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Hydraulic Behaviors of KSTAR PF Coils in Operation

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***Abstract*-- The superconducting coil system is one of the most important components in Korea Superconducting Tokamak Advanced Research (KSTAR), which has been operated since 2008. Nb_3Sn and NbTi superconductors are being used for cable-in-conduit conductors (CICCs) of the KSTAR toroidal field (TF) and poloidal field (PF) coils. The CICCs are cooled by forced-flow supercritical helium about 4.5 K. The temperature, pressure and mass flow rate of the supercritical helium in the CICCs are interacting with each other during the operation of the coils. The complicate behaviors of the supercritical helium have an effect on the operation and the efficiency of the helium refrigeration system (HRS) by means of, for instance, pressure drop.**

The hydraulic characteristics of the supercritical helium have been monitored while the TF coils have stably achieved the full current of 35 kA. In other hands, the PF coils have been operated with various pulsed or bipolar mode, so the drastic changes happen in view of hydraulics. The heat load including AC loss on the coils has been analyzed according to the measurement. These activities are important to estimate the temperature margin in various PF operation conditions.

In this paper, the latest hydraulic behaviors of PF coils during KSTAR operation are presented.

1. INTRODUCTION

KSTAR has been operated since 2008 and 5th campaign will be carried out in 2012. It is very important to operate stably the full superconducting magnet system for plasma experiments so the performance of magnet system is one of key issues in superconducting tokamak like KSTAR and International Thermonuclear Experimental Reactor (ITER).

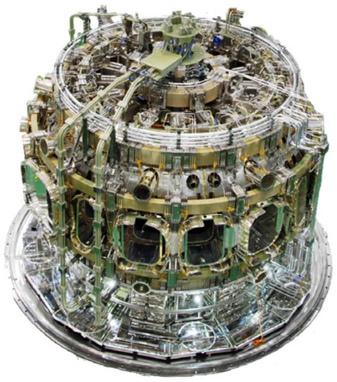

Fig. 1. Inside of KSTAR cryostat.

In particular, each KSTAR magnet consists of CICC and it is operated in cryogenic temperature with supercritical helium as a coolant inside of CICC. So it is required for us to understand the hydraulic behaviors of CICC. It is a first step to predict and estimate the stability and the flexibility of superconducting magnet system for KSTAR.

2. KSTAR SUPERCONDUCTING MAGNET

KSTAR magnet system consists of 16 TF coils and 14 PF coils which are cooled down less than 5 K with helium [1]. In the world, KSTAR is the only operating superconducting tokamak adopting Nb_3Sn superconductor, so the experimental results are so interesting not only for KSTAR but also ITER even though KSTAR CICC is formed into rectangular shape and has no central hole for helium flow. In the past, several preliminary tests of Nb_3Sn coil and magnet like ITER Toroidal Field Model Coil (TFMC) and Central Solenoid Model Coil (CSMC) were carried out and the Experimental Advanced Superconducting Tokamak (EAST) of China has also operated since 2006, however only KSTAR can show us the integrated performance as full magnet system using ITER-like superconductors. Most of all KSTAR followed a unique procedure of manufacture like the continuous winding scheme of coil to reduce the electrical and hydraulic joint resistance [2] and then we carried out the room temperature tests of each coil as a part of the quality assurance activities until completion of tokamak. Especially, we didn't carry out the cool-down and current charging tests of the whole KSTAR coils except several model coil tests. It was very careful attempt to develop the superconducting magnet system compared to the conventional way. It was possible to reduce the cost and construction period within the project schedule.

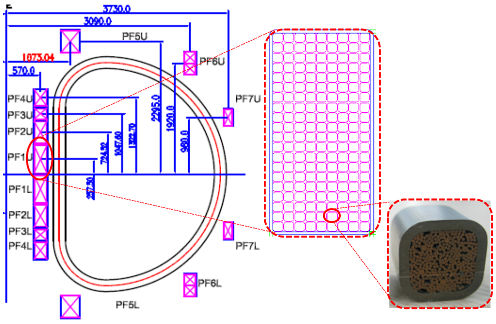

Fig. 2. Cross section of KSTAR magnet system.

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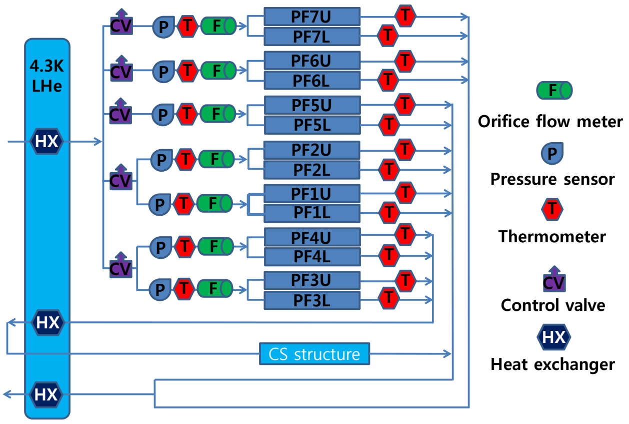

Fig. 3. The cooling scheme of KSTAR PF coils.

3. HYDRAULIC BEHAVIORS

3.1. Pressure gradient

The mass flow uniformity is very important for stable operation of the magnet system to prevent temperature difference between adjacent coils during cool-down and experiments. For example, KSTAR PF coil's cooling scheme is presented in Fig. 3. It is not easy to keep the uniform mass flow distribution of each cooling channel because the control valve and flow meter are not enough to control and measure the helium flow of PF1 and PF2 (as same in PF3 and PF4). In spite of these restrictions, the mass flow deviation of each hydraulically connected PF coil is within 10 % and the cool-down was completed in 20 days.

The pressure drop measurement of each PF coil has been carried out annually and the pressure gradient is usually used to compare the pressure drop among PF coils with different cooling length. The PF1 and PF2 coils have lower pressure gradients compared to the others under the same mass flow rate conditions since 1st campaign. We are presenting the pressure gradient of 3 PF coils such as PF3, PF5 and PF7. As a result of measurements, we can confirm that the tendency of the pressure gradient according to the mass flow rate has been consistent since 2008.

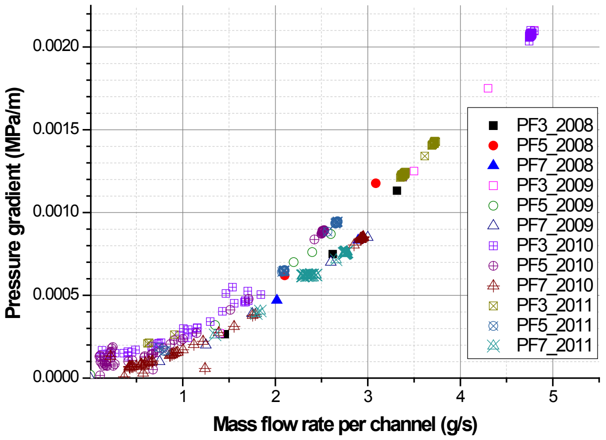

Fig. 4. Pressure gradient tendency of PF coils.

3.2. Friction factor

The pressure drop between the inlet and outlet of a coil has tight relationship with the geometric characteristics of the CICC and the operational conditions. To generalize this effect, the friction factor is introduced as below. Before determination the friction factor according to Darcy's equation, the mass flow uniformity of each cooling channel in the same coil and the consistency of hydraulic characteristics from room temperature are assumed.

$$\text{Friction factor} = \frac{8\times\rho\times A^3\times\Delta P}{L\times U\times\dot{m}^2} \tag{1}$$

ρ : density (kg/m^3)
A : helium area (m^2)
ΔP : pressure drop (Pa)
L : coil length (m)
U : wetted perimeter (m)
$\dot{m}$: helium mass flow rate (kg/s)

The friction factor of charged coil has been already measured and analyzed such as ITER CSMC and Central Solenoid Insert Coil (CSIC) tests [3], [4]. According to the previous experiments, the mass flow rate increased for current charging period compared to the zero current state and the pressure drop decreased simultaneously. It may be caused by the electromagnetic force of current charging and it would make a new helium channel inside of CICC bundle area by moving cable.

KSTAR PF5L coil shows different behaviors such as the mass flow rate per cooling channel decreasing and pressure drop increasing in Fig. 5.

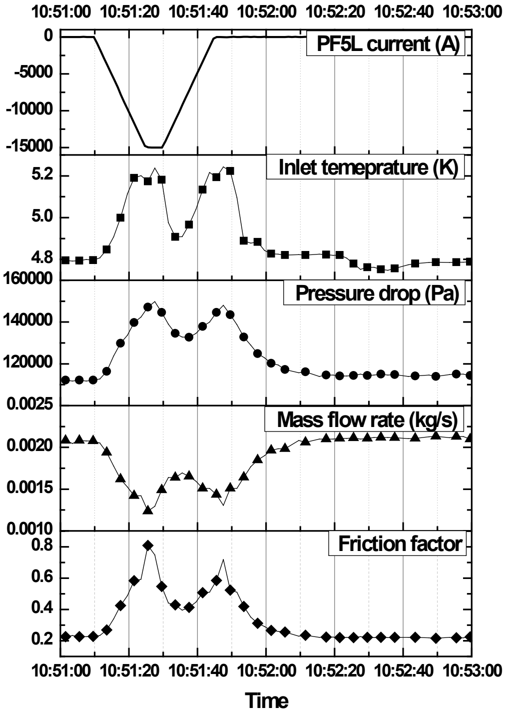

Fig. 5. Hydraulic behaviors of KSTAR PF5L coil.

ITER CSIC was charged up to 40 kA with ramp rate of 5 kA/min. In other hands, KSTAR PF5L was charged lowly and fast up to – 15 kA with 1kA/s. The mass flow reduction of KSTAR PF5L coil may be caused by the heat generation of AC losses by current changing but the change of helium area by the electromagnetic force is not a dominant factor such as ITER case. The trend in accordance with the current ramp rate and the maximum operation current will be evaluated and analyzed seriously in the near future.

3.3. Measurement in real coil system

Most sensors such as thermometer, pressure gauge and flow meter are located outside of coils. For example, inlet pressure gauges are in the distribution box (DB) #2 of Helium Distribution System (HDS) and inlet thermometers are at the manifold line in front of coils. Outlet pressure gauges are at the common line connected with several coils and outlet thermometers are located in each outlet of cooling channels as below. Temperature is measured in HRS, HDS and Tokamak Monitoring System (TMS) so we can archive relatively enough data.

However, pressure and mass flow rate measurements are limited compared to the temperature because of less sensors and lower data sampling rate in Fig. 6. We can measure only the supplied helium mass flow rate by the flow meter located in DB#2. In addition, it is impossible to measure the mass flow rate per one cooling channel so we assume that the mass flow distribution of same upper and lower coils is uniform.

3.4. Temperature variation due to current ramp rate

The temperature variation is useful and complicated characteristic in the superconducting magnet system because it is affected by all operating parameters such as coil current, helium mass flow rate, magnetic field, and so on. The temperature rising is mostly caused by the heat loads of PF coil operations because of AC losses according to the variations of current and magnetic field.

The individual superconducting coil tests are carried out to check KSTAR PF magnet system's performance and stability before the plasma operation every year. We have already recognized that PF1 coil shows a larger temperature rise compared to other PF coils and it will become one of important factors for KSTAR PF coil operation.

TABLE I
KSTAR PF INDIVIDUAL COIL TEST.

Coil	Max. current (kA)	Ramp down rate (kA/s)
PF1	15	0.5, 1, 2, 4, 6
PF1	15	0.5, 1. 2
PF3U/L	15	0.5, 1, 2, 4, 6
PF4U/L	15	0.5, 1, 2
PF5U/L	15	0.5, 1, 2, 4, 6
PF6U/L	10	0.5, 1, 2
PF7	10	0.5, 1, 2

In 2011, KSTAR PF coil should be charged up to 15 kA and then 25 kA in a few years. The current charging tests of PF coils were carried out individually during this campaign. At first, each PF coil was charged up to maximum 15 kA with ramp rate of 1 kA/s and kept the current for 5 seconds and then discharged with various current ramp rates such as Table. 1.

For convenience, we focus on PF1L coil and then calculate the energy loss by the calorimetric method in one cooling channel where the highest temperature rise happened in 2010. The total heat load for 500 seconds is shown in Fig. 7. The fastest current ramp down rate of 6 kA/s generated the highest heat load peak of near 180 W and the highest temperature peak of 8.79 K. It is a little difficult to determine and analyze AC losses because of several complicated parameters such as additional heat source, cooling circuit, and so on.

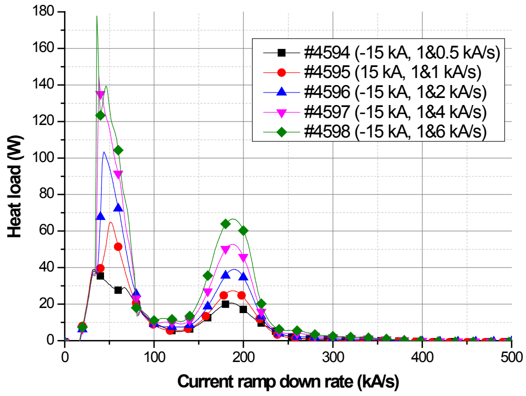

Fig. 7. The heat load of PF1L coil.

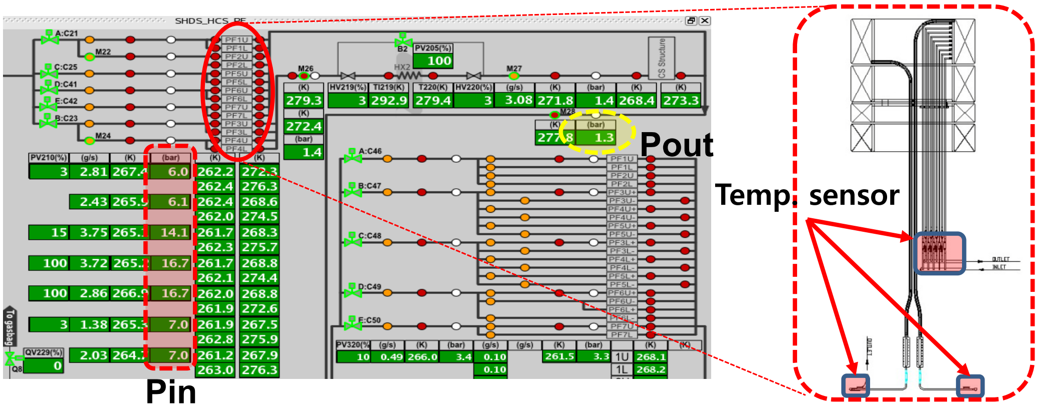

Fig. 6. PF1L coil outlet temperature measuring points.

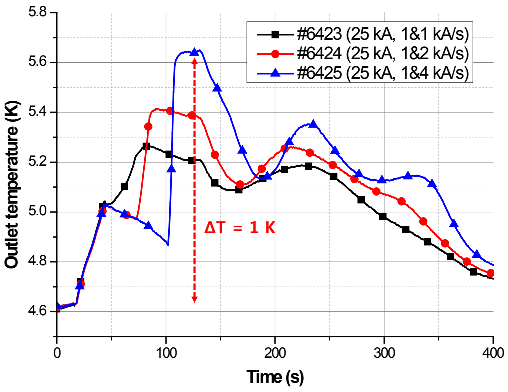

Fig. 8. PF4L coil outlet temperature with 25 kA charging.

As mentioned before, the maximum KSTAR PF coil current is 25 kA so we carried out the full current charging test of PF4L coil at end of last campaign. In the test, the current ramp up rate of 1 kA/s was fixed but the current down rate was variable from 1 to 4 kA/s and flat-top duration was also changed from 5 to 60 seconds.

Maximum temperature rise of PF4L coil was about 1 K during the highest current charging of 25 kA. And we can confirm that the effect of flat-top duration to temperature rise during current charging. According to the experiments, the flat-top of 60 seconds helps to reduce the temperature rise of more than 0.1 K.

3.5. Quench detection

First quench occurred at the KSTAR PF individual coil test [5]. The primary quench detection system (QDS) was disabled just before shot. The PF1 upper and lower coils were charged simultaneously up to -15 kA with ramp rate of 1 kA/s, kept for 5 seconds, zero crossing to +15 kA with ramp rate of 6 kA/s, and then discharged to 0 current with ramp rate of 0.5 kA/s according to the shot scenario. The temperature over than 12 K and duration of 2 seconds are criteria for QDS but the first temperature peak did not activate temperature QDS because of the threshold delay time of 4 seconds even though it kept over than 12 K for 3.2 seconds. The quench suddenly happened in a certain channel of PF1L coil after reaching at +15 kA. As a result of quench, the outlet temperature of the quenched channel increased up to 35.8 K after fast discharge by the quench detection system in Fig. 9.

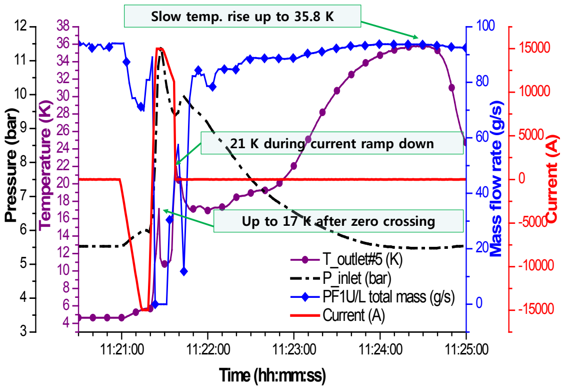

Fig. 9. Quenched PF1L coil.

TABLE II
KSTAR PF1L COIL TEMPERATURE.

Shot	#4852	#4857	#4855	#4858
Max. current	± 3 kA		± 15 kA	
Ramp rate	1&1kA/s		1&0.5 kA/s	
Zero crossing	1 kA/s		4 kA/s	
PF1L coil	Temperature rise (K)			
Outlet#1	0.34	0.33	3.97	3.74
Outlet#5	0.77	0.74	5.85	5.73

After quench shot (#4856), we checked the quench effect to PF1L coil by current charging up to ±3 kA with zero crossing rates of 1 kA/s and ±15 kA with 4 kA/s respectively. The difference of temperature increasing between before and after quench shot was less than 6 % as Table. II and the thermohydraulic behaviors were almost same. As a result of experiments, there was no serious change by quench of PF1L coils.

4. CONCLUSIONS

KSTAR PF superconducting coil has good achievements since 2008. At first, the cool-down was well done because of the acceptable temperature difference among coils which was introduced from stable and balanced pressure drop between each coil inlet and outlet.

For operation, each PF coil has been charged up to ±15 or ±10 kA depending on the magnet power supply in 2011. Maximum PF coil current and ramp rate were enough for this year's operation. We also confirmed that the performance of PF4L coil and power supply by current charging test up to 25 kA. In addition, we could confirm the stability of KSTAR PF superconducting coil through the quench detecting shot because there was no serious change after quench shot and check the performance of secondary QDS, too.

Further it is required to study harder the superconducting coil itself because of unclear parts such as friction factor variation in accordance with current driving, the additional heat load source for more accurate AC losses estimation, and so on.

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