas line from the LHD's vacuum pumping system, and the vacuum vessel ventilation line from the roughing pump and other pumping systems. Two thermal mass flow meters (Bronkhorst High-Tech BV, F-106AZ [0 - 20 Nm^3/h] and Oval Co., Model MFT-B [0 - 600 Nm^3/h]), three hydrogen sensors (New Cosmos Electric Co. LTD, PE-2 type), and a hygrometer (VAISALA, Model HMT334) were installed in the exhaust gas line. The average dew point in the exhaust gas was less than −20°C during plasma operation. Three types of hydrogen sensors were used: the hot-wire semiconductor type for high sensitivity monitoring (from 0% to 10%), the thermal conductivity type for wider range (0% to 100%), and the combustion type (0% to 4%). The latter type were installed to discriminate between hydrogen and helium, because the first two react to both hydrogen and helium.

Thermal mass flow meters were installed in the vacuum exhaust gas line and the vacuum vessel ventilation line. The hydrogen sensors and dew point indicator connected in series collected sample gas from the vacuum exhaust gas line.

3. Monitoring Results

The observation of the gas stream was performed during the preparation phase and during the actual plasma experiments of the 18th cycle of the LHD's operation.

3.1 Flow of rough pumping from the vacuum vessel of the LHD

After maintenance work in the LHD, the vacuum vessel was evacuated prior to conducting plasma experiments. The exhaust gas composition was room air without hydrogen gas. The volume of the vacuum vessel was approximately 250 m^3. Figure 2 shows the variation in the roughing pump flow rate of the LHD vacuum vessel. As shown, the maximum flow rate reached 309 Nm^3/h after the evacuation was started. The flow rate reduced for approximately 2 hours as the other large vacuum components making up the NBI vacuum vessel were evacuated for the NBI conditioning operation. The maximum roughing pump flow rate of the NBI vacuum vessel was observed to be similar to that of the LHD vacuum vessel. Therefore, when the

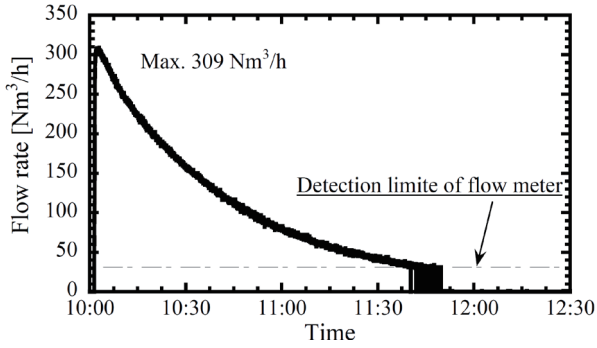

Fig. 2 Variation in the roughing pump flow rate of the LHD vacuum vessel.

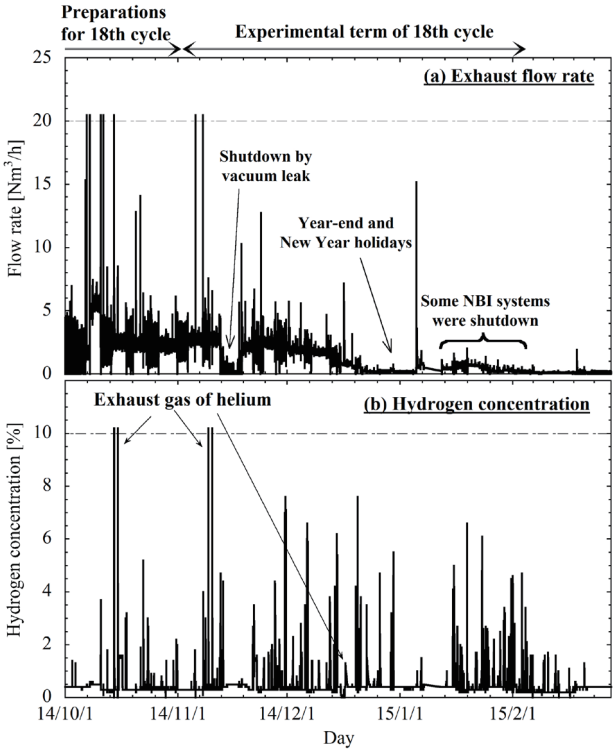

Fig. 3 Variation of gas stream during the 18th cycle of LHD plasma experiments: (a) vacuum exhaust gas flow rate, (b) hydrogen concentration.

vacuum vessel was pumped from atmospheric pressure, the flow rate through the EDS that requires processing is approximately 300 Nm^3/h. This was also the same as the torus purge flow rate during the LHD vacuum vessel maintenance period.

3.2 Vacuum exhaust gas flow and hydrogen concentration during plasma operation

In the 18th cycle of LHD plasma operation, hydrogen was used as the main operating gas. Helium was also used for discharge cleaning. Figure 3 shows the variation of vacuum exhaust gas flow rate and hydrogen concentration during these experiments. The flow rate depended on exper-

imental conditions and the operation mode. The vacuum exhaust gas flow rate was 2 - 3 Nm^3/h under normal operation. However, the flow rate reduced to less than 1 Nm^3/h when some NBI systems were shut down. The main exhaust gas flow thus might comprise exhaust gas from the NBI system.

In the 18th cycle of LHD plasma experiments, hydrogen concentration temporarily increased to 7% as transitory phenomenon when the cryopump for the LHD vacuum vessel was regenerated. To avoid a hydrogen explosion in the EDS, the hydrogen concentration has to be diluted below 4%, which is the explosion limit of hydrogen gas in air. Thus, the EDS has to maintain sufficient throughput for the dilution of hydrogen.

During the hydrogen ice pellet injection experiments, hydrogen concentration was observed to be steady at approximately 2% during operation, although plasma discharge was conducted every 3 min. Hydrogen concentration and vacuum exhaust flow rate were varied and depended on each plasma experiment's condition and pump operation.

3.3 Flow during regeneration of the NBI cryopump

The largest exhaust gas flow rate is during the regeneration process of the cryopump for the NBI system, because nitrogen gas is used to purge the shaft of the roughing pump. Figure 4 shows the variation of exhaust gas flow rate by the regeneration of each NBI cryopump. High flow rate and variation caused by the shaft seal gas of roughing pumps and regenerated gas was observed. When all NBI cryopump systems were regenerated simultaneously, the total exhaust gas volume was estimated to be 42.5 Nm^3 for a few hours. Thus, the exhaust gas stream from the regeneration of NBI cryopumps is the most critical issue to the EDS. The regeneration gas of cryopumps has to be temporarily stored in a large tank to mitigate the gas flow.

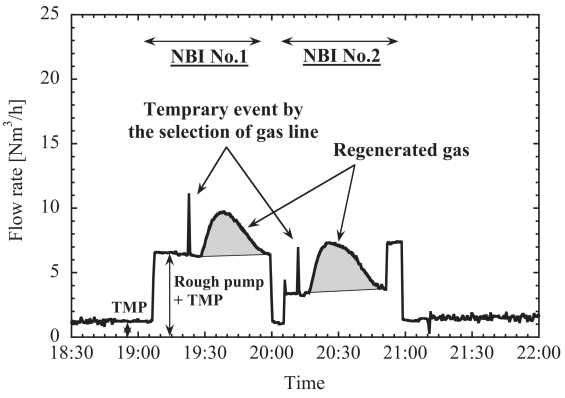

Fig. 4 Variation of exhaust gas flow rate by the regeneration of NBI cryopumps: "TMP" is turbo molecular pump.

4. Conceptual Design of the EDS for LHD

The EDS design policy for the LHD was determined on the basis of the observations of the exhaust gas stream. According to the safety management plan for the LHD [6], the detritiation factor is designed to be more than 20, corresponding to a tritium recovery rate of 95%. The exhaust gas flow rate and the hydrogen (tritium) concentration are broadly divided into the following two specifications: (1) high hydrogen (tritium) concentration and low flow rate during plasma operation and (2) low hydrogen (tritium) concentration and high flow rate during the vacuum vessel maintenance period and during roughing pump operation. The former demands high reliability because the tritium concentration in the exhaust gas would be high under plasma operation. Thus, conventional tritium removal systems comprising an oxidation catalyst and absorbent such as molecular sieves are applied. A compact system is required due to limited space. A high throughput is required because the maximum flow rate would be 300 Nm^3/h. Thus, a polymer membrane that can recover water vapor continuously [7, 8] would be applied instead of an absorbent. The conceptual diagram of the EDS is shown in Fig. 5. The proposed EDS comprises a molecular sieve (MS) system, a polymer membrane (PM) system, and a water storage and delivery system.

4.1 MS system in the EDS

The MS system comprises three components. The first component comprises temporary gas storage tanks for the NBIs. The regeneration gas from the cryopump with high flow rate is treated by the MS system because the tritium concentration in the exhaust gas will be high. In the conceptual design, the regeneration gas from the cryopump is stored by the large buffer tanks in the first component system. Subsequently, the gas processing takes some time to introduce gas into in the main process line. The total volume of the buffer tanks would be designed to store 90 m^3 of gas at 0.65 MPa, because the total regeneration gas volume from the NBIs was estimated to be 42.5 Nm^3.

The second component is an oxidation catalyst system for the combustion of hydrogen and hydrocarbons. The third component is the recovery system for water vapor, using two absorbents. These main component systems are applied in conventional tritium recovery systems. However, because the exhaust gas from the vacuum vessel does not contain oxygen and a high hydrogen concentration in the exhaust gas was observed, (Fig. 3), dry air is introduced upstream of the catalyst reactor to dilute the hydrogen and add oxygen for hydrogen combustion. The designed process flow rate after dilution would be 20 Nm^3/h. Because the vacuum exhaust gas flow rate was approximately 2 Nm^3/h under normal operation, the hydrogen concentration would be diluted to less than 1%. Moreover, hydrocarbons are observed in the vacuum exhaust gas of large fusion test devices such as JT-60U and JET [9,10]. Thus, two

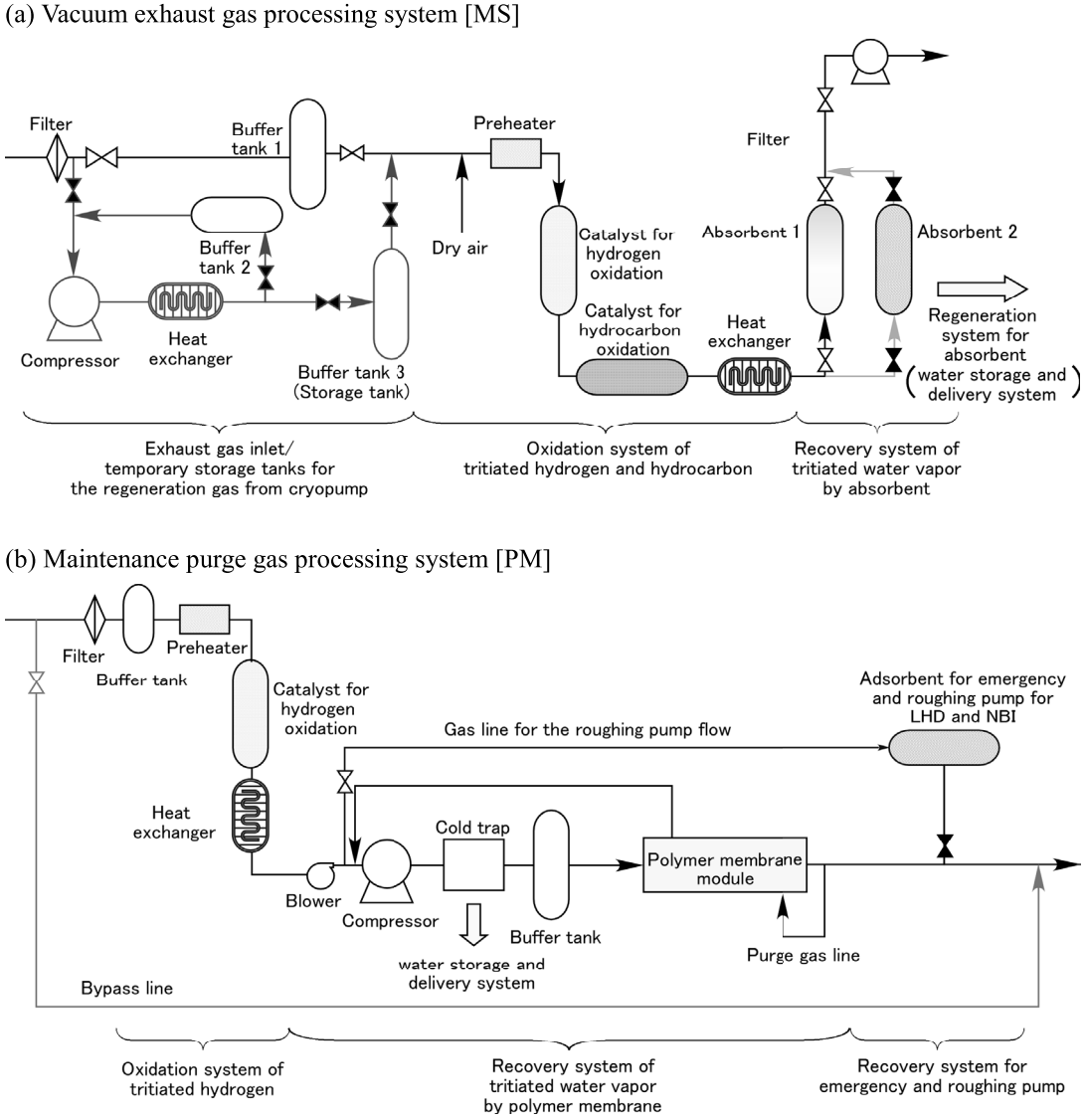

Fig. 5 Conceptual diagram of EDS: (a) vacuum exhaust gas processing system [MS] for high hydrogen concentration and low flow rate and (b) maintenance purge gas processing system [PM] for low hydrogen concentration and high flow rate.

types of platinum and palladium catalyst with different operating temperatures are designed for the oxidation of hydrogen and hydrocarbons. The platinum catalyst has high activity for hydrogen oxidation and the palladium catalyst for hydrocarbon oxidation [11, 12]. According to the experimental results given in ref. 11, the commercially available catalysts based on Al_2O_3 would be operated at 200°C for hydrogen oxidation and at 450°C for hydrocarbon oxidation.

The third component is the recovery system for tritiated water vapor and uses molecular sieves as absorbents. The dew point after the molecular sieve bed reaches less than −60°C, corresponding to a water vapor concentration of 20 ppmv at atmospheric pressure. The dual absorbent beds packs are designed for the recovery of tritiated water vapor. The dual bed system is used with one bed on adsorption and the other on regeneration or standby. Regeneration requires taking the absorbent bed off-line, passing gas at 350°C through it, and then condensing the tritiated water with a cooling unit [13].

Tritium in the main process line would be at such a low concentration that it might not be possible to monitor it in real time. Moreover, because the ionization chamber for tritium monitoring is affected by the gas composition, it would be difficult to perform calibrations of the ionization chamber for tritium monitoring in an MS system. Thus, instead of the ionization chamber, hydrogen sensors and hygrometers will be installed in the EDS to evaluate the hydrogen isotope recovery rate. The tritium concentration in the main process line will be measured by another monitoring system such as a tritium sampler system with water bubbler.

4.2 PM system in the EDS

The PM system also comprises three components as shown in Fig. 5 (b). The main process gas is room air. The dew point in room air is controlled to within a few degrees, corresponding to a water vapor concentration of several thousand ppmv. The designed process flow rate is 300 Nm^3/h to treat the torus purge flow during the LHD vacuum vessel maintenance period and the roughing pump flow from the vacuum vessels. The first component of the PM system is the oxidation catalyst system. The platinum catalyst, which is the same catalyst used for hydrogen oxidation in the MS system, is applied to oxidize hydrogen at 200°C.

The second component is the recovery system for water vapor using the commercially available hollow fiber polyimide membrane module. The feed pressure for this module is designed to be 0.6 MPa. Because the specification of the process flow rate of the largest polyimide membrane module unit is approximately 15 Nm^3/h, at a dew point of −50°C, the required number of membrane module units is 20. The polyimide membrane module has to be operated at a constant flow rate. Therefore, this system treats the torus purge gas flow from the vacuum vessel during the maintenance period. The recovery rate of water vapor by the polyimide membrane module is measured by the hygrometers.

The third component is the recovery system for the roughing pump flow using an absorbent. The process gas flow from the roughing pumps of the LHD and the NBIs, which changes with time as shown in Fig. 2, bypasses the polyimide membrane module and then passes through the absorbent recovery system.

Tritium concentration at the inlet to the PM system will be monitored by a proportional counter. When the tritium concentration is extremely low, the process gas is bypassed to the main process line.

4.3 Water storage and delivery system in the EDS

The tritiated water recovered by the MS and PM systems is transported from local storage tanks to a large temporary wastewater storage tank by the water delivery system. The tritiated water in this storage tank will be transferred to 25 L bottles and delivered to the Japan Radioisotope Association at regular intervals.

5. Summary

The exhaust gas from the LHD and the NBI during the 18th cycle of LHD plasma experiments was observed for the design of an EDS. The roughing pump gas streams from the LHD and the NBIs were observed to have a high flow rate of 300 Nm^3/h. This flow rate is similar to that of the purge gas during torus maintenance. The vacuum exhaust gas stream from the LHD has a high hydrogen concentration greater than 7% and a low flow rate less than 5 Nm^3/h during plasma experiments. The regeneration gas stream from the cryopump systems has a high flow rate. The total regeneration gas volume from the NBIs cryopumps was estimated to be 42.5 Nm^3.

Based on the observed exhaust gas stream, an EDS was designed. This design uses two systems for tritium recovery. The first is the MS system comprising two types of catalyst and dual absorbent beds. The second is a PM system comprising an oxidation catalyst system and two recovery systems, one for water vapor and the other for roughing pump flow. The detailed design and the construction of the EDS are intended to be completed before the 19th cycle of LHD plasma experiments.

Acknowledgments

This study was supported by the NIFS budget (NIFS14ULAA023 and ULGG801).

[1] A.H. Domba *et al.*, Proc. 15th Symposium on Fusion Technology, Utrecht, Netherland, 1988 (1988) p.1301.
[2] A.C. Bell *et al.*, Proc. 16th Symposium on Fusion Technology, London, UK, 1990 (1990) p.1457.
[3] D.P. Wong *et al.*, Fusion Technol. **21**, 572 (1992).
[4] F. Sabathier *et al.*, Fusion Eng. Des. **54**, 547 (2001).
[5] A. Komori *et al.*, Fusion Sci. Technol. **58**, 1 (2010).
[6] http://www.nifs.ac.jp/j_plan/pamph_030.pdf [in Japanese]
[7] H. Ito *et al.*, Fusion Technol. **21**, 988 (1992).
[8] T. Hayashi *et al.*, Fusion Eng. Des. **39-40**, 901 (1998).
[9] K. Isobe *et al.*, Fusion Eng. Des. **81**, 827 (2006).
[10] S. Grünhagen *et al.*, Fusion Sci. Technol. **60**, 931 (2011).
[11] T. Uda *et al.*, Fusion Sci. Technol. **48**, 480 (2005).
[12] M. Tanaka *et al.*, Fusion Eng. Des. **84**, 1818 (2009).
[13] J.M. Miller, "Tritium Containment" in *Safety in Tritium Handling Technology*, Ed. by F. Mannone (1992) p.131.