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Cryogenic Characteristics of a Large Thin Superconducting Solenoidal Magnet Cooled by Forced Two-phase Helium

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A prototype thin superconducting solenoidal magnet for the SDC detector (Solenoidal Detector Collaboration for the former SSC project) was developed. The magnet was cooled down and excited up to 12,000A in the performance test at KEK. The magnet is 3.8 m in diameter, 2 m in length with a total cold mass of 4.5 tonnes. It was cooled by using indirect two-phase helium flow passing through a 64 m serpentine cooling path. The hydrodynamic characteristics has been investigated. The measured result and preliminary analysis are discussed.

INTRODUCTION

The SDC detector required a large thin superconducting solenoidal magnet to provide an axial magnetic field of 2 T over the particle tracking volume [1]. A full size solenoidal magnet was designed to be 3.8 m in diameter and 8.8 m in length. In order to investigate the feasibility of the magnet, a full diameter and a quarter length prototype magnet was designed and developed successfully.

The prototype magnet was cooled by using a helium refrigerator with a cooling capacity of 700 W at 4.4 K. It took five days to cool the magnet by single-phase cold gas of 20 g/s supplied by the helium refrigerator.

In order to study hydrodynamic characteristics of a 64 m serpentine cooling path, single-phase helium mass flow $\dot{m}$ and pressure drop ΔP were measured at 289 K, 254 K, 230 K, 83 K and 5.2 K. Experimental results agreed with the prediction based on the frictional pressure drop at turbulent condition. However, in case of two-phase helium cooling, the pressure drop indicated higher value than the predicted one. Also, at high mass flow condition, a slight pressure oscillation was observed, although it did not make serious effect on magnet operation.

MAGNET HEAT LOAD

Figure 1 shows the isometric view of the prototype magnet. The magnet is 3.8 m in diameter, 2 m in length with a total cold mass of 4.5 tonnes. A helium cooling pipe of 25 mm in diameter and 64 m in length was welded on to the outer surface of the support cylinder with a single serpentine configuration. Forced two-phase helium flow was used to cool the magnet. The magnet heat load was measured by three different ways. These methods are based on:

- helium consumption when the magnet was cooled only by liquid helium supplied from the dewar (this was done in the preliminary test at the manufacture);
- enthalpy difference in single-phase helium gas at around 5 K;
- rate of magnet warming up after cooling stop.

As a result, the heat loads of the magnet and the chimney pot were estimated as 11 W and 16 W, respectively, with consistency among three independent tests.

CRYOGENIC SYSTEM

The magnet was cooled by using a cryogenic facility in the East experimental hall at KEK. It was connected to a dedicated helium refrigerator having a 3,000 L liquid helium dewar through ~60 m long insulated transfer lines.

Figure 2 shows a schematic diagram of the magnet cooling system. The helium refrigerator has a cooling capacity of 700W at 4.4 K, or liquefaction capacity of ~200 L/h by using two L'Air liquid turbines. Two MYCOM screw compressors with flow capacities of 1,100 and 1,900 Nm³/h, respectively, are operated to feed the pressure of 1.5 MPa helium gas for the Brayton-cycle refrigerator.

The cryogenic system is controlled by the CENTUM computer system. Main operations such as compressor starting-up, system gas purification, cold box cool down, gas temperature control, emergency sequence operation, etc. can be carried out automatically.

MAGNET COOL DOWN

To avoid excessive thermal stress, the magnet was cooled gently at cooling speed of ~3 K/h down to 80 K. Precooling gas temperature was controlled by mixing warm and cold gas properly at the cold box exit. After the magnet temperature reached at ~80 K, two turbines were started. It took five days to cool the magnet from 300 K to 4 K. Figure 3 shows the temperature profiles of the magnet coil, support cylinder and the radiation shield.

During cool down, single-phase helium mass flow and the pressure drop were measured at 289 K, 254 K, 230 K, 83 K and 5.2 K. Figure 4 shows the relationship between $\dot{m}$ and ΔP at 289, 230 and 83 K. At high temperature, there are some discrepancy between the prediction and measured values, and good agreements were obtained at 230 K and 83 K.

Based on the measured relationship of $\dot{m}$ and ΔP , hydrodynamic characteristics of the magnet cooling path was investigated. Only the frictional pressure drop should be considered in this case. In case of the turbulent flow, the theoretical pressure drop ΔP is given by [2]

$$\Delta P = (\lambda_s \frac{L}{D} + n\zeta_b) \left(\frac{8\dot{m}^2}{\pi^2 D^4 \rho_G} \right) \quad (1)$$

$$\lambda_s = \frac{0.3164}{Re^{0.25}} \quad (2)$$

where, λ_s is the friction factor of the cooling pipe, L is total length of straight pipe (58 m), D is the pipe diameter (0.025 m), n is the total number of bends (54), ζ_b is the coefficient of pressure drop in bend (0.175), ρ_G is the density of saturated gas helium and Re is the Reynolds number. Substituting $\rho_G(P, T) \propto T^{0.972}$ and viscosity $\eta(T) \propto T^{0.647}$ into equation (1), pressure drop is given by

$$\Delta P \propto \dot{m} T^{1.13} \quad (3)$$

and then,

$$\frac{\Delta P}{\dot{m}} \propto T^{1.13} \quad (4)$$

Figure 5 shows the $\Delta P/\dot{m}$ at each temperature and fitting line represented by equation (4). This diagram is useful to estimate single-phase helium mass flow at any precooling temperature, only by measuring pressure drop across the magnet.

TWO-PHASE HELIUM COOLING

Under the steady two-phase cooling condition, the minimum mass flow was measured, which is defined as flow required to keep the magnet temperature and helium level in the chimney LHe pot constant. It was measured to be 5.36 g/s. In this case, evaporated gas of 3.5 Nm³/h in each current lead was used to cancel heat input through the current leads.

Based on the minimum mass flow, the heat load of the 58 m long helium transfer line was calculated to be 71 W at 4.6 K. Helium quality at the inlet and outlet of the magnet were also calculated to be 0.74 and 0.84, respectively.

A high precision differential pressure transducer was used to monitor the pressure drop across the magnet. The pressure drop was measured with a precision of ± 0.25 % F.S. (± 0.05 kPa). Helium mass flow, the inlet and outlet pressures were measured by absolute-type pressure gauges and orifice flow meter, respectively.

Figure 6 shows the relationship between mass flow and the pressure drop of two-phase flow. Up to 7 g/s, the pressure oscillation did not occur. It is interesting that the pressure drop starts to fall at around 6.5 g/s of mass flow.

Although two-phase helium of ~6 g/s (quality is around 0.7-0.8) flows through the 64 m long cooling path with pressure drop of only ~1.5 kPa, experimental results indicate much larger pressure drop than the prediction based on the separated two-phase flow model[3][4]. This large discrepancy will be investigated.

Slight two-phase flow oscillations were observed at relatively high mass flow region. When the mass flow was increased to ~10 g/s at the full excitation, the pressure oscillation occurred with a time period of 5-6 s. The amplitude of differential pressure across the magnet oscillated with 1.7 kPa peak-to-peak, at the mean pressure of 2.06 kPa. The magnet inlet and outlet pressure oscillated with 0.98 kPa and 0.25 kPa peak-to-peak, at the mean pressure of 0.129 MPa and 0.127 MPa, respectively. Both the coil and support cylinder temperature were slightly affected possibly due to this oscillation. The coil temperature increased ~10 mK, and the support cylinder temperature increased ~40 mK compared to the steady state. Slight oscillations were observed for hours, but the magnet was operated without any problem.

EXCITATION AND QUENCH RECOVERY

The nominal operating current of full size SDC magnet is 8,000 A, providing 2 T as a central magnetic field associated with iron yoke. The prototype magnet was excited up to 12,000A with a central field of 1.5 T and the maximum field of 3.8 T in the coil without iron yoke to verify the required performance.

The magnet performance test was successfully carried out for over a month, achieving nearly 50 excitations and 25 quenches induced by using heaters etc. without any permanent damage. Details of the magnet performance test will be presented elsewhere soon [5].

CONCLUSION

A large thin superconducting solenoidal magnet was successfully cooled and excited at KEK. Hydrodynamic characteristics of the magnet cooling path, such as temperature dependence of the single-phase pressure drop, two-phase pressure drop, etc. were experimentally investigated. Slight oscillations were observed during two-phase steady cooling, but magnet was operated without problems. The magnet performance test was carried out successfully, achieving nearly 50 excitations and 25 quenches.

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Figure 1 SDC prototype magnet

Figure 3 Cool down characteristics

Figure 5 Measured $\Delta P/\dot{m}$ - T relationship

Figure 2 Magnet cooling system at KEK

Figure 4 Single-phase pressure drop at 289, 230 and 83 K

Figure 6 Two-phase pressure drop