Influence of Inlet Pressure and Mass Flow Rate on the Temperature Rise of Superconducting Strands in SSTF Under the Normal Operating Conditions

Cheon Seog Yoon, Qiuliang Wang, Yeong Sung Suh, Sun Woong Choi, Wooho Chung, Hyunki Park, and Keeman Kim

***Abstract*—In order to estimate the operating characteristics of the main coils, blip and compensating coils of SSTF (Samsung superconducting test facility) which will be operated under the pulsed field to simulate the operating scenarios of KSTAR (Korean Superconducting Tokamak Advanced Research), an analysis has been performed to study the influence of cryogenic parameters, such as inlet temperature, pressure and mass flow rate on the temperature margin for the main, blip and compensating coils. The temperature margin is studied under the given operating scenarios. The reduction of mass flow rate and peak temperature rise, which are strongly depending on the inlet pressure and inlet position of supercritical helium in the CICC (Cable-In-Conduit Conductor) are studied. It is noticed that the initial mass flow rate remarkably influences on the peak temperature of superconducting strands. The large mass flow rate can reduce the temperature rise when the helium inlet is installed at the high field region. On the other hand, the small initial mass flow rate results in the low peak temperature in strands when the helium inlet is located at the low field region, since the heat induced flow occurs to improve the cooling condition of the superconducting strands.**

***Index Terms*—CICC, superconducting magnets, superconducting test facility, transient thermal analysis.**

I. Introduction

THE MAJOR mission of SSTF is to test short samples of CICC and superconducting magnets in KSTAR device, such as toroidal and poloidal field coils. The planned parameters of SSTF magnets including size, field and ramp rate of the main coil (MC) will verify that this facility is one of the most universal and powerful all over the world for testing of large superconducting magnets [1]. To simulate the operating conditions of KSTAR, the main, blip and compensating coils should operate under the pulsed current and field. The main coils give birth to a pulsed background field, and the blip coils generate a fast varying field at the center of SSTF. The compensating coils are designed to eliminate voltage imposed on the main coil while the blip coils discharge. According to the operating condition, the large thermal loads of AC losses in strand lead to the temperature rise in the strands and generate the thermal expansion of supercritical helium. Notice is hereby given that the heat deposition and transfer in the coils are studied. If the temperature rise reaches to the current sharing temperature of superconducting strands, the Joule heat is generated in the superconducting strands and then the magnet may be in the quench state [2]. In the design stage, the transient process of normal operation must be considered to calculate the temperature margin and maximum energy deposition in the main, blip and compensating coils.

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Fig. 1. Configuration of SSTF, which includes transformer, supporting structure, main, blip and compensating coils.

II. SSTF Magnets and Mail Design Parameters

The configuration of the SSTF test device is shown in Fig. 1. Two halves of the split main coil (MC) generates the background magnetic field up to 8 T at the center of magnet. The nominal gap size between these two coils is 250 mm and can be increased up to 750 mm, and MC should withstand charging or discharging at ramp rate up to 3 T/s. Two halves of blip coils (BC) produce an additional field up to 1 T in the same gap, along or in opposite direction to the MC field. These coils should be able to produce the field variation rate up to 20 T/s being discharged exponentially with time constant, 50 ms. Two halves of compensating coils (CC) are used to reduce the electromagnetic influence of BC on MC. Superconducting transformer (ST) can supply the tested sample with the current up to 50 kA in 1 s. The main coils consist of eight double pancakes. Each main

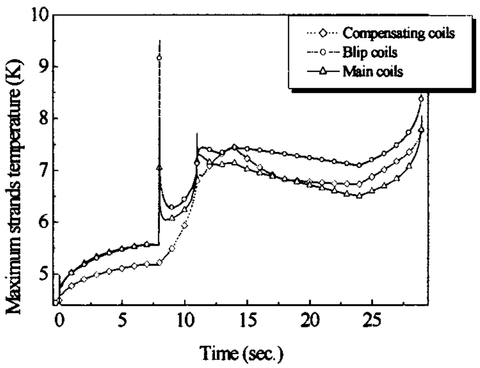

Fig. 2. Profiles of maximum peak temperature of superconducting strands versus time for the main, blip and compensating coils.

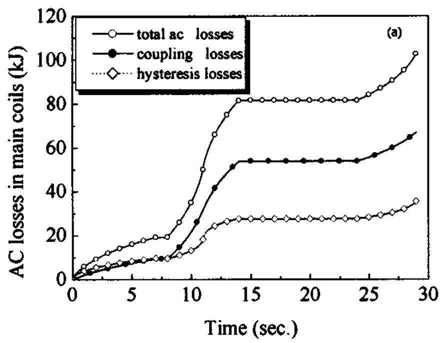

Fig. 3. Coupling, hysteresis and total losses in main coils with respect to time.

coil is divided into four cooling channels because of acceptable pressure drop and pre-cooling time. The blip and compensating coils have a solenoid-shaped structure. The place of the cold helium inlet is selected by design considerations for the blip and compensating coils. Inner side of blip coils is pressed to inner flange of main coils in the cryostat wall through blip and compensating coils. Outer side of compensating coils is in touch with the flange that provides pressing force. So all current and helium feeders should be shifted between blip and compensating coils, where they have free sides. Because the inner layers of coils have short lengths, the inlet is placed between the third and fourth layer, which counted from inside, meanwhile the total number of layers in this coil is six. The outlets are at the beginnings of the 1st layer and at the end of 6th layer, just in the liquid helium baths. The inlet temperature and pressure for main coils are 4.5 K and 0.6 MPa, respectively, and the inlet temperatures for the blip and compensating coils are 4.4 K.

III. The Temperature Margin and Transient Heat Removal Characteristics in SSTF

A numerical code, quasithree-dimensional model, simulates the conductor temperature rise due to the high AC losses in the pulsed magnetic field in SSTF [3]. Since the long pulse operation of SSTF, the effect of nonuniform current distribution is assumed to be small. The heat coupling terms between turns, layers, pancakes and channels are included in the equations of mass, momentum and energy conservation of supercritical helium. The calculation of AC losses is based on an analytical

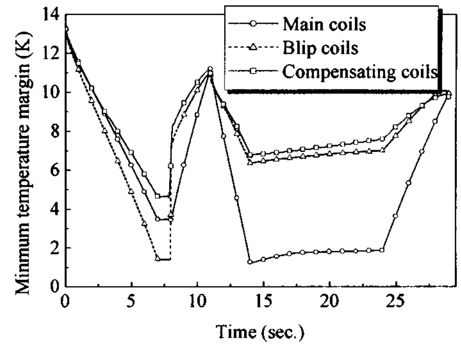

Fig. 4. Temperature margin in SSTF for given operating condition.

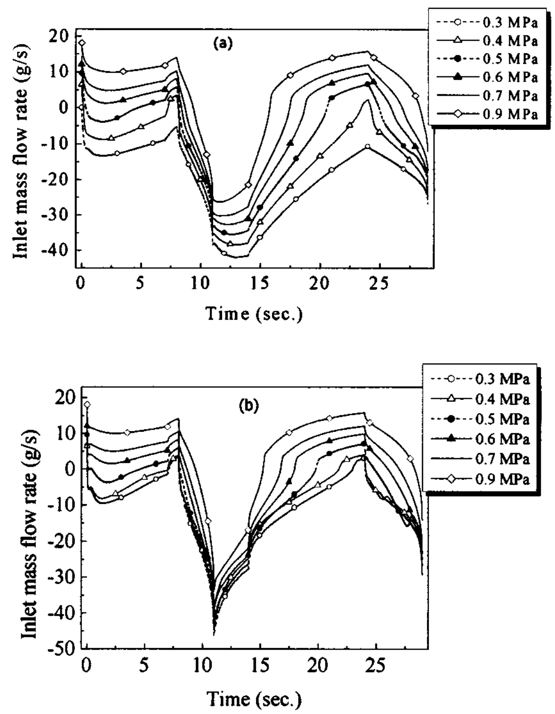

Fig. 5. Inlet mass flow for various inlet pressures and inlet positions in the main coils, the outlet pressure of 0.3 MPa, (a) helium inlet located at the low field region and (b) helium inlet located at the high field region.

model and includes the coupling, eddy current and hysteresis losses. Based on the previous statement as above, new code has been developed and used to the analysis of transient thermal characteristics and the energy deposition in the SSTF magnet system. According to the operating condition, the maximum temperatures in the superconducting strands of main, blip and compensating coils with respect to time are shown in Fig. 2. The fast current variation for the blip and compensating coils generates a sharply increasing the temperature in the superconducting strands. The maximum peak temperatures for the blip and compensating coils are about 9.5 K and 8.02 K, respectively. Since helium absorbs the AC losses and heat induced flow occurs, the heat transfer coefficient between the supercritical helium and the stands is remarkably increased. The increasing heat transfer of the helium can suppress the temperature rise of strands. After the fast discharging the blip and compensating coils, the temperature of the strands in the two coils is rapidly decreased. The peak temperature of 7.9 K for the main coils is located at time

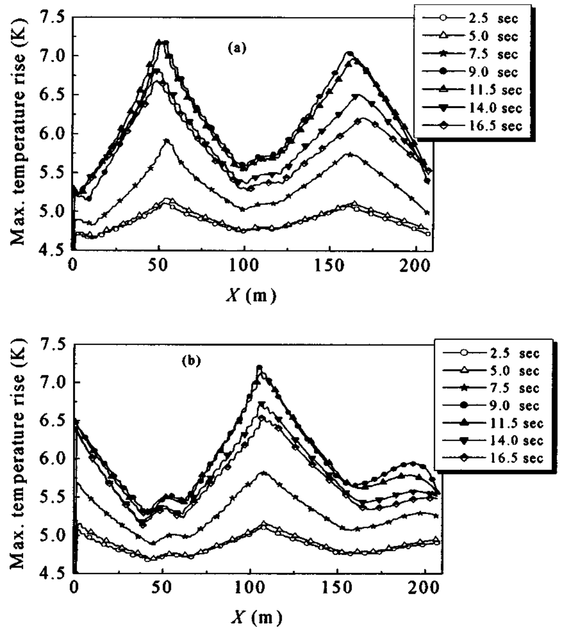

Fig. 6. Profiles of superconducting strands temperature versus space coordinate for inlet pressure of 0.6 MPa and outlet pressure of 0.3 MPa, (a) helium inlet located at the low field region and (b) helium inlet located at the high field region.

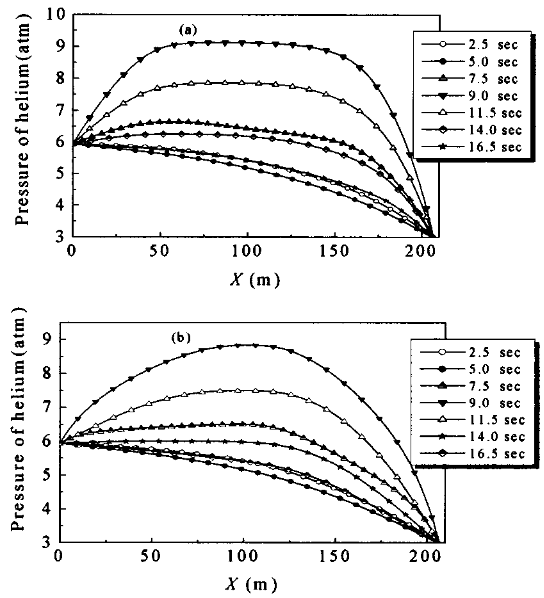

Fig. 7. Profiles of pressure of helium with respect to space coordinate for inlet pressure of 0.6 MPa and outlet pressure of 0.3 MPa, (a) helium inlet located at the low field region and (b) helium inlet located at the high field region.

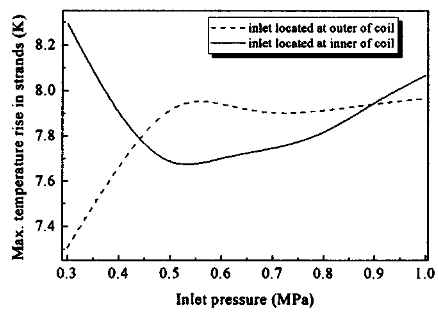

Fig. 8. Variation of the maximum peak temperature rise in superconducting strands with inlet pressure and positions for the outlet pressure kept in constant of 0.3 MPa.

of 29 s, i.e., the main coils are fully discharged. The temperatures of the coolant and strands are increased due to the AC losses of the pulsed operation. The friction of the cooling paths is increased by the temperature rise of the coolant, and it increases the pressure drop of the cooling path. The AC losses for the main, blip and compensating coils that include the coupling, hysteresis and total losses are illustrated in Fig. 3. From the Fig. 3, the coupling loss in the main coils is much higher than hysteresis losses.

The temperature margin of the SSTF is plotted in the Fig. 4. The minimum temperature margin for the main, blip and compensating coils are approximately 1.29 K, 1.44 K and 4.3 K, respectively. Fig. 5 plots the inlet mass flow rate with respect to time for various inlet pressures of the inlet location at the high field region of innermost turn and at the low field region of outermost turn of main coils when the outlet pressure is fixed at 0.3 MPa. The higher inlet pressure can abundantly reinforce the supercritical helium after the fast charging and discharging the main coils.

As in Fig. 6, the temperature distribution of superconducting strands is illustrated for inlet location at the high and low field regions when inlet pressure is 0.6 MPa, respectively. The maximum temperature rise of strands is influenced by the initial mass flow rate and inlet position of helium.

The pressure profile with respect to the space coordinate is shown in Fig. 7. The maximum pressures are located at the upstream and downstream in the flow path for the inlet position of helium located at the innermost and outermost turn of main coils, respectively. Fig. 8 illustrates the temperature rise of strands with respect to the inlet pressure and the varieties of inlet position of helium. If the helium inlet is located at the low field region, i.e., the helium inlet is at the outermost turn of the main coils, low inlet pressure can reduce the maximum temperature of strands. On the other hand, when the helium inlet of CICC is located at the high field region, i.e., the helium inlet is at the innermost turn of the main coils, there is an optimum inlet pressure that corresponds to the minimum value of the maximum peak temperature rise of strands in the main coils. The steady state heat transfer coefficient, h, between helium and superconducting strands depends on the helium velocity, u, i.e., $h \propto u^{0.8}$.

According to Fig. 6, the maximum temperature rise of strands is near to the upstream zone. Because the high AC losses due to the fast variation of the current and field are deposited in the superconducting strands, and the energy is absorbed by the helium. The heat induced flow can remarkably suppress the maximum temperature rise of strands. The low inlet pressure causes the high heat induced velocity in the upstream of the CICC, i.e., the circumferential expansion velocity of helium is $u = |u_{hif} - u_{in}|$ in upstream, where u_{hif} and u_{in} represent the heat induced flow velocity and initial flow velocity of helium, respectively.

Thus, the heat transfer coefficient between the helium and strands strongly increases to suppress the maximum temperature rise. By contrast, when the helium inlet is located at the

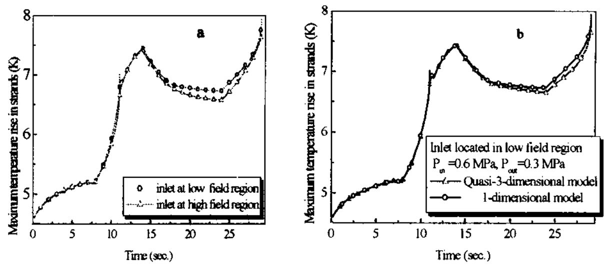

Fig. 9. Maximum peak temperature of main coils versus time for inlet pressure of 0.6 MPa and outlet pressure of 0.3 MPa, and helium inlet located in the low field region and the high field region (a) for various heat transfer models such as 3-d and 1-d (b).

high field region, the maximum temperature rise of strands is located at the downstream region. The high inlet pressure issues in the large helium mass flow, i.e., the total velocity is $u = |u_{hif} + u_{in}|$ in the downstream of flow path. The helium with the high initial flow velocity and high inlet pressure are able to improve the cooling condition between the helium and strands [4]. But, high helium flow velocity induced to the large friction losses to increase the strand temperature. This depends on the thermal equilibrium between the heat generation and convective heat transfer. Thus, there is an optimum inlet pressure corresponding to minimum temperature rise of strands and the inlet position of helium has an influence on the peak temperature rise of superconducting strands. The profile of the peak temperature in the strands of main coils with respect to time is illustrated in Fig. 9(a). It is noticed that the temperature of strands is lower than that of helium inlet located at the high field region. The difference is about 0.25 K for the inlet pressure of 0.6 MPa.

In reality, the thermal coupling between the pancakes and various cooling channels should be taken into account. The temperature profile with respect to time is plotted in Fig. 9(b), where the thermal coupling is included in the quasithree-dimensional model and that is not included in the one-dimensional model (adiabatic model). The temperature of the thermal coupling is lower than that of without thermal coupling, and its difference is about 0.16 K.

IV. Discussions

The influence of inlet pressure and mass flow rate on the temperature margin and heat removal characteristics in SSTF are studied. The high AC losses due to the pulsed current generate the helium expansion and reduction of the inlet mass flow. The inlet pressure of helium has an influence on the maximum temperature. Since the heat induced flow of helium occurs to improve the cooling condition of superconducting strands, the low inlet pressure leads to the small peak temperature rise in the strands for helium inlet located at the low field region. The initial helium mass flow rate can influence the maximum peak temperature rise. According to the simulation, it is advantage to install the helium inlet at the high field region because this limits the maximum temperature rise. There is an optimal inlet pressure for the fixed outlet pressure when the helium inlet is located at the high field region. Furthermore, the simulation shows that there is large temperature difference between the superconducting strands and helium during fast charging and discharging the blip and compensating coils. The maximum temperature depends not only on the initial helium mass flow, but also on the inlet position of helium.

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