Design of cryogenic system for the KSTAR device

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The KSTAR tokamak device for advanced research in the field of fusion experiment requires a large amount of refrigeration power at several temperature level. The design of the KSTAR helium refrigeration system is based on the refrigerator and distribution system. The helium refrigerator is designed to operate stably to cope with the pulse heat loads of the superconducting magnet operation in tokamak device. The helium distribution system is designed to distribute refrigeration to KSTAR cooling components such as 30 superconducting coils, magnet supporting structures, thermal shields and current leads with a minimal temperature variation. In this paper, the development of the cryogenic system for the KSTAR tokamak device is described.

INTRODUCTION

The purpose of the KSTAR helium (He) refrigerator is to keep the superconducting (SC) components of the KSTAR device below their current sharing temperature and maintain the thermal shields (TS) and current leads (CL) at a suitable cryogenic temperature. The SC coils, their corresponding structures, and the SC buslines are cooled with forced flow of supercritical He (SHe) whereas the CL and TS are kept at the proper operating temperature by liquid He (LHe) and pressurized gaseous He (GHe), respectively [1]. For the KSTAR helium refrigeration system, a safe and stable operation and fully automatic control is required because of the long-term operation time and a various cooling modes such as cool-down and warm-up, normal operation and abnormal events such as coil quench and electrical power failure.

KSTAR COOLING COMPONENTS

The duty of the refrigerator concerning the SC coils is to remove the static thermal load due to radiation and conduction and the dynamic load due to current charging in order to maintain the coils far below a certain critical temperature. Table 1 shows the thermal-hydraulic parameters of the SC coils. The required mass flow rate of the SHe to cool the SC coils is about 600 g/s during the normal operation. All magnet structures are cooled with forced flow supercritical helium. The magnet supporting posts are installed below the TF coil structures. These posts absorb the thermal shrinkage of the magnets and support the magnet weight and plasma disruptions load. The supporting ring and posts are cooled with 4.5 K SHe and 55 K GHe, respectively [1].

The power transmission system for the KSTAR device requires current leads to link the SC bus-lines at 4.5 K to the normal bus-lines at 300 K. The current lead system consists of 11 pairs of brass overloaded vapor-cooled leads for the CS and PF coils, one pair of copper vapor-cooled leads for the TF coils, and two current lead boxes which consist of cryostat, thermal radiation shield, and liquid helium reservoir. The KSTAR SC bus-lines have 2 ducts and 12 pairs of CICCs. Each bus duct consists of NbTi CICCs, thermal shields, electrical insulations, and support structures. The average length of one bus duct is about

10 m. The thermal shield reduces the thermal radiation from the room temperature side to the coil temperature (4.5 K) region. The cryopanel has been designed to maintain a maximum temperature of 80 K during normal operation and 100 K during vacuum vessel baking. In table 2, the cryogenic characteristics of KSTAR cooling components are summarized.

Table 1. Thermal-hydraulic parameters of the KSTAR SC coils

	Unit	TF coils	CS coils				PF coils		
			CS1U&L	CS2U&L	CS3U&L	CS4U&L	PF5U&L	PF6U&L	PF7U&L
Strand		Nb3Sn					NbTi		
# of coils		16	2	2	2	2	2	2	2
Total coil mass	ton	46	13				37		
Coil connection		serial		parallel					serial
Cryogen		SHe							
He inlet	ea	32	10	8	2+2	3+3	4+4	4+4	6
He outlet	ea	33	11	9	3+3	4+4	5+5	5+5	7
cooling channel/coil	ea	4	10	8	4	6	8	8	6
total cooling channel	ea	64	20	16	4+4	6+6	8+8	8+8	12
L coil	m	~640	~660	~540	~285	~410	~1550	~2510	~1670
L cooling channel	m	~160	~66	~68	~71	~68	~194	~314	~278
DH	mm	~0.5							
*A*He	mm2	138	107						
*T*in	K	4.5							
*T*out	K	5.0	6.6				5.0		
*P*in	bar	5.5-5.7	5.5-7.8						
*P*out	bar	3.0							
m dot	g/s	300	183				117		

Table 2. Summary of KSTAR cooling components

Device		No	Cold mass (ton)	Operating temp. (K)	Cryogen	Amount of cryogen
SC coils	TF coil	16	100	4.5	SHe	3000 liter
	CS coil	8 (4 pairs)				
	PF coil	6 (3 pairs)				
Magnet structu	TF/CS/PF	16/1/80	140			500 liter
Supporting structures		1 ring	10			
		8 posts		55	GHe	
Current lead	Lead	12 pairs		4.5	LHe	2000 liter
	Lead box	2		55	GHe	
SC bus-line	Bus-lines	12 pairs	20	4.5	SHe	
	Bus duct	2		55	GHe	
Thermal shield		CRTS, VVTS	20			500 liter

OPERATION SCENARIO

The annual operation mode of KSTAR device consists of clean-up, cool-down, warm-up and operation period. The operation period is about 8 month. Before cool-down process, each part of the cryogenic passages (pipes, magnet passages, heat exchangers) must to be cleaned by a stream of purified helium. Helium flow for the cleanup process is supplied and controlled by the refrigerator. A special procedure will be applied to the coil and bus-line CICC: pure helium provided by the purifier will supplied to the CICC until moisture and impurity content at the discharge side is corrected. All cold mass should be cooled down by the refrigerator system from 300 K to the operation temperature. Cool-down time from 300 K to 4.5 K is estimated about 1 month. SC magnet system requires a limitation of the temperature difference between any components of KSTAR should be less than 50 K and the temperature of the TF coils should be always higher than that of the TF coil structures.

In order to estimate the refrigeration power for the KSTAR device, the baseline operation mode was considered. During the baseline mode, a daily operation time is 8 hr/day (18 shot/day), the plasma shot time is 70 sec and pulse repetition time is 1200 sec. During the shot mode, TF coils are fully charged to 35 kA, PF coils pulsed operated to its maximum current and plasma current charged up to 2 MA. The daily operation scenario is listed in table.

THERMAL LOADS DURING NORMAL OPERATION

Table 3 shows the various thermal loads of the KSTAR cryogenic system components at each operating modes [2]. Considered thermal loads during each operating modes are;

- Idle mode: conduction loss, radiation loss
- TF ramp/de-ramp, stand-by mode: conduction loss, radiation loss, joint DC loss, eddy current loss, AC loss.
- Shot mode: conduction loss, radiation loss, joint DC loss, joint AC loss, Eddy current loss, AC loss, nuclear heat loss, friction loss.

Table 3. Thermal loads at each operating modes of KSTAR cooling components

Mode	Period (hr)	SC Coil (kW@4.5K)	SC structure (kW@4.5K)	SC bus (kW@4.5K)	Lead (g/s @ Lhe)	TS (kW@70K)
Idle	14	0.5	0.8	0.06	10	13
TF ramp	1	0.6	0.8	0.1	16	13
Standby	7.65	0.6	0.8	0.1	16	13
Shot	0.35	11	4.0	1.0	52	13
TF deramp	1	0.6	0.8	0.1	16	13

The design power of the He refrigerator is based on the “day average” thermal load of the KSTAR device and the constant thermal losses of the refrigerator and the cryogenic He transfer lines [3]. Since the temporal variation of the KSTAR thermal load is very large (the thermal load during the shot mode is about 10 times that of the other modes), the additional cooling power required during the various operation modes is obtained by vaporizing LHe which has been liquefied and stored in the LHe storage tank during the idle mode (day average cooling scheme). The day averaged thermal load of the KSTAR cold components is about 3.8 kW @ 4.5 K. This value does not incorporate the heat losses of the liquid helium storage tank, cryogenic circulators, and the distribution losses of the cryogenic transfer lines and thermal dampers, etc.

DESIGN OF THE REFRIGERATOR

The present design specifications of the KSTAR He refrigerator is summarized in Table 4 [4]. In the compressor station GHe is isothermally compressed. By expanding the high pressure GHe via turbines and valves, He at cryogenic temperatures is produced in the cold box and transferred to the distribution valve (DV) box. The function of the DV box is to supply to each cooling objects with the proper type and amount of cryogenic He, in accordance with the day average cooling scheme. Especially, the amount of SHe to cool the SC coils and structures is far beyond the capacity of the cold box SHe production. To overcome this problem a circulator, which is a cryogenic compressor, is used to circulate the SHe in a closed circuit. The thermal load of the coils and structures is then absorbed via SHe/LHe heat exchangers (HX's) immersed in the so called by thermal damper which is a temporary LHe storage located in the DV box. The present LHe capacity of the thermal damper has been determined on the basis of a continuous operation of the TF magnets even in the case of a plasma disruption.

All the cold components of the KSTAR system have to be linked to the distribution box through the vacuum insulated transfer lines. At the limit of the distribution box, all circuits must be isolated by valve. The helium distribution system should be with vacuum insulated housing, thermal damper, cryogenic circulator and cryogenic valves, etc. to supply various kind of helium to the KSTAR cold components. The energy that is released by the various components is dumped into the liquid helium that is stored in the thermal damper capacity. The quantity of liquid that is vaporized depends on the cooling power. The liquid helium in the thermal damper shall be in 4.3 K, 1.1 bar. The required SHe flow rate for the all SC coils is estimated as a 600 g/s. This flow rate is generated by cryogenic circulators because the JT mass flow is not sufficient to circulate all loads. The cryogenic circulator is operating at almost constant pressure.

Table 4. The design specification of KSTAR helium refrigerator system

Helium Compressors	**an oil flooded screw compressors** **Total mass flow rate : ~1 kg/s at 18 bara** **Oil removal system : under 10 ppbw**
Helium purifier	**Mass flow capacity : 32 g/s at 17 bar** **Air reduction : inlet : 500 ppm, outlet : < 1 ppm**
Cold Box	**Total Capacity : 7 kW at 4.5 K (day average)** **Operate without Liquid Nitrogen pre-cooling** **6 oil-free, static gas bearing turbo-expanders** **12 aluminum plate fin heat exchangers**
Storages	**Liquid Helium Tank : 20,000 liter** **Warm Helium Storage : 900 m^3 at 20 bara** **Recovery Gas Bag : 100 m^3** **Liquid Nitrogen Tank : 20,000 liter**
Distribution System	**Thermal damper : LHe at 4.3 K** **SHe circulation capacity : 600 g/s (300 g/s X2 EA)** **Circulation SHe pressure : 3 bar ~ 6 bar** **No. of cryogenic valves : ~ 100 ea**

CONCLUSION

Basically, the KSTAR helium refrigeration system was designed by considering a various requirements of the KSTAR cold components and operation modes. The static and pulse heat loss of the KSTAR cold components was estimated. The main design feature for the KSTAR helium refrigerator is peak power save system by using the thermal damper and LHe storage tank because the KSTAR tokamak will be pulse operated device. The typical day average heat losses of each device are 1.7 kW at 4.5 K of supercritical helium, 13 kW at 70 K of gaseous helium and 13 g/s of liquid helium.

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REFERENCES

1. Kim Y.S. *et al*. “Cryogenic System for the KSTAR device”, International Cryogenic Engineering Conference, Grenoble, France (2002) 109-112
2. Kim Y.S. *et al*. "ANALYSIS OF THE THERMAL LOADS ON THE KSTAR CRYOGENIC SYSTEM", CEC/ICMC 2003, Alaska, USA (2003)
3. Kim Y. S. *et al*., Technical Requirement for the KSTAR Helium Refrigeration System (2004).
4. Fuenzalida P. *et al*., KSTAR Helium Refrigeration System TECHNICAL PROPOSAL (2004).