COMMISSIONING RESULT OF THE KSTAR HELIUM REFRIGERATION SYSTEM

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To keep the superconducting (SC) magnet coils of KSTAR at proper operating conditions, not only the coils but also other cold components, such as thermal shields (TS), magnet structures, SC bus-lines (BL), and current leads (CL) must be maintained at their respective cryogenic temperatures. A helium refrigeration system (HRS) with an exergetic equivalent cooling power of 9 kW at 4.5 K without liquid nitrogen (LN_2) pre-cooling has been manufactured and installed. The main components of the KSTAR helium refrigeration system (HRS) can be classified into the warm compression system (WCS) and the cryogenic devices according to the operating temperature levels. The process helium is compressed from 1 bar to 22 bar passing through the WCS and is supplied to cryogenic devices. The main components of cryogenic devices are consist of cold box (C/B) and distribution box (D/B). The C/B cool-down and make the various cryogenic helium for the KSTAR Tokamak and the various cryogenic helium is distributed by the D/B as per the KSTAR requirement. In this proceeding, we will present the commissioning results of the KSTAR HRS. Circuits which can simulate the thermal loads and pressure drops corresponding to the cooling channels of each cold component of KSTAR have been integrated into the helium distribution system of the HRS. Using those circuits, the performance and the capability of the HRS, to fulfill the mission of establishing the appropriate operating condition for the KSTAR SC magnet coils, have been successfully demonstrated.

KEYWORDS : KSTAR, Tokamak, Helium Refrigeration System (HRS), Warm Compression System (WCS), Compression Station (C/S), Oil Removal System (ORS), Commissioning

1. PREFACE

The cold components to be cooled down to cryogenic temperatures in the KSTAR Tokamak [1] are: (i) the superconducting (SC) magnet system and its supporting structure, (ii) the current-feeder system [SC bus-line and current lead (CL) system] that transfers the current from the power supply to the magnets, and (iii) the thermal shield (TS) system that protects the SC components and the cryogenic part of the CL system from ambient radiation. The calculated thermal load of each cold component during the various operation modes of the KSTAR is summarized in Table 1 [2].

The main components of the helium refrigeration system (HRS) itself can be divided into the following major parts [3]: (i) The compressor station (C/S) and the oil removal system (ORS), which is called the warm compression system (WCS); (ii) The cold box (C/B) where the cryogenic helium is produced; (iii) The distribution box (D/B), which distributes various cryogenic helium to the secondary helium distribution system (SHDS); and (iv) The helium inventory system including the liquid nitrogen (LN_2) storage and vaporizer unit. Fig. 1 shows the system layout and arrangement of the KSTAR HRS.

2. SYSTEM DESCRIPTION

2.1 Warm Compression System (WCS)

A simplified process flow diagram of the WCS of the KSTAR HRS is shown in Fig. 2. The WCS consists of

Table 1. Summary of the Cooling Load of the KSTAR

Item	duration [hour]	TF magnet [W@4.5K]	PF magnet [W@4.5K]	SC BL [W@4.5K]
Idle	14	961.9	359.6	68.1
TF current ramp	1	1,045.9	388.6	101.7
PF current ramp	7.65	1,045.9	388.6	101.7
PF current shot	0.35	6,335.9	8,329.6	415.2
TF current de-ramp	1	1,045.9	388.6	101.7
Day average	24	1,074	487.5	86.7
Shot/Stand-by avg.	8	1,277.3	736	115.4
Item	**duration [hour]**	**TS [W@4.5K]**	**CLS [g/s@55K]**	**SUM [W@4.5K]**
Idle	14	12,168	10.3	**3,219**
TF current ramp	1	12,168	15.9	**3,928**
PF current ramp	7.65	12,168	15.9	**3,928**
PF current shot	0.35	12,168	52.5	**21,143**
TF current de-ramp	1	12,168	15.9	**3,928**
Day average	24	12,168	13.2	**3,765**
Shot/Stand-by avg.	8	12,168	17.5	**4,681**

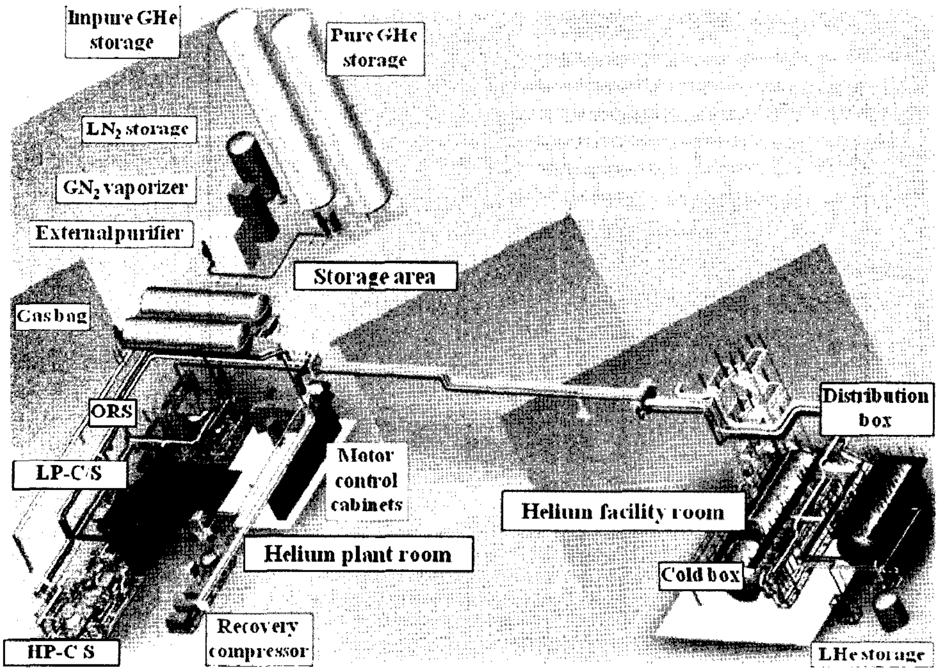

Fig. 1. System Layout and Arrangement of the KSTAR HRS

the C/S and the ORS, which includes the pressure regulation panel with the pressure regulation valves. The components of the WCS have been integrated on skid structures in order to save building space and for

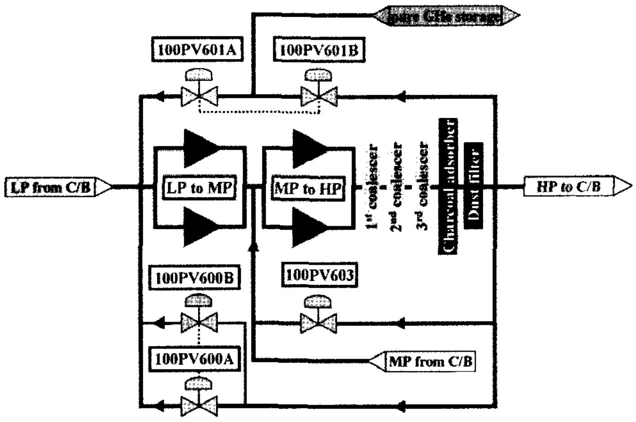

Fig. 2. Simplified P&ID of the C/S and the ORS

bar (HP). Each of the C/S skids consists of two oil injected screw compressors, two air-cooled electric motors, and an oil circulation system equipped with a bulk oil separator and its redundancy. The ORS is installed downstream of the HP-C/S and decreases the oil content of the process helium to 10 ppbw upstream of the cold box. The ORS itself consists of three stages of coalescing cartridges retaining small droplets (3 μm) of oil, followed by a charcoal adsorber bed that removes the remaining oil vapor. A trapping filter is installed downstream the charcoal adsorber in order to prevent the particles of the charcoal adsorbent from being carried over by the process helium flow. The pressure drop across the ORS is less than 500 mbar. Table 2 shows the detailed specifications of the C/S and the ORS.

Table 2. Specifications of the C/S and the ORS

Items		LP-C/S	HP-C/S	ORS
Main equip.	compressor	2 × MYCOM 400S	2 × MYCOM 320S	NA
	motor	2 × SIEMENS 5010S	2 × SIEMENS 5810S	NA
	oil filter	11 × F0-120	11 × F0-120	3 × CGF09, charcoal (4,500 kg)
Perfor mance	flow rate	536 g/s	1,046 g/s	NA
	shaft power	2 × 549 kW	2 × 981 kW	NA
	oil content	*~ 100 ppm*	*~ 100 ppm*	< 10 ppb

Table 3. Performance Estimation of the C/B in Terms of Equivalent Cooling Power at 4.5K

Item	Unit	TS	SC BL	SHe circulator	TD	LHe (CL)
thermal load	[W]	21,000	200	489	5033	-
mass flow	[g/s]	267.1	45	290	248.4	17.4
inlet press.	[bar]	18	5.5	1.089	1.089	1.303
outlet press.	[bar]	16	3	1.3	1.089	1.05
inlet temp.	[K]	55	4.4	4.3	4.3	4.5
outlet temp.	[K]	70	5.26	4.69	4.3	300
Eq. @ 4.5 K	**[W]**	**1,533**	**265**	**160**	**5,260**	**1,782**

convenience of transportation. According to the working pressure, the C/S can be classified into the low pressure compressor station (LP-C/S) skid and the high pressure compressor station (HP-C/S) skid. The process helium is compressed in the LP-C/S from 1 bar (LP) to 5.0 bar (medium pressure: MP) maximum and then sent to the HP-C/S where it is compressed up to a maximum of 22

2.2 Cold Box (C/B)

The design value of the total refrigeration capacity exergetic equivalent to 4.5K of the C/B is 9 kW, excluding a safety margin of 5%. The PFD of the C/B is shown in Fig. 3. As shown in Fig. 3, the C/B of the

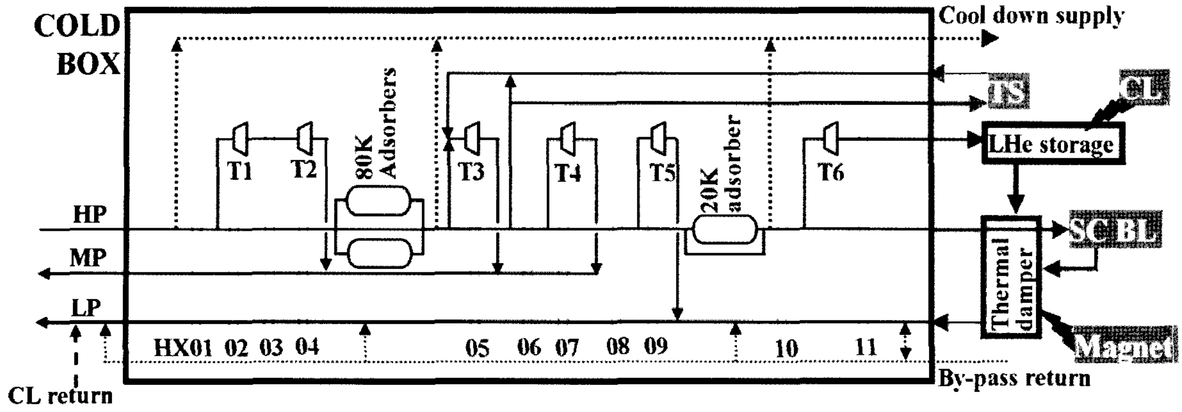

Fig. 3. Schematic PFD of the C/B Internals and an Outline of the Helium Distribution

KSTAR HRS is equipped with 6 AL-DTA model TC4-500 and TC5-500 oil-free static gas bearing turbo expanders (turbines), 11 plate-fin type aluminum heat exchangers (HXs), double-bed 80K and single-bed 20K adsorbers, and associated instrumentation (not shown for clarity). Instead of a LN2 pre-cooler, a cool down circuit that can supply up to 500 g/s GHe at 70K and 18 bar has been implemented inside. The return GHe during cool down can be merged into different temperature levels of the LP circuit. Table 3 summarizes the design values of the cryogenic helium that can be produced in the C/B during nominal operation (the helium consuming modules in Table 3 are marked in bold letters hereafter in this sub-section) [4]:

By expanding helium via the turbines T1–T3, the HP stream of the C/B is cooled serially in the HX's HX01–HX05 and supplied to the TS system. The design value of the $\dot{m}$ (~270 g/s) is about twice the value that is required during normal operation. However, the C/B has a flexible design and can reduce $\dot{m}$ down to ~140 g/s. The remaining cooling power can be used to produce LHe but also serves as a safety buffer to prepare for the increase of heat load due to: (1) the contamination of the TS system surface, which will result in an increase of the emissivity; and (2) the baking period of the vacuum vessel, which will increase the radiation to the corresponding TS, all of which eventually requires more $\dot{m}$ to reduce the radiation to the SC components.

The HP stream at the cold end of the C/B is depressurized and sent to the SC bus-lines. Owing to the flexibility of the C/B, during the shot mode of the KSTAR, $\dot{m}$ can be increased from the design value of 45 g/s up to 80 g/s by decreasing the LHe production.

The cold compressor (CP) is implemented at the helium return line of the thermal damper (TD) in the D/B (cold end of LP line, refer to Fig. 2). It is used to keep the LHe temperature inside the TD at 4.3 K and to pressurize the vaporizing helium at 1.1 bar up to 1.3 bar to create the required pressure difference between the two endpoints of the LP line.

LHe is produced by expanding helium downstream of turbine T6 via a J/T valve into the LHe storage. Most of the LHe is then sent to the TD, where the circulating supercritical helium (SHe) in the SC magnet system and the supply SHe to the SC bus-lines are cooled by using the enthalpy difference of the LHe to GHe phase change.

2.3 Distribution Box (D/B)

The distribution box is connected to a cold box and LHe dewar for supply and distribution of the cryogenic helium. Also, the D/B shares 16 interfaces with the secondary helium distribution system (SHDS) to supply helium to Tokamak. The D/B is equipped with a thermal damper (TD), 2 supercritical helium circulators, a cold compressor, and 7 heat exchangers. It is also equipped with electric heaters and valves for a HRS acceptance test. Fig. 4 shows the schematics of the D/B process.

Table 4. Characteristics of the SHe Circulators

Item	300C100 (TF circuit)	300C200 (TF circuit)
Efficiency	> 73.5 %	> 73.5 %
Heat Load eq. @ 4.5K	945 W	945 W
Flow Rate	300g/s	300g/s
Inlet Pressure	2.9 bar	2.9 bar
Outlet Pressure	5.6 bar	5.6 bar
Inlet Temperature	4.4 K	4.4 K
Outlet Temperature	4.9 K	4.9 K
Heat Inleak	7 W	7 W

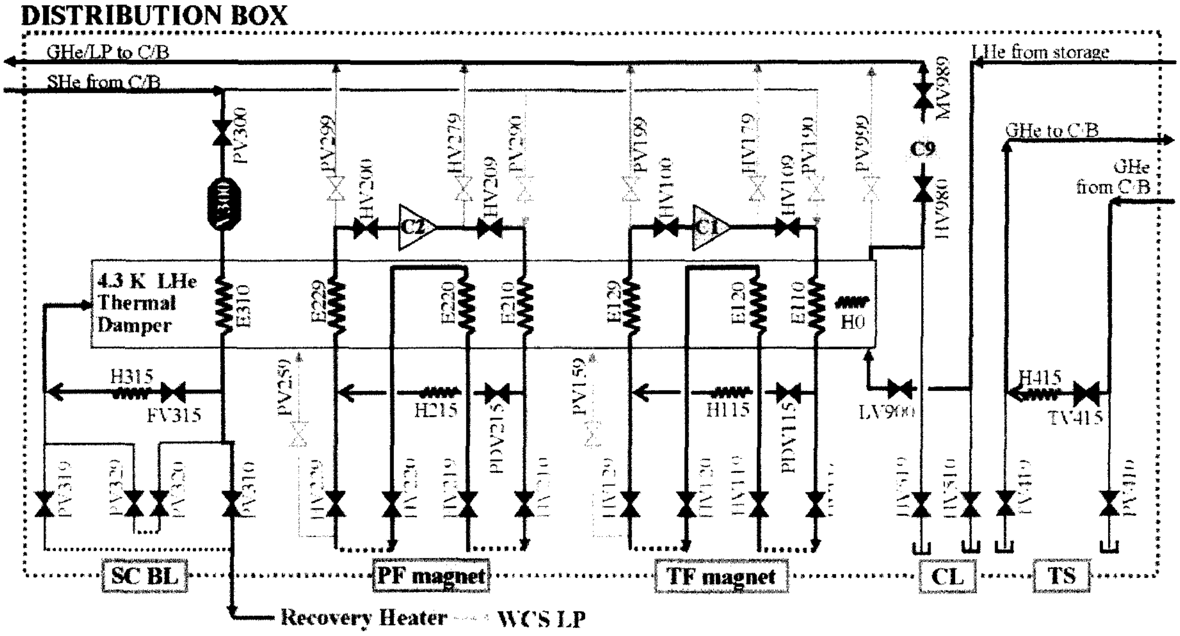

Fig. 4. Helium Circuits of the D/B used During Commissioning and Simulation of KSTAR Cold Components

In order to obtain a temperature of 4.3K in the thermal damper, the damper pressure must be 1.09 bar. Under these conditions, a cold compressor is necessary to return the GHe from the TD to the LP-C/S suction across the cold box heat exchangers. Indeed, the LP-C/S suction operates above the atmospheric pressure, at 1.05 bar. The efficiency of the cold compressor is greater than 66 % and the flow rate can exceed 310 g/s.

The D/B is equipped with dynamic gas bearings type SHe circulators made by IHI that allow circulation of supercritical helium (SHe) in the TOKAMAK magnets coils and structure. The characteristics of the SHe circulators are listed in Table 4.

Seven heat exchangers are installed in the thermal damper and are fully immerged in liquid helium (LHe). They make it possible to achieve design conditions of an outlet temperature difference of 0.1K between the LHe and the SHe.

2.4 Gas Management System (GMS)

Helium released during abnormal events of the KSTAR and impure GHe are first gathered in 2 $\times$ 50m^3

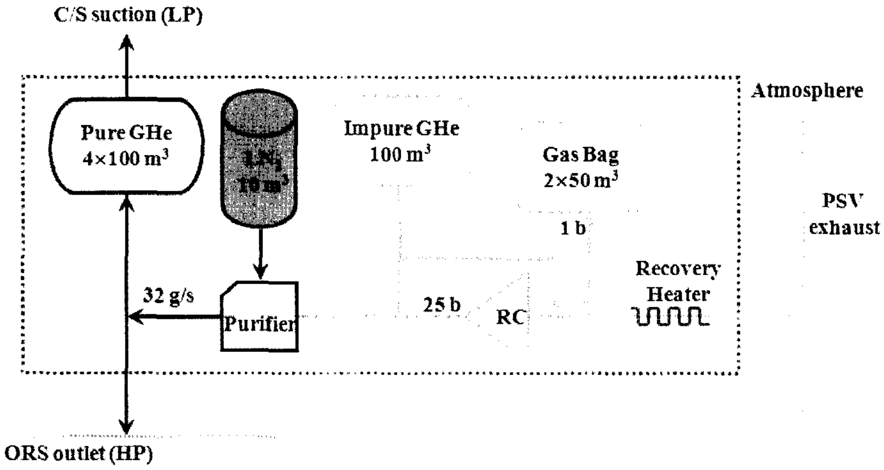

Fig. 5. Process Flow Diagram of the GMS and its Interfaces

Table 5. Guideline of Motor Temperature

Equipment		Alarm temp	Trip temp	DCS trip set
LP motor	Winding	155 °C	170 °C	155 °C
	Bearing	100 °C	105 °C	105 °C
HP motor	Winding	155 °C	170 °C	155 °C
	Bearing	90 °C	95 °C	95 °C

gas bags. If the temperature of the helium is too low to enter the gas bag, it is heated up by a 24 kW recovery heater upstream of the gas bag. The helium mass flow rate ($m^{\cdot}$) exceeding this heater capacity is released via a safety valve to the atmosphere. From the gas bag or the impure GHe storage (100 m^3), helium is sent to the recovery compressor (RC, capacity >32 g/s). From here it is issued either to an external purifier or to impure GHe storage if $m^{\cdot}$ exceeds the purifier capacity. The purifier can continuously process 32 g/s of 500 ppm air and 700 ppm water contaminated helium for 50 hours. When the pressure is high enough, it is also possible to feed the helium directly from the impure GHe storage to the purifier without intervention of the RC. The pure GHe downstream of the purifier is then gathered in the pure GHe storage (4 x 100m^3) or joins the pure GHe circuit. Fig. 5 shows the PFD of the GMS and its interfaces.

3. COMMISSIONING RESULTS

3.1 WCS Commissioning Result

As per the start-up sequences of the WCS, the HP-C/S was started first followed by the LP-C/S. In all the compressors, slide valves, which are used for capacity control, were in unload positions in order to minimize the torque and electrical load during the start-up of the compressors. The reactor starting method has been employed in order to reduce the start-up current. The set values of the reactor voltage taps were at 65 % for the HP-C/S and 90 % for the LP-C/S. Since high inertia forces were expected during the LP-C/S start-up at the design stage, speed sensors and additional protect relays have been applied to the LP-C/S MCC for safe operation.

In the case of the motors, for safe operation it is important to monitor the temperature values of the windings and bearings. Table 5 shows the temperature guidelines for motor windings, bearings, and PCS trip set points [5].

Once the WCS was started, helium from the pure GHe storage was compressed in the C/S and the remaining oil was removed in the ORS. The compressed helium downstream of the ORS was by-passed upstream of the LP- and HP-C/S. The LP, MP, and HP pressure set-points were regulated by using related pressure regulation valves and the pure GHe storage was used as a buffer. As shown in Fig. 1, the HP set-point was regulated by loading/unloading the process helium from/to the pure GHe storage via valve 100PV601A/601B. The LP and MP set-point values were controlled by manipulating valves 100PV600A/600B and 100PV603, respectively [6]. All the pressure regulations were performed automatically by the PCS following the pre-programmed sequences. The pressure values at each process point and the power consumption of the whole WCS were measured in order to evaluate the performance during the WCS commissioning.

Table 6. Summary of the WCS Commissioning

Item	Test result	Spec.	Remark
WCS HP	22.1 bar	22.0 bar	Accept
WCS MP	5.0 bar	5.0 bar	Accept
WCS LP	1.05 bar	1.05 bar	Accept
Total Flow	1,040 g/s	1,046 g/s	Accept
LP Flow	516 g/s	536 g/s	Accept
Total power	3,600 kW	3,700 kW	Accept

A summary of the WCS performance test is presented in Table 6. The total mass flow rate was slightly lower than the specification mainly due to the provisional filters that had been installed upstream of the suction strainer of each compressor in order to prevent foreign particles from entering and damaging the compressor profiles during commissioning. The flow rate reached the specification values after removal of the provisional filters.

3.2 C/B Commissioning Result

The duty of the C/B is to produce three kinds of cryogenic helium summarized in Table 7. The C/B is

Table 7. Cryogenic Helium Produced in the C/B and Corresponding KSTAR Cold Components

cryogen	T	P	cold components to be cooled
GHe	<55 K	<20 bar	thermal shield
LHe	4.5 K	1.3 bar	magnets (isothermal), CL (non-isothermal)
SHe	~5 K	>5.5 bar	SC bus-lines

designed and operated without LN_2 pre-cooling and "COLD" is only produced by quasi-isentropic expansion of the 6 turbo-expanders. Tuning of the C/B process was achieved during commissioning by adjusting the rotational speed and operating pressure values of T1~T6.

The results of fine tuning of the turbo-expander are shown in Fig. 6 (a) and Table 8. The rotational speed values were very stable and, except for T4, the isentropic efficiencies were higher than 75 %. T4 was operated at reduced power and was affected by its off-design operating conditions, resulting in rather low efficiency (* of Table 8), whereas the unusually high efficiency of T3 and T6 can be attributed to uncertainty of the temperature measurements (** of Table 8).

As the C/B operation is fully automatic, verification and optimization of the numerous sequences presented the major tasks of the commissioning. The automatic regeneration sequences of the cryo-adsorbers at 20 and 80 K were one of the most sophisticated ones. As shown in Fig. 6 (b), the regeneration and switching of the 80 K adsorbers was performed smoothly without affecting the main process. This was also the case with the 20 K adsorber, where, however, switching occurred between the single adsorber and a parallel process line.

Figure 6. Trends of the C/B operation; (a) rotational speed curves of the turbo-expanders (b) Trends of automatic regeneration and connection of the 80 K adsorbers.

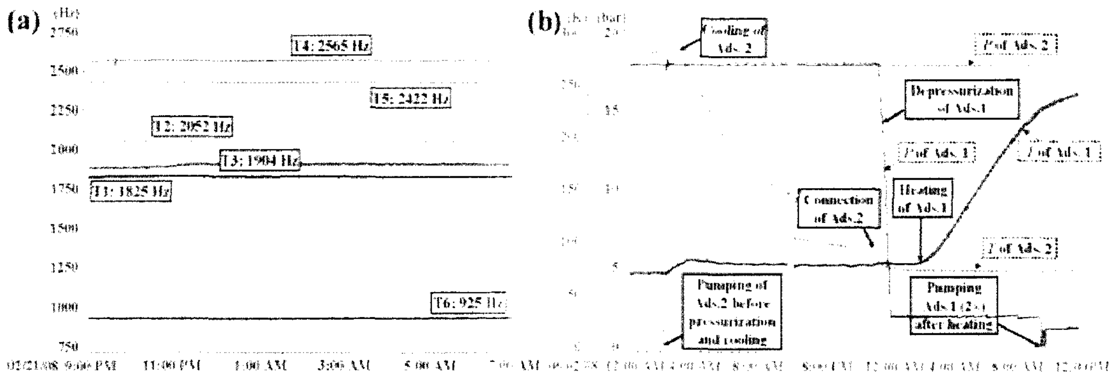

Fig. 6. Trends of the C/B Operation; (a) Rotational Speed Curves of the Turbo-Expanders (b) Trends of Automatic Regeneration and Connection of the 80 K Adsorbers.

Table 8. Characteristics of the Turbo Expanders.

		T1	T2	T3	T4	T5	T6
RPS	[Hz]	1,825	2,052	1,904	2,565	2,422	925
T_{in}	[K]	212.0	125.0	69.49	50.49	28.63	7.910
T_{out}	[K]	188.5	95.18	45.89	38.86	13.46	5.490
P_{in}	[bar]	20.30	12.65	16.90	17.19	19.11	16.91
P_{out}	[bar]	13.74	4.90	4.90	4.92	1.28	2.94
efficiency		0.77	0.76	**0.87	*0.59	0.79	**0.88

Table 9. Simulation Circuit of the KSTAR Cold Components with Simulation Modules

	TF magnet	PF magnet	SC BL	TS	CL
Simul. circuit	C1→ E110→ [PDV115]→ {H115})→ E129→C1	C2)→ E210→ [PDV215]→ {H215}→ E229→C2	PV300→ E310→ [FV315]→ {H315}→ expansion into TD	from C/B→ [TV415]→ {H415}→ to C/B	PV310→ {Recovery heater}→ to WCS LP suction

Table 10. Simulation Results of the KSTAR HRS

		SC BL	TS	CL	**H0**	**C9**
heater	[kW]	0.20	21.27	~20	5.14	
flow	[g/s]	45	291	17.5		282
T_{in}	[K]	4.44	55.25	4.41	4.31	4.31
P_{in}	[bar]	6.80	19.97	4.83	1.10	1.10
T_{out}	[K]	4.31	69.20	~290	4.31	4.64
P_{out}	[bar]	1.10	17.49	~3	1.10	1.28
4.5 K eq	[kW]	**0.39**	**1.63**	**1.66**	**5.37**	**0.13**

3.3 D/B Commissioning Result

As noted in chap. 2.3, the D/B is equipped with heater elements and valves that can separately simulate the thermal loads and pressure drops of each KSTAR cold component. The simulation elements and circuits corresponding to each KSTAR cold component are summarized in Table 9. In the case of the CL circuit, where no simulation elements were built in, some of the supercritical helium (SHe) flow from the SC BL circuit was extracted temporarily outside the D/B, and heated using the recovery heater of the GMS in order to mimic the LHe to ambient temperature GHe transition inside the CL.

To measure the maximum cooling capacity of the HRS, the simulation circuits of the SC BL, TS, and CL were activated. The isothermal cooling power was simulated by operating heater "H0", which was immersed in the LHe of the thermal damper (TD). Cold compressor "C9" was activated to lower the vapour pressure of the LHe inside the TD, thereby reducing its temperature down to 4.3 K. Table 10 provides a summary of the simulation results. Considering the calculated heat in-leak of the D/B and LHe storage (~0.28 kW at 4.5 K) [7], the total exergetic equivalent cooling power of the HRS at 4.5 K was about 9.45 kW, or 5 % higher than the supplier-guaranteed value of 9 kW, thus coinciding with the 5 % design margin.

The SHe circulators "C1" and "C2" have to compress the SHe, which will be depressurized while passing the cooling channels of the TF (toroidal filed) and PF (poloidal field) magnet systems. To test the performance of the circulators, simulation circuits, as described in Table 9, were set up. The suction pressure of the circulators was controlled to be around 3.2 bar and the maximum pressure rise was held below 3.4 bar by manipulating PV190/PV290 and PV159/PV259. The thermal load and pressure variation during plasma generation of the 2 MA-plasma-current operation scenario of KSTAR [8] were simulated by H115/H215 and PDV115/PDV215, respectively.

Fig. 7 (a) shows the performance test result for single plasma shot simulation in the case of "C2", which was exposed to more severe condition than "C1". When the pressure drop increased, the SHe mass flow rate decreased, following the path of the constant-rotational-speed curve given in Fig. 7 (b). 72 iterations of this shot simulation were performed in succession for 24 hours

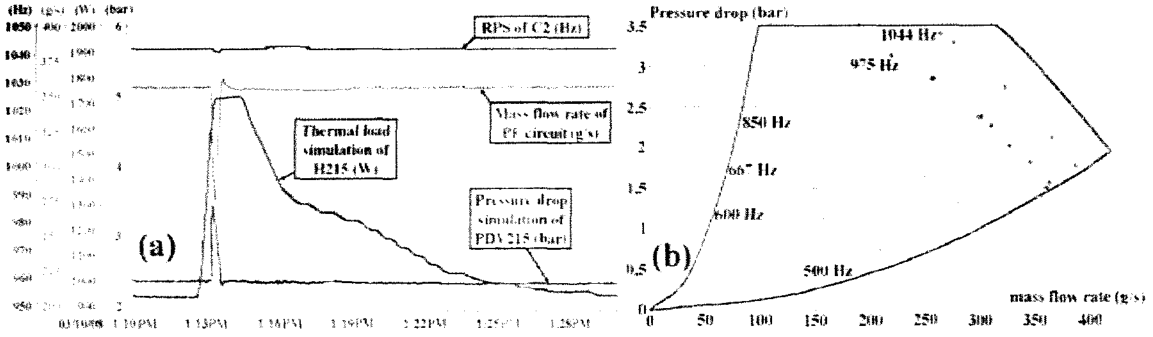

Fig. 7. (a) PF Circulator "C2" Related Parameters During One KSTAR Plasma Shot Period Simulation; (b) Operability Range (Area Inside the Bold Lines) and Tested Operation Points of the PF Circulator "C2.

and the operation of the circulators including the pressure regulation was always stable. The isentropic efficiencies of both circulators were around 70 %. This, however, has to be reinvestigated due to inaccuracy of the temperature sensors.

3.4 GMS Commissioning Result

To test the performance of the GMS, two gas bags each having 50 m^3 capacity were filled with gaseous helium (GHe) from the impure GHe storage. The polluted GHe (>100 ppm of N_2 and H_2O) from the gas bags was compressed by the recovery compressors at a maximum pressure and mass flow rate of 25 bar and 32 g/s, respectively, and then sent to an external purifier, where the impurity level was reduced to less than 1 ppm. For continuous performance measurements, spare interfaces upstream of the gas bags and downstream of the purifier were connected temporarily to form a closed loop.

4. CONCLUSION

Commissioning of the KSTAR HRS was performed according to the KSTAR operating scenario. The following is a summary of the related results:

Commissioning of the WCS has been performed successfully and the necessary performance for operation of the KSTAR HRS been demonstrated. A 0.5 % loss in the GHe mass flow rate was recovered after removal of the provisional filters. The noise and vibration level of the C/S were acceptable only at full load conditions and additional repair to be needed.

The KSTAR HRS has been commissioned successfully and its availability for operation of the KSTAR Tokamak has been confirmed. Using heater elements and valves integrated inside the D/B, it was possible to simulate thermal load and pressure drop variation of the cold components of KSTAR. In particular, the stability of the HRS and the operability of the two SHe circulators with respect to the 2 MA-plasma-current scenario of KSTAR have been clearly demonstrated.

After commissioning, the HRS supported cool-down and the 1st campaign of the KSTAR successfully. The cool-down and the operation results of the HRS during the 1st campaign of KSTAR will be discussed later.

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