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Analysis of the flow imbalance in the KSTAR PF cryo-circuit

Hyun-Jung Lee*, Dong-Seong Park, Sang-Woo Kwag, Jae-Jun Joo, Kyung-Mo Moon, Nam-Won Kim, Young-Joo Lee, Young-Min Park, Hyung-Lyeol Yang

National Fusion Research Institute, 305-806 Daejeon, Republic of Korea

HIGHLIGHTS

- Investigate of flow imbalance trend for the KSTAR PF superconducting magnet.
- Flow imbalance is compared with individual magnet test and integration magnet test.
- Intensifying of flow imbalance is proven from the flow monitoring in the KSTAR PF circuit.
- Flow behavior is analyzed during magnet charging in the circulator circuit.
- Variation of magnet outlet temperature is analyzed due to flow imbalance.

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ABSTRACT

The KSTAR PF cryo-circuit is a quasi-closed circulation system in which more than 370 g/s of supercritical helium (SHe) is circulated using a SHe circulator. The heated helium from superconducting magnet is cooled through sub cooler (4.3 K). The circulator is operated at 4.5 K and 6.5 bar, and the pressure drop of the circuit is kept at 2 bar in order to maintain the supercritical state and circulator stability. The circuit is connected with helium refrigerator system, distribution system, and supercritical magnet system. It has a hundred branches to supply supercritical helium to the poloidal field superconducting magnet. The branch was designed to optimize the operation conditions and they are grouped for one cryogenic valve has the same length within the cardinal principle of the optimization. Five cryogenic valves are installed to control the mass flow rate, and seven orifice mass flow meters, differential pressure gauges and temperature sensors were installed in front of the magnet in the distribution because upper magnet and lower magnet is symmetric theoretically. The cryogenic pipe line was manufactured with elevation about 10 m between upper magnet and lower magnet. The inlet and outlet helium feed-through were installed at the coil inside in case of KSTAR PF1–PF5 upper magnet and lower magnet. The flow imbalance is caused by void fraction and it could be changed due to manufacturing process even if it has the same length of cooling channel. This creates an imbalance among cooling channels and temperatures are slightly different. The flow was reduced and detoured due to the pressure rise rapidly at inlet and outlet during magnet operation. Therefore, the orifice mass flow meters are installed in front of the PF1–PF5 upper magnet and lower magnet in order to investigate flow trend and the thermos-hydraulic behavior is analyzed during PF magnet operation.

1. Introduction

The Korea Superconducting Tokamak Advanced Research (KSTAR) is a fully superconducting tokamak [1], and the cooling circuit consists of three supercritical helium (SHe) circuits as well as a liquid helium circuit and a gas helium circuit as per the operation condition. The various required cryogenic helium (gaseous, liquid, and supercritical helium) were produced by a helium refrigerator system of 9 kW at 4.5 K equivalent power without LN2 pre-cooling and were provided to the cold components.

Three supercritical helium circuits were designed for the cooling of the Toroidal Field magnet and structure (TF circuit), the Poloidal Field magnet and structure (PF circuit), and the superconducting busline, respectively. The KSTAR superconducting magnet and busline are type of a Cable-In-Conduit Conductor (CICC), which has a twisted cable of hundreds superconducting strands and Cu strands with porosity 0.36 and is wrapped a Inconel 908 jacket. The SHe with force flow provides cryogenic stability and reliable

* Corresponding author.
E-mail address: yaeban@nfri.re.kr (H.-J. Lee).

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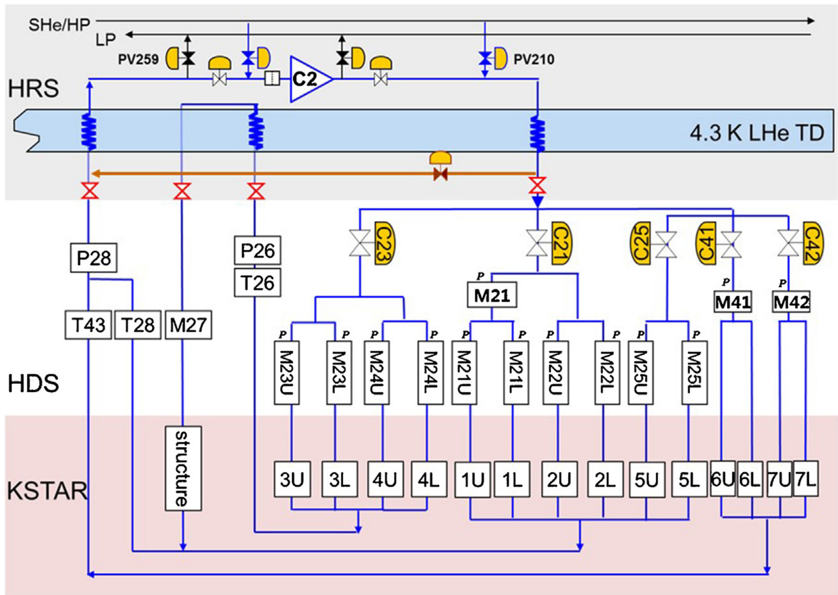

Fig. 1. KSTAR PF cryo-circuit.

Table 1
KSTAR cryo-circuits.

Circuit	Coolant	Component	Heat load (design value)	Index
Circuit 1	SHe	TF and TF structure	1.5 kW	Circulator
Circuit 2	SHe	PF and PF structure	1.7 kW	Circulator
Circuit 3	SHe	SC busline	0.26 kW	
Circuit 4	GHe	Thermal shield	2.1 kW	
Circuit 5	LHe	Current lead	17.4 g/s	

operation of the device. The TF and PF circuits with SHe circulators, which circulate a large amount of SHe effectively (>370 g/s), are quasi-closed loops. Because the flow was circulated in the steady state but it is inflow and outflow for pressure stabilization by active controlling of cryogenic valves (PV259, PV210) during the magnets operation as shown in Fig. 1. The heated helium is cool-down by a heat exchanger at the thermal damper [2,3]. The operation condition of the circulator is 4.5 K at 6.5 bar with a pressure drop 2 bar in order to maintain the supercritical state and stability of the circulator. The liquid helium circuit is for the low temperature superconducting current lead system, and the gas helium circuit (55 K) is for thermal shields (vacuum vessel, cryostat, current leads). Table 1 shows a summary of the KSTAR cryo-circuit.

The entire cooling circuit was designed according to the cooling condition and friction factor, and the flow imbalance test of the magnet cooling channels was conducted using Ar gas at room temperature during the magnet manufacturing, and it was carried out again after magnet assembly. The results satisfied the KSTAR criteria [4]. In case of the TF circuit, the mass flow rate was controlled to be uniformly distributed to the 16 geometrically symmetrical TF magnets by 4 cryogenic valves. The PF magnets were assembled into 7 pairs, and they were composed of Central Solenoid (CS) magnets, (PF1–4 upper and lower) and PF magnets (PF5–PF7 upper and lower). Thus, the mass flow rate of the PF circuit is controlled by five cryogenic valves and should be adjusted to be distributed uniformly to the upper (U) magnet and lower (L) magnets because of geometrically vertical symmetry. It means that the mass flow rate is supplied equally to upper and lower magnets theoretically, but the distributed mass flow rate to the UL magnet could be slightly different in the real system because of the friction factor difference in accordance with the pipe grouping and void fraction of the CICC as well as other reasons. In the case of the KSTAR PF circuit, the measured flow imbalance of each PF1–5UL magnets was within 10% during manufacturing period, and it could be changed during the PF magnets operation because the flow is blocked and detoured according to the generated heat load in the CICC [5]. In 2011, a quench occurred and developed for 11 s at the PF1L magnet despite the fact that the PF1UL magnets are connected in an electrical series [6]. Therefore, the orifice flowmeters were mounted on the pipeline of the PF1–PF5UL magnets in order to investigate the thermo-hydraulic behavior due to the flow imbalance between upper and lower magnets during PF magnet operation.

2. Installation of the flow meters at HDS

The KSTAR helium distribution system (HDS) distributes the cryogenic helium to the cold components. For the PF circuit, the five cryogenic valves (C21, C23, C25, C41, C42) were mounted on the helium lines to control the mass flow rate [7]. The cooling channels with the same friction factor were grouped by one cryogenic valve, which has to be adjusted according to operation mode. Although the PF1–4UL magnets have the same cooling channel length (64 m), the PF12UL and PF34UL are separated into two groups by the cryogenic valve C21 and C22, respectively, because the outlet pipe line of the PF34UL magnets has been connected with the CS structure pipe lines. The flow of the PF5–7UL magnets (the length of the cooling channel: 175 m, 310 m, and 280 m) is controlled by C25, C41, and C42, respectively, and seven mass flow meters (M21, M22, M23, M24, M25, M41, M42), pressure transmitters, and a pair of temperature sensors were installed in the manifold for the monitoring of the helium behavior as shown in Fig. 1.

For the imbalance analysis between upper and lower, 10 flow meters (M21–M25UL) were installed in 2014 and M22, M23, M24, and M25 were dismantled from the pipeline. M21 was kept for accurate comparison of the measured mass flow rate and the new flow meters were located in a symmetrical place between the upper and lower pipelines. A detailed layout of the PF circuit is shown in Fig. 1. Two types of the new orifice were designed: one for the PF1UL and PF2UL magnets and the other for the PF3–5UL magnets. The specification of the orifice is summarized in Table 2.

The beta ratio of the orifice was optimized to minimize the pressure loss because it affects the operation condition of the SHe circulator. As a part of the quality assurance before the installation