LN2 forced flow cooling on HTS power cables

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A high temperature superconducting power cable requires forced flow cooling. Liquid nitrogen is circulated by a pump and cooled back by cooling system. Typical operating temperature range is expected to be between 65K and 77K. A subcooler heat exchanger uses saturated liquid nitrogen as a coolant to cooling the circulating liquid nitrogen stream that cools the HTS power cable. The HTS power cable needs sufficient cooling to overcome its low temperature heat load. To achieve successful cooling, it is required to investigate the hydraulic characteristics to design the cables. Especially, the pressure drop in the cable is an important design parameter, because the pressure drop decides the length of the cable, capacity of the coolant circulation pump and circulation pressure, etc. This paper describes measurement and investigation of the pressure drop of the cooling system.

INTRODUCTION

The discovery of high temperature superconductors in 1986 by Bednorz and Muller has refreshed the research in the field of superconducting cable. In the superconducting state, the maximum current density for which current flows with no electrical resistance can be made extremely large.

The HTS power cable is cooled with forced flow of subcooled liquid nitrogen. The heat leak into the cable or dissipated heat in the cable itself is absorbed by liquid nitrogen. The amount of heat, which can be absorbed by liquid nitrogen at a given mass flow rate, is limited by the freezing temperature of nitrogen at the cold end and the critical temperature of the conductor at the warm end. Thermal load of the HTS cable is determined on the basis of a unit length. In other words, the total refrigeration load depends on the length of the cable. The thermal load from surroundings and electrical heating load depend on the thermal performance of the cryostat installed in the system. Therefore the hydraulic characteristics of the HTS power cable must be well investigated to design the cables. Especially, the pressure drop in the cable is an important design parameter, because the pressure drop decides the length of the cable. Corrugated pipes may be adopted as the guide pipes of refrigerant due to flexibility of those pipes. The current cable cooling system design is based upon corrugated flexible cryostat.

Unfortunately the friction factor in corrugated pipes has not been studied sufficiently[1]. Weisend II and Van Sciver reported the dependence of the friction factor on Reynolds number, however their results are for smaller diameter bellows[2]. The modified Blasius equation which is proposed by S. Fusino et al. shows a good agreement with the experimental data in above 1.0×10^4 Reynolds number region[3]. However, geometric shape of S. Fusino et al. is not suitable for the current cable cooling system. Consequently, we measured the pressure drop through the cable cooling passage, control valve, and mass flowmeter for various mass flow rates.

DESCRIPTION OF THE COOLING SYSTEM

The cooling system of the HTS power cable is shown in Figure 1. The length of cryostat is 30m, the maximum flow rate of liquid nitrogen is 0.5kg/s. Sub-cooled liquid nitrogen is divided into cable passage and termination cooling passage in the distribution box. Liquid nitrogen of the cable cooling passage flows into a inner tube(former) and returns through the space between the former outer surface and cable cryostat inner surface. The termination cooling passage is composed of two supply passages for two terminations and one return passage. The liquid nitrogen supply and return lines are connected using bayonets. The pressure tank serves to maintain the circulating loop pressure. The internal circulation loop consists of the circulation pump, followed by the subcooler. The subcooler heat exchanger uses saturated liquid nitrogen boiling on the shell side to subcool the circulating liquid nitrogen stream that cools the cable system. The nitrogen gas boiled off in the subcooler can be directly vented to atmosphere or can be discharged through a vacuum pump system. The vacuum pump system is used to produce sub-atmospheric pressure on the shell side of the subcooler heat exchanger to keep temperature below 77 K. The auto filling system is used to replenish the liquid nitrogen boiled off in the subcooler. The heat loads were determined by measurements of the temperature drop across the subcooler and measured flow rates of liquid nitrogen. The pressure drops in the cooling system are calculated from pressure gauge measurements(see Figure 1).

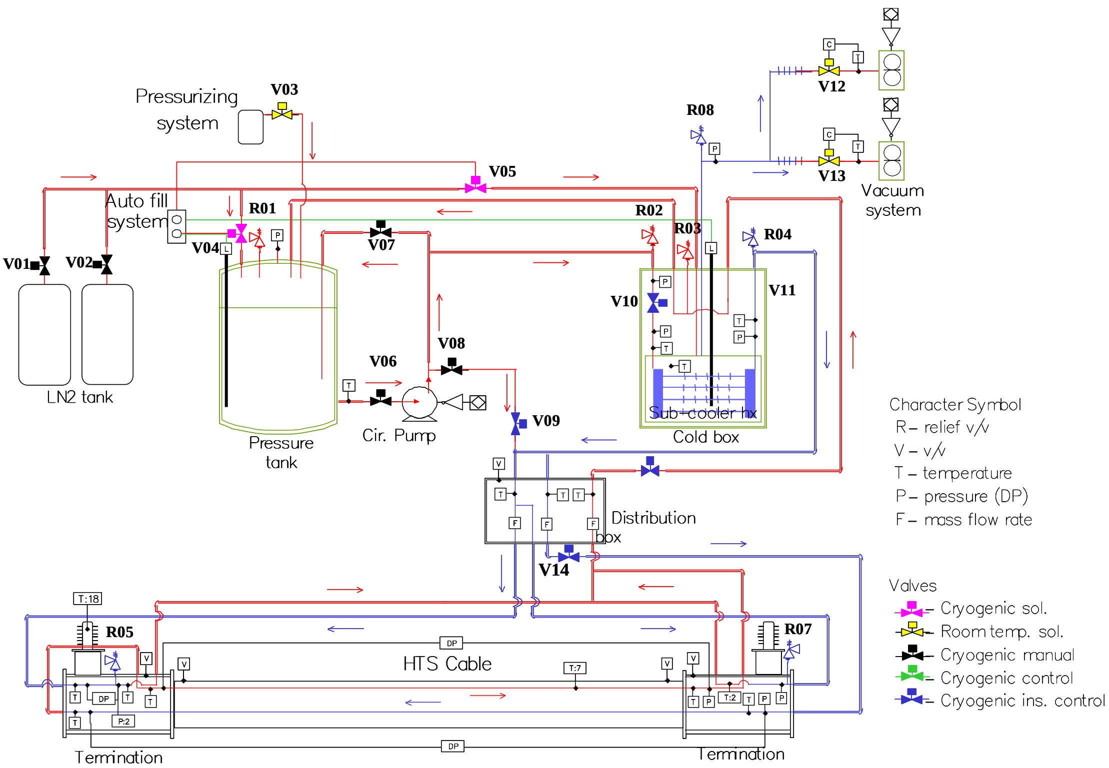

Figure 1 The schematic diagram of the HTS power cable cooling system

EXPERIMENTS

The pressure drop along the cooling passage is main design parameter of long cable cryostat, because structural strength, length, circulation pressure and pump power are decided by the pressure drop. In general, a pressure drop of a flow passage can be expressed by mass flow rate, hydraulic diameter, length of flow passage and friction factor[4]. The steady state pressure drop of liquid nitrogen dP(MPa) in the cooling passage is given by the following equation,

$$\Delta P = 2 f \rho v^2 L / D \tag{1}$$

where f is the friction factor of the cooling passage, ρ (kg/m^3) is the density of subcooled liquid nitrogen, v(m/s) is the velocity of liquid nitrogen in the cooling passage, L/D is ratio of the cooling passage length and diameter. The pressure drop of the corrugated cooling passage is larger than the smooth passage, because generally the complex flow patterns (such as the re-circulation, flow reattachment, and etc.) enlarge the friction. The friction factor f is expressed by the following experimental correlation[5],

$$f = 2.596(e/d_e)^{1.08}(P/d_e)^{-0.57} \tag{2}$$

where e(mm) is the rib height of corrugated tube(cooling passage) , p(mm) is the pitch of the rib, d_e is the average diameter of the corrugated tube.

The pressure drop through the supply and return cooling passages of the cable is shown in Figure 2. The pressure drop increases as the mass flow rate increase. Especially, the pressure drop of the supply passage is bigger than that of the return passage because the area of the supply flow passage is bigger than that of the return flow passage. Figure 3 shows the variation of the pressure drop of the termination cooling passage when the mass flow rate increases. Since the flow passage of high pressure region is designed more complex, the pressure drop of the high pressure region is bigger than that of the low pressure region.

Figure 4 shows pressure drop through the flowmeters(coldbox, cable, termination) when mass flow rate increases. The pressure drop is proportional to the square of the mass flow rate and the increases of the mass flow rate yields the huge increases of the pressure drop. The whole liquid nitrogen flows through the cold box flowmeter and is divided into cable passage and termination flow passage in distribution box. Therefore the mass flow rate passing through each flowmeter is different.

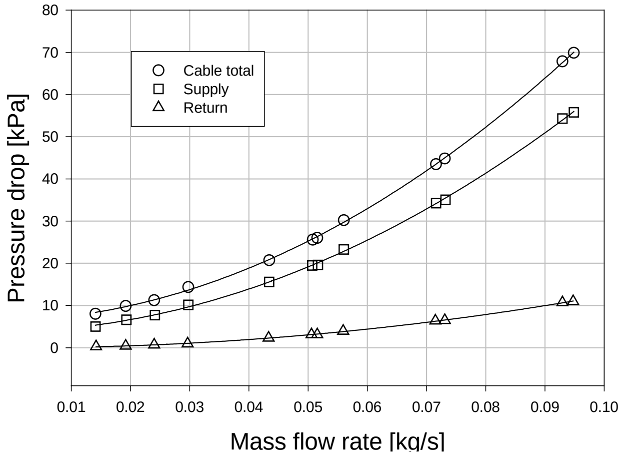

Figure 2 Pressure drop of the cable cooling passage versus mass flow rate.

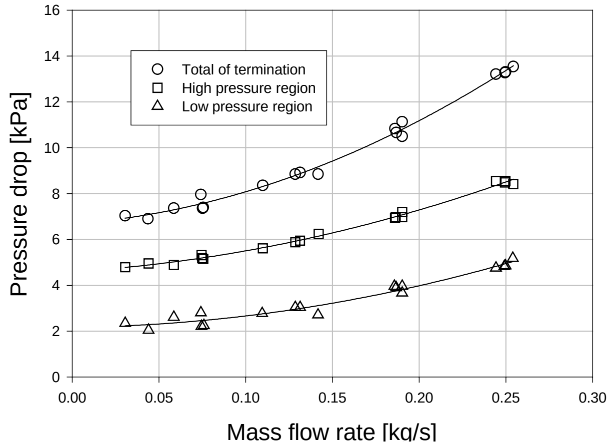

Figure 3 Pressure drop of the termination cooling passage versus mass flow rate.

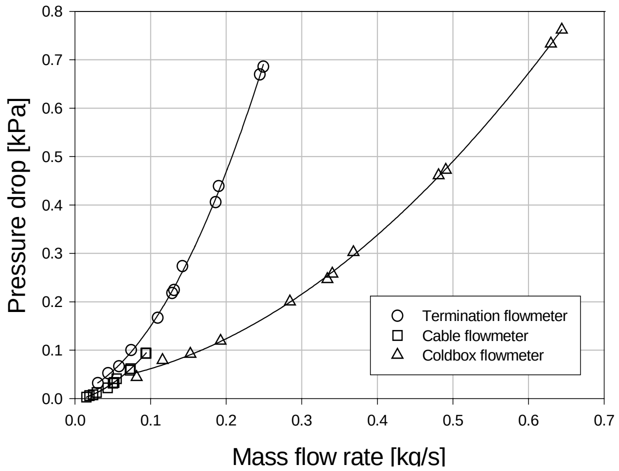

Figure 4 Pressure drop through the each flowmeter versus mass flow rate.

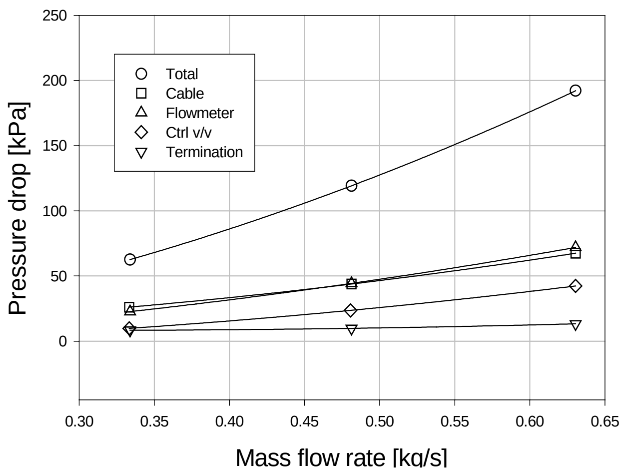

Figure 5 Pressure drop of the each compoment of the cooling system versus mass flow rate.

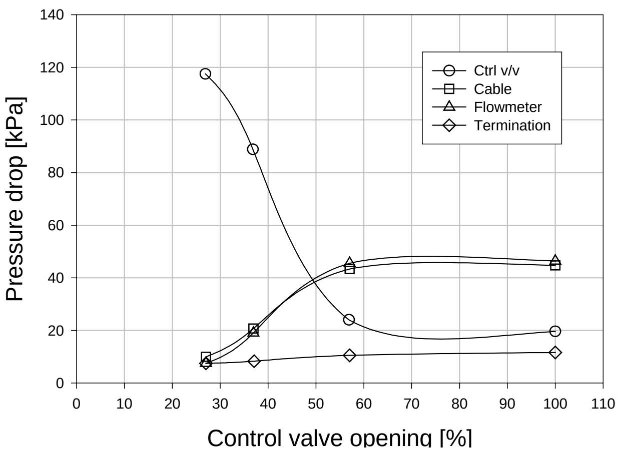

Figure 6 Pressure drop of the each component for the control valve opening.

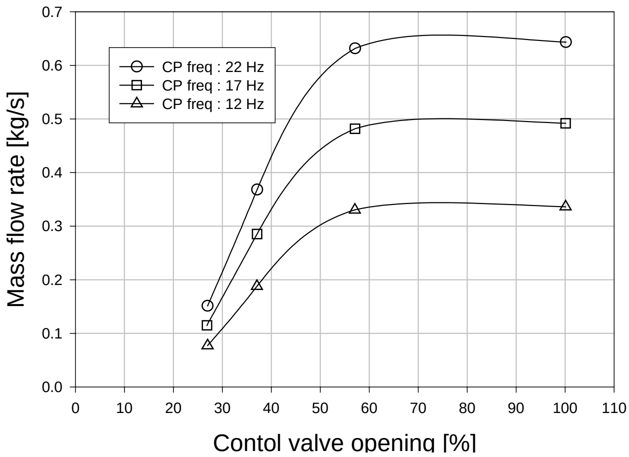

Figure 7 Mass flow rate versus control valve opening rate with various pump frequency.

Figure 5 shows pressure drops of the components(cable, termination, flowmeter, control valve) when flow control valve opens 57%. Pressure drops through the cable and flowmeter have almost same value and it is bigger than the other components. Because the cable flow passage is longer than the termination flow passage and the passage three flowmeters installed in the system. The pressure drop through the flow control valve shows small when valve opens 57%. On the other hand, the pressure drop through the valve is biggest when the flow control valve opens below 45%.

It shows that pressure drop of the components for the control valve opening in Figure 6. The pressure drop through the flow control valve is very high as valve opens below 45%. In order to reduce the total pressure drop of the cooling system, liquid nitrogen flow rate is controlled by rotational speed of the circulation pump as the flow control valve has been kept opening over 45%. Variation of the mass flow rate with the flow control valve opening rate is shown in Figure 7. When the flow control valve opens over 60%, the mass flow rate becomes nearly constant and it means that pressure drop is nearly constant.

CONCLUSION

Pressure drop characteristic of the cooling system for the HTS power cable is analyzed by experiments with the following results.

(1) The pressure drop through the flowmeters is proportional to the square of the mass flow rate.
(2) The pressure drop through the flow control valve is very high as valve opens below 45%.
(3) In order to reduce the total pressure drop of the cooling system, the flow rate of liquid nitrogen must be controlled by rotatonal speed of the circulation pump as the flow control valve opens over 45%.

ACKNOWLEDGEMENT

This research was supported by a grant from Center for Applied Superconductivity Technology of the 21st Century Frontier R&D Program funded by the Ministry of Science and Technology, Republic of Korea.

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