Thermohydraulic Characteristics of KSTAR Magnet System Using ITER-like Superconductors

S.H. Park 1), Y. Chu 1), H. Yonekawa 1), I.S. Woo 1), K.P. Kim 1), Y.O. Kim 1), W.S. Han 1), J.S. Hong 1), K.R. Park 1), H.K. Na 1), M. Kwon 1), and KSTAR Team 1)

1) National Fusion Research Institute (NFRI), Daejeon, Korea

E-mail contact of main author: parksh@nfri.re.kr

Abstract. Korea Superconducting Tokamak Advanced Research (KSTAR) has been operated since 2008 and third campaign is now in progress. KSTAR is the world's only superconducting tokamak constructed of Nb_3Sn having a cable-in-conduit conductor (CICC) formed into a rectangular shape with no central hole for helium passage. Most importantly, KSTAR is the world's only tokamak using an integrated full magnet system with ITER-like superconductors. KSTAR has already achieved maximum TF current of 36.2 kA with the bipolar operation of PF coils during second campaign. The thermohydraulic characteristics and behavior including the temperature variation during operation, the pressure drop between inlet and outlet of coil and the friction factor of CICC were investigated. This paper introduces the thermohydraulic results of KSTAR magnet system up to now and offers suggestions for ITER and other superconducting tokamak under construction.

1. Introduction

Korea Superconducting Tokamak Advanced Research (KSTAR) was completed in 2007, and began operation in 2008. KSTAR is a world-unique fusion device in the world because several advanced technologies are adopted. Most important one is that KSTAR is a fully superconducting tokamak using ITER-like superconductor. It is very important to have the steady state operation by superconducting tokamak, so the performance of magnet system is one of the key issues in superconducting tokamaks.

In particular, each KSTAR magnet was manufactured using a cable-in-conduit conductor (CICC) and magnets are kept and operated in cryogenic temperature during each operation period. This system undergoes various conditions including long term cool-down and short plasma shot. Because of that, we have to understand the thermohydraulic characteristics and behaviors of the CICC and coils. This is a first step to predict and estimate the stability and the flexibility of superconducting magnet system for KSTAR.

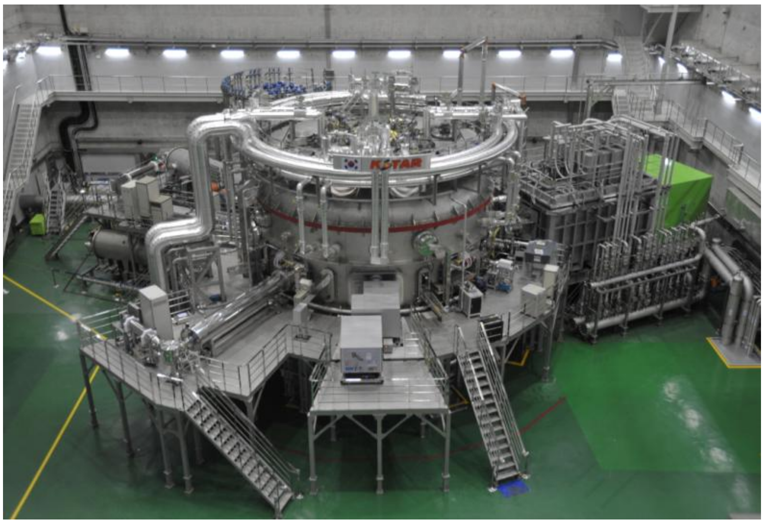


FIG. 1. KSTAR tokamak in 2010

2. KSTAR Superconducting Magnet System

KSTAR magnet system consists of 16 toroidal field (TF) coils and 14 poloidal field (PF) coils which are cooled down less than 5 K with liquid helium.[1] In the world, KSTAR is the world's only operating superconducting tokamak adopting Nb_3Sn superconductor except 2 pairs of PF coils (PF6 and PF 7) which are made of NbTi. It is an interesting point for us to motivate strongly and it means that there are many things to verify and solve in the operation and every campaign.

TABLE I: KSTAR SUPERCONDUCTING MAGNET PARAMETERS

	TF	PF1	PF2	PF3	PF4	PF5	PF6	PF7
Superconductor	Nb_3Sn						NbTi	
Conduit	Incoloy908						STS316LN	
No. of coil	16	2	2	2	2	2	2	2
CICC length per coil (m)	610	652	516	258	387	1404	2487	1689

Of course, several tests of Nb_3Sn coil and magnets, such as, ITER TFMC and CSMC were carried out as ITER preliminary project before KSTAR's first campaign and the EAST which is located in China has also operated since 2006. However, KSTAR has the relevant integrated performance of full magnet system using ITER-like superconductors. KSTAR magnets were manufactured by a unique procedure using the continuous winding scheme of coil to reduce the electrical and hydraulic joint resistance [2] and then, the room temperature tests of each coil were conducted for the quality assurance until the completion of KSTAR. Obviously during construction, the cool-down and current charging tests of the whole KSTAR coils, except several model coils, like TF00 and CSMC, were not undertaken. A very careful attempt to develop the superconducting magnet system compared with the conventional system was utilized. It was possible to reduce the cost and construction period within the project schedule.

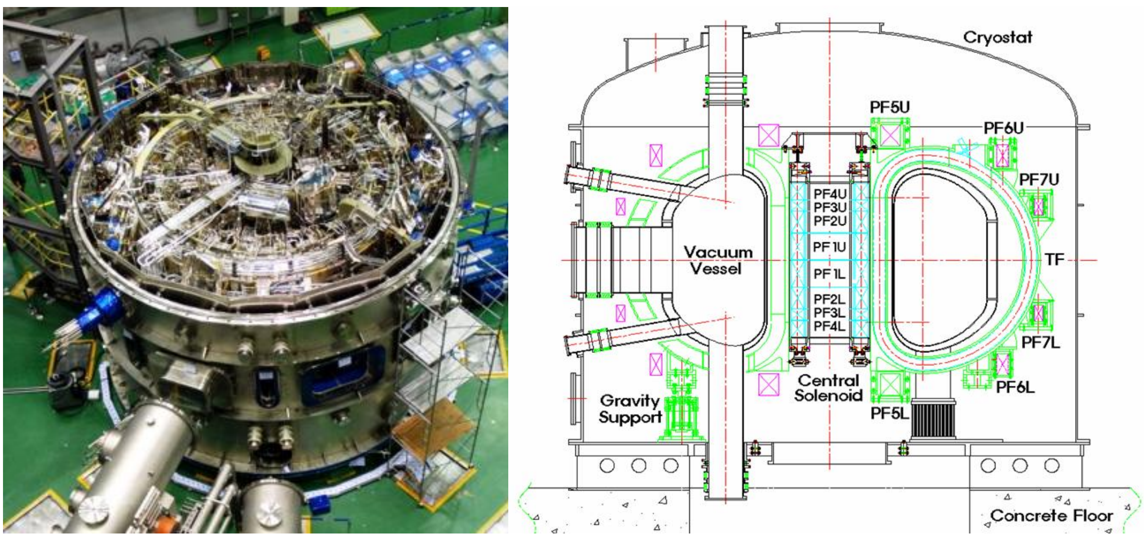


FIG.2. KSTAR magnet system

3. Preliminary Characteristics of KSTAR Coils

3.1. Mass Flow Distribution

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. KSTAR has 30 superconducting magnets with different lengths of cooling channels and void fraction. Real void fraction and mass flow distribution were measured and their consistency has also been checked at room temperature condition.

Management of mass flow uniformity of, not only each quadrant of 16 TF coils, but also, among 4 quadrants must be maintained. Control valves have a role to minimize the flow imbalance and to keep the stable coolant flow during operation [3]. However, only one control valve was installed in front of each quadrant, so it was difficult to control. The total mass flow rate of TF magnet system was around 300 g/s in normal operating conditions. The uniformity of mass flow was reasonable because the deviation was less than 5 % of the averaged value and knowing the specific hydraulic characteristic which is the certain TF coil's lower mass flow rate at room temperature

The mass flow rates of the PF1 and PF2 coils were controlled by one hydraulic valve and PF3 and PF4 coils were controlled by same way. In spite of this restrictions, the mass flow deviation of each hydraulically connected PF coil was within 10 %.

3.2. Pressure Drop

The pressure drop of each TF quadrant and PF coil was measured respectively with the helium refrigeration system (HRS). The second TF quadrant, which consists of TF5 to TF8, had the biggest pressure drop because of the higher impedance of TF6 than others. The difference of pressure drop among quadrants at the same mass flow rate increased in proportion to mass flow rates.

To compare the pressure drop among PF coils, a pressure gradient was introduced for convenience. The PF1 and PF2 coils have lower pressure gradients compared to the others under the same mass flow rate conditions. In the first campaign, we found out that the flow meters of PF1 and PF2 were unstable in the lower mass flow rate compared to the normal operation range. In spite of this difficulty, we can confirm that the tendency between mass flow rate and pressure gradient is consistent in the three campaigns and it was also similar to KSTAR CSMC.

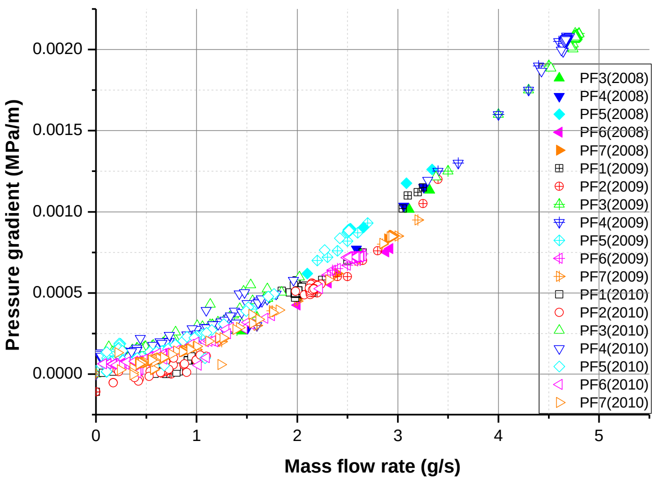


FIG. 3. Pressure gradient in PF magnets

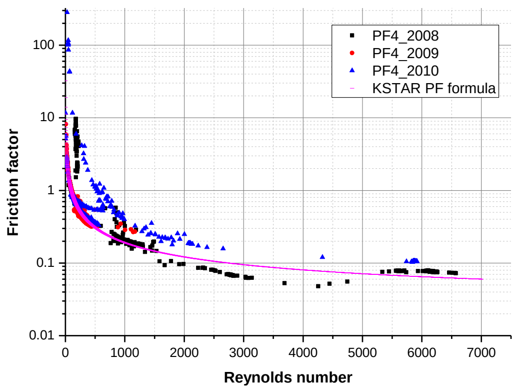
3.3. Friction Factor

The pressure drop between the inlet and outlet of a coil is strongly related to the geometric parameters of the CICC, such as the void fraction, and the operational conditions, such as mass flow rate. This affects not only the performance of magnet system, but also the operational efficiency of the HRS. To check the hydraulic characteristics in the many conditions of KSTAR, a friction factor is useful and subjective for comparison with other fusion devices. [4] Before determination the friction factor according to Darcy's equation, some assumptions are calculated, such as the mass flow uniformity of each cooling channel in the same coil and the consistency of hydraulic characteristics between room temperature and cryogenic temperature. And then, the Katheders's friction factor formula [5] was modified for the KSTAR PF coil using the KSTAR PF CICC short sample data [6] and the measured void fraction of CICC from the sampling test. [7]

$$f_{32.69\%} = \left(\frac{1}{void\ \ fraction}\right)^{0.45} \times \left(0.013 + \frac{19.5}{R_e^{\ 0.76}}\right) \qquad (1)$$

The relationship between Reynolds number and friction factor during the KSTAR campaigns is presented in FIG. 4. The measured friction factors were mostly 10 % higher than the calculation by formula (1) in operation range. The results of PF3 and PF4 coils were located in higher Reynolds number region than others because of an excessive mass flow rate in PF3 and PF4 and the difference in cooling circuit.

Mostly, the friction factors were similar in the three campaings, but the deviation according to the operational conditions and campaigns was observed, such as the PF 4 coil. It means that individual coils faced different situations in each campaigns even though the tedency was kept since the first campaign. In addition, the friction factor of KSTAR PF is higher than the LHD Inner Vertical (IV) coil at the same first campaign respectively. It was caused by the difference of CICC specification, such as a larger void fraction of LHD than KSTAR. [8]



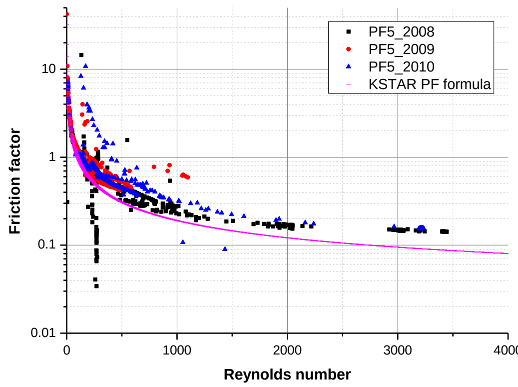


FIG. 4. Friction factor of PF4 (left) and PF5 (right)

4. Thermohydraulic Behavior in Operations

The temperature variation is a representative characteristic of the superconducting magnet system during operation because it is affected by all parameters such as current, mass flow rate, resistance, magnetic field and so on. According to the design and predictions, temperature rising in coils normally occurs and most heat loads of PF coil operations were caused mainly by AC losses according to the variations of current and magnetic field. This heat load raises coil temperature, but the designed cooling power of supercritical helium was expected to eliminate the heat load efficiently. Temperature rise in the PF coils was caused for several reasons. One of reasons was the mass flow reduction during current charging and discharging operation. There are different experiment results about this issue. One is that the current changing makes a new cooling passage inside CICC to reduce the pressure drop in bundle region such ITER CSMC coil and then it helps to increase the mass flow rate. The other is that a mass flow reduction by the current variation which could decrease the stability was reported in other device such as JAEA SMES coil. [9]

4.1. Bipolar Operation of PF Coils

In the second KSTAR campaign, the bipolar operation from 4 kA to - 4 kA for the PF magnet system was carried out for the first time. The current magnitude was larger than the first campaign and the mass flow reduction occurred. We compared the mass flow reduction among the PF coil operations according to the scenarios. For this comparison, the PF1 upper coil (PF1U) and cooling channel #3 were selected because most of the PF coils have similar pressure gradients during the normal operation range as shown in section 3.2.

The hydraulic behavior of a single PF coil test with the pulsed current was checked. The inlet pressure and the outlet temperature of PF1U increased together according to the current charging. On the other hand, the mass flow rate decreased continuously during the current ramp up period. The measured temperature and pressure during the flat-top period had little change compared to the ramp-up period, and the mass flow rate was increasing at the same time. As soon as the blip and ramp-down of current were started, the inlet pressure and outlet temperature increased rapidly up to maximum values but the mass flow rate decreased oppositely and was kept at the minimum value for a while. The outlet temperature of the PF coil did not exceed our prediction in each single coil charging test. This phenomenon is understandable even though there is a delay time between the current change and the coolant behavior like reduction. The larger heat load is generated during the blip and ramp-down period and it causes an increase of outlet temperature and the decreasing of mass flow rate. As a result of vicious circle, the helium temperature rising by AC loss introduces a pressure increase and the helium behavior was changed, such as the mass flow reduction and then the temperature increases again. The point of the minimum mass flow rate is almost same with the point of the maximum inlet pressure in time.

It is difficult to supply independently supercritical helium to each KSTAR PF coil and to individually control the uniform mass flow distribution because of the cool-down circuit. The inlets of PF1 and PF2 coils were connected with one coolant supply line. If the mass flow rate of PF1 coil decreases, the decreased mass flow rate goes to the PF2 coil simultaneously during the current charging test of PF1 and the total mass flow rate remains almost the same.

A current charging test of all PF coils together with the TF coils of 20.36 kA current was checked. The different thermo-hydraulic behaviours such as the temperature rise and the mass flow reduction were observed in comparison with the previous current charging test of single PF coil. The mass flow rate starts to decrease just after blip. Contrary to the previous test, the mass flow rate keeps on decreasing and reaches “zero” mass flow rate and then it is maintained for a while. As a result of the simultaneous current charging operation, it was apparent that a few PF coils had a higher rise of temperature compared to the single coil test.

A mass flow reduction causes the additional temperature rise at PF outlet. In the second campaign, the maximum rise of temperature was about 4 K in the PF2 coil. Of course the temperature margin was still acceptable for the PF coil operation. Importantly, the relationship between the rise of temperature and the mass flow reduction caused by AC loss and operational conditions must be clearly understood. Several ways can be considered to operate the magnet system more stably, for example, increasing supply pressure, optimizing operational procedure and modification of the cooling scheme.

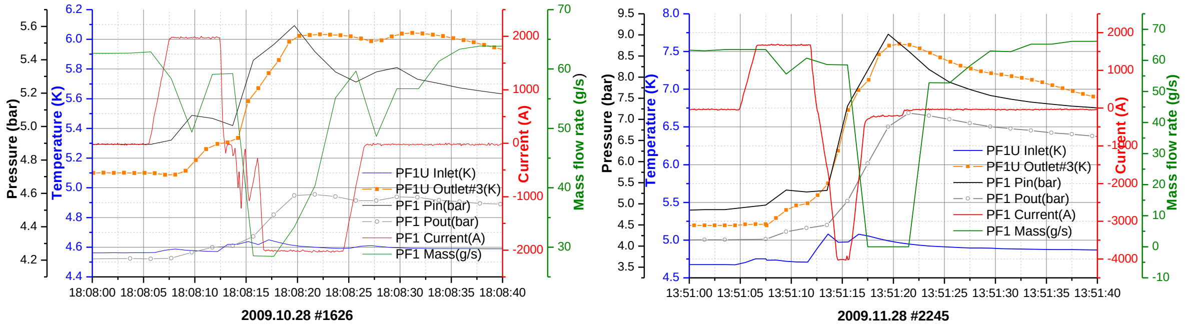


FIG. 5. Single (left) and simultaneous (right) current charging tests in 2009

4.2. The Way to Steady State Operation

To achieve the goal of KSTAR third campaign in 2010, the operational stability of the superconducting magnet system is needed for plasma current of 500 kA and D shaped plasma. The temperature rise of the PF magnet, especially PF1 and PF2, was observed in 2009 and operations measuring the related data from PF individual tests in accordance with the operational scenario in 2010 are underway. For more stable operation, a new approach in experiments was adopted. The total mass flow rate for the PF magnets was about 300 g/s and it was possible to increase the total mass flow rate and to control the mass flow distribution within the hydraulic valve's capability in the cooling circuit.

At first, the same amount of mass flow rate for the PF1 compared to the second campaign was supplied. Some outlet temperatures increase above 10 K during current variation and, therefore, this current value is higher than during the second campaign. The easiest way for stable operation of the superconducting magnet system is to increase the mass flow rate to about 50 % in PF1. It is helpful to reduce the temperature rise within about 1 K at -6 kA to 6 kA zero crossing operation and about 2 K at 10 kA trapezoidal current operation. The duration of zero mass flow also decreases from 8 s to 4 s in # 2526 shot and the PF coil recovers faster to the initial temperature than at normal mass flow rate. The mass flow increase is effective to reduce the temperature rise in case of faster current ramp rate in PF1L.

We have also increased the mass flow rate of PF2 and measured the temperature rise with the current ramp rate variation. The tendency between them could be obtained, but much data should be needed to exactly analyze the relationship and to optimize the cryoplant operation.

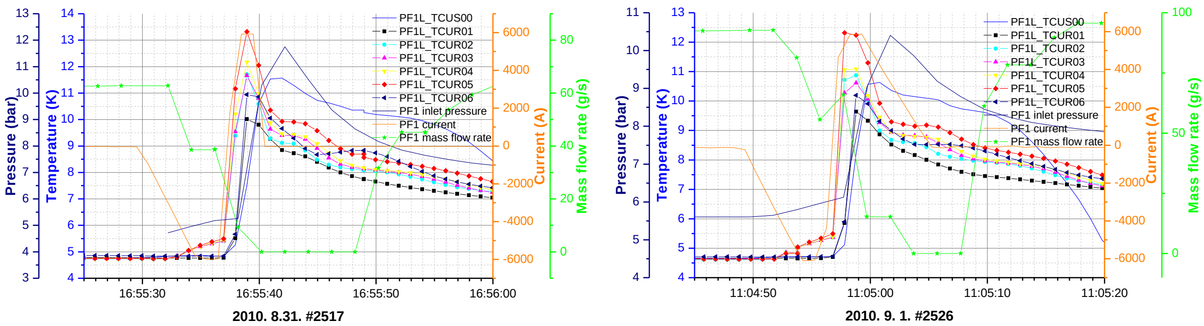


FIG. 6. Temperature rise of PF1L in normal mass flow (left) and increased mass flow (right)

We compare the two same shots except the current ramp rate during zero crossing in PF1L. The ramp rate decreased from 10 kA/s to 7 kA/s and then the temperature rise also decreased about 0.15 K. It seems that the decreased ramp rate is not an effective way to decrease the temperature rise. However we should consider the stability of not only the magnet system, but also the helium refrigeration system (HRS). It helps that the HRS was operated in the operational safety zone which is confirmed by the individual HRS test.

In addition, the blip has a role to increase the temperature about 1 K in - 3 kA to 3 kA zero crossing operation with the ramp rate of 3 kA/s however the blip duration doesn’t have large impact on the temperature rise in the same operation conditions of PF2L.

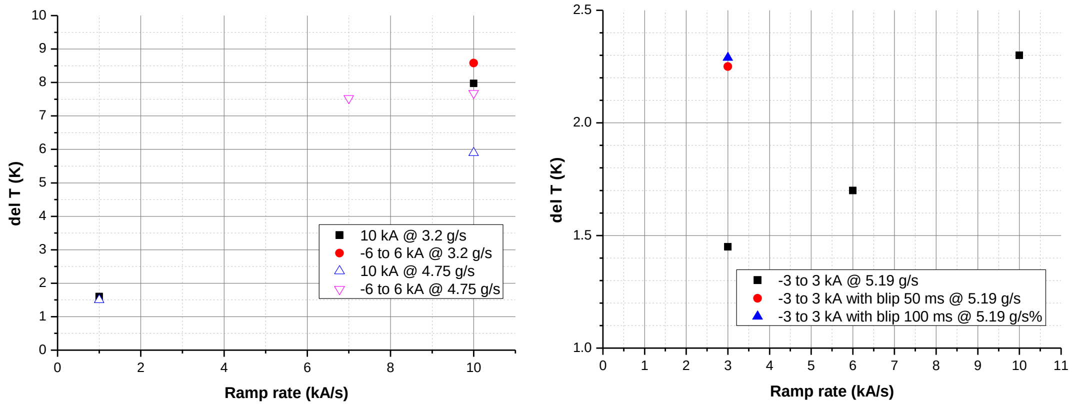


FIG. 7. Relationship between current ramp rate and temperature rise in PF1L (left) and PF2L (right)

In PF simultaneous coil test with - 3 kA to 3 kA zero crossing operation, a significant phenomenon about the superconducting magnet system can be observed. The temperature rise and the mass flow reduction of PF2L increase compared to the single coil test (#2553 shot) even though the current ramp rate decreases from 3 kA/s to 2 kA/s at #2915 shot. The difference of temperature rise is about two times in simultaneous coil test and the zero mass flow which didn’t show this at single coil test with the faster ramp rate is also observed in other PF coils such as PF1 and PF5. The heat load by AC losses of all PF coils is so complicated and then the thermohydraulic behavior is also difficult to predict and estimate exactly before real experiments.

The result from the individual coil test before the assembly of tokamak should be considered one of the useful data, not as the perfect representative information about the whole magnet system. More research is needed dealing with the integrated relationship between one component and related systems. Most of all, it is continuously required to optimize the operation procedure of the KSTAR superconducting magnet system to achieve the maximum tokamak performance.

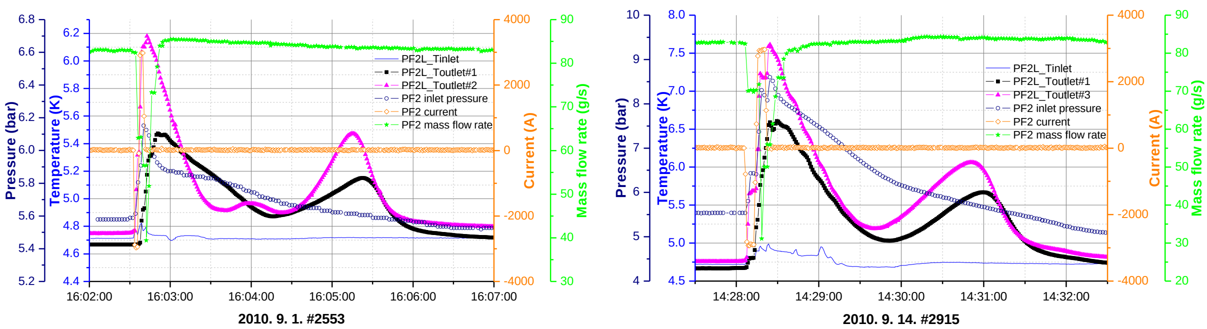


FIG. 8. Temperature rise of PF2L in single coil test (left) and simultaneous coil test (right)

5. Conclusion

The KSTAR has already carried out the second campaign and is currently in its third campaign now. Tracking of the thermohydraulic behaviors of the KSTAR magnet system using ITER-like CICC from room temperature to cryogenic temperature is underway. KSTAR has already achieved the maximum TF current of 36.2 kA and the bipolar PF coil operation during second campaign and is doing the bipolar operations up to 10 kA with 3.5 T in 2010. The thermohydraulic characteristics and behaviors like the temperature rise and the pressure drop inside cooling channels and the friction factor of CICC were measured and estimated. The data of KSTAR magnet system are consistent with our expectations within the acceptable margins. It is helpful to do the computational simulation work using the physical phenomena of experiments for the next campaign. Of course, plans to optimize the operational procedure of the superconducting magnet system for the steady state operation and the maximum performance in the tokamak are being made because KSTAR still has further goals to achieve.

Through the KSTAR campaigns, data of the superconducting magnet system using the Nb_3Sn and NbTi superconductors is being complied and it points the way to develop new superconducting tokamak like ITER, JT-60SA and, to operate the steady state tokamaks of the near future.

Acknowledgement

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