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A Study on the Thermal Characteristics of the Epoxy Insulator in the Stop Joint Box of HTS Power Cable

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Abstract

The HTS power cable is cooled by the circulation of liquid nitrogen. The cooling capacity of refrigerator increases with cable length. As the length of power cable increases, a joint box should be installed to reduce the cooling capacity and pressure drop for unit cooling system. The type of joint box can be divided into two groups. There are NJB(Normal Joint Box) and SJB(Stop Joint Box). Generally, SJB can separate each cooling system. In case of long distance DC cable, it is necessary to separate the cooling line in the regular distance of cooling system so SJB should be used. However, SJB, which has a difference from the insulation method of existing joint box, uses solid electrical insulation method. At the primary cooling time, thermal stress is generated by the temperature difference between the internal and external epoxy. So to prevent the damage stress analysis is required for the electrical insulation structure of SJB. In this paper, using the FEM analysis we study the cooling method and optimal shape of SJB to reduce the thermal stress result from temperature difference during the cooling time.

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Keywords: HTS power xable; stop joint box; thermal stress

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1. Introduction

According to the continuous development of HTS (High Temperature Superconductor) tape, HTS power cables are now to be commercialized in a practical power grid [1],[2]. However, the length of HTS power cable is restricted by the manufacturing technology, transportation and cooling method. In particular, when the length of HTS power cable will be longer, the burden of cooling system should increases related with the pressure drop and the total heat load from the HTS power cable. Therefore, joint boxes are considered to split the HTS power cable and cryogenic cooling system [3]. The joint box can be divided into two types, NJB (Normal Joint Box) and SJB (Stop Joint Box) according to refrigerant flow path. Fig. 1 shows the basic structure NJB and SJB. The liquid nitrogen in NJB passes through the joint box. However, SJB has the function that blocks the liquid nitrogen path and it is possible to separate each cooling system. If it is possible to separate of cooling system, it can solve the problems such as pressure drop and temperature rise with length of HTS power cable [4]. Therefore, SJB is an essential component for the long HTS power cable. To block the

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flow path, an epoxy insulation spacer should be considered for SJB. However, thermal stress can be a problem due to the different thermal expansion coefficient and non-uniform temperature distribution during the cool down period. Therefore, it is necessary to prevent damage/separation phenomenon of the epoxy insulator by the thermal stress analysis.

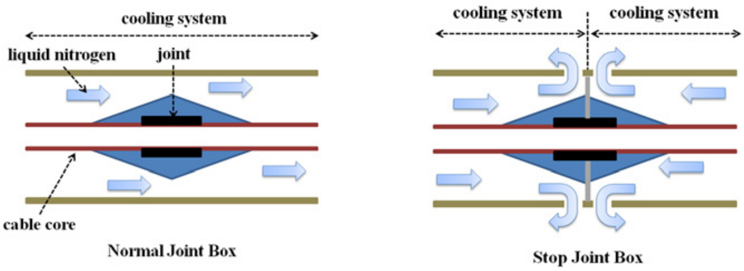

Fig. 1. Normal joint box and stop joint box

In this study, we find the optimal cooling time and shape of the SJB to reduce the thermal stress result from temperature difference during the cooling time using the FEM analysis.

2. Stop joint box (SJB) and solid insulation

The SJB blocks the nitrogen cooling path while connecting the cable core [5] and it is composed of the cable core, the epoxy insulator, flange, nitrogen tank and additional insulation paper.

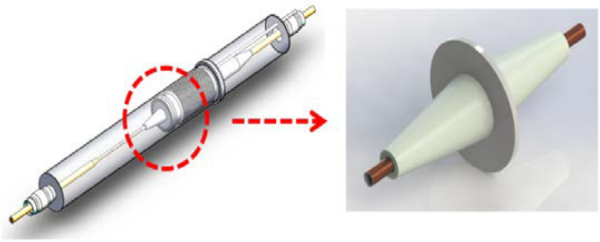

Fig. 2. Basic shape of Stop Joint Box

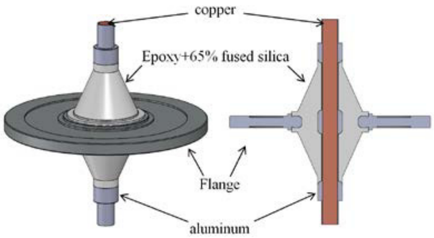

Fig. 3. Structure of epoxy insulator

The cable core, which consists of copper former and superconductor tape, gives electric connection between the separated HTS power cables. The epoxy insulator is composed of epoxy and silica glass to reduce the thermal contraction and match the thermal contraction with the metal flange. It supports the cable core and blocks the liquid nitrogen flow. The epoxy should have sufficient electrical insulation performance because of the high voltage between the cable core and the flange. In this work, the design voltage level is 80 kV DC. Fig. 2 shows the overall structure of SJB. Fig. 3 shows the structure of epoxy insulator, which is composed of the epoxy composite, a SUS flange, an aluminum tube and a copper core.

3. Thermal stress analysis

3.1. Thermal stress by non-uniform temperature distribution

To perform the thermal stress analysis, the material properties of the epoxy insulator should be verified. The epoxy insulator is composed of 35 % of epoxy and 65 % of fused silica in weight. The mechanical properties such as thermal conductivity, thermal contraction, Young's modulus and yield strength were obtained experimentally. Table 1 shows the measured mechanical properties of the epoxy composite. Fig. 4 and 5 show the thermal conductivity and the stress-strain relation of the epoxy composite. According to the experimental results, the fracture strength of epoxy was 130 MPa at 77 K. By considering the safety factor of 1.3, we defined the maximum stress 100 MPa.

Table 1. Measured mechanical properties of the epoxy composite

Temperature (K)	E (GPa)	Poisson's ratio	Thermal contraction (%) 300 K to 77 K	Coefficient of thermal expansion, α ($\times 10^{-6}$) 300 K to 77 K
300	10.4	0.277	-0.366	16.65
77	18.7	0.249		

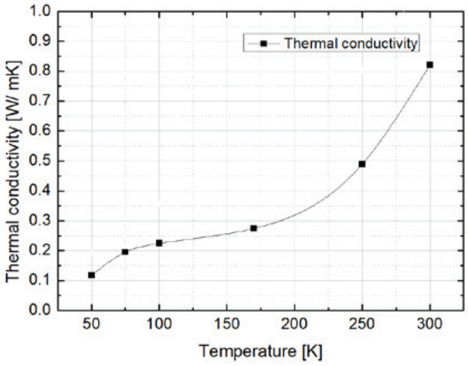

Fig. 4. Thermal conductivity of epoxy + 65% fused silica

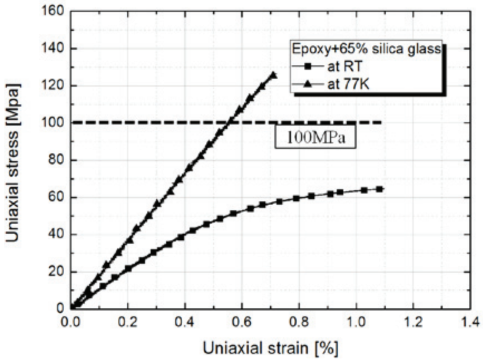

Fig. 5. Stress-strain relation of epoxy + 65% fused silica

The FEM analysis was carried out based on the obtained material properties to confirm the thermal stress. The thermal stress appears due to the non-uniform temperature distribution and it can be simulated by adjusting the temperature variation on the surface of epoxy insulator during the cool down process. Two types of the cooling condition of the epoxy were considered. The one is pool boiling that is rapid cooling of the epoxy. Another is slow cool down by slowly reducing the surface temperature with time. Consequently, the optimal cooling rate can be decided at the condition under the maximum thermal stress of 100 MPa.

The maximum von-Mises stress point (σ_1) and temperature(T_1, T_2) in Fig. 6 were investigated for the different cooling conditions.

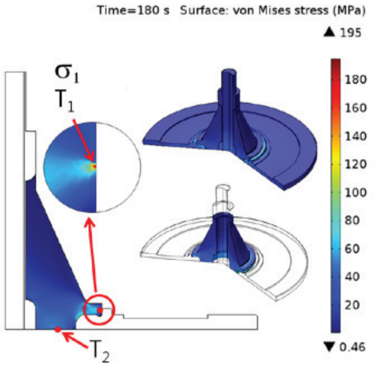

Fig. 6. Thermal stress analysis model

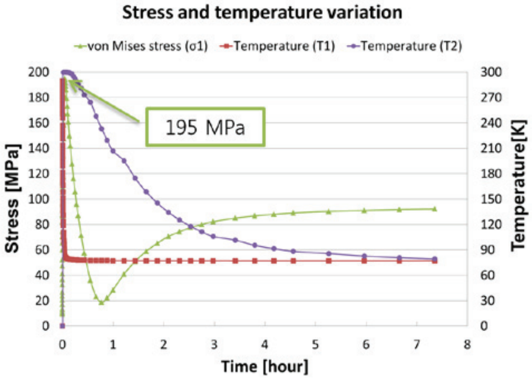

Fig. 7. Stress and temperature variation for pool boiling cooling condition

Fig. 7 shows the stress and temperature variation for the pool boiling condition. The maximum stress was about 200 MPa due to the large temperature difference. This value is much larger than the allowable maximum stress of 100 MPa. Although the epoxy is immersed completely in the liquid nitrogen, the analysis result shows that it takes 7 hour of cooling time to completely cooling the internal epoxy because the complete cooling time was decided when T_2 dropped under 78K.

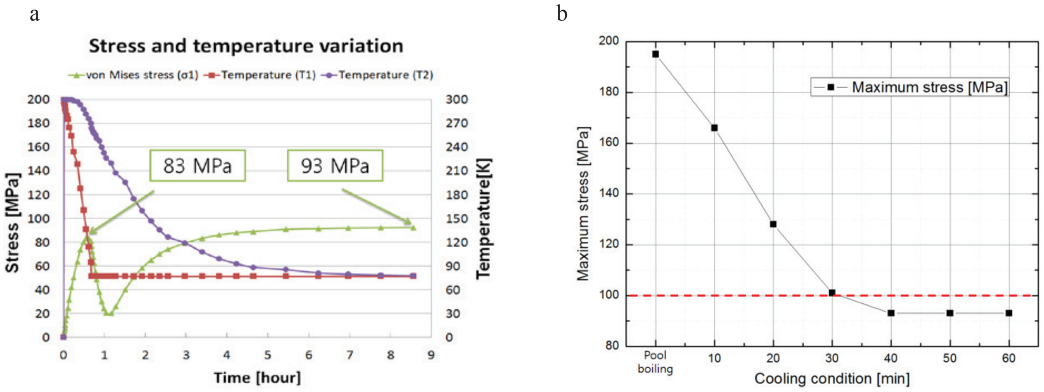

Fig. 8. (a) Stress and temperature variation according to cooling time 40 min; (b) Maximum stress according to cooling condition

Fig. 8 shows the analysis results which express the stress variation for the cooling time of 40 minutes and maximum stress according to cooling condition from pool boiling to 1 hour cooling. When the cooling time is longer than 40 minutes, it is possible to get maximum stress is 93 MPa and it is under the maximum allowable stress of epoxy. Therefore, it is thought that at least 1 hour is required to safety cool down the epoxy insulator.

3.2. Relaxation of stress concentration

To minimize the stress at the sharp edge of the epoxy insulator, we performed the FEM analysis by changing the shape of epoxy. For the analysis, the most severe thermal condition was applied. We examined stress variations when the temperature of SUS flange was 77 K while the temperature of epoxy was kept 300 K.

Fig. 9 shows an analysis result for the various edge shape. In case of the original shape, maximum thermal stress was 209 MPa. The stress can be reduced to 75 MPa by applying the double fillet at the edge as in Fig. 9. The variation can have an effect on the dielectric performance and investigation on the electric field for the different shape is required. However, it will be reported in other paper because the DC di-electric analysis is related with complex space charge problem and various material properties for quantitative comparison.

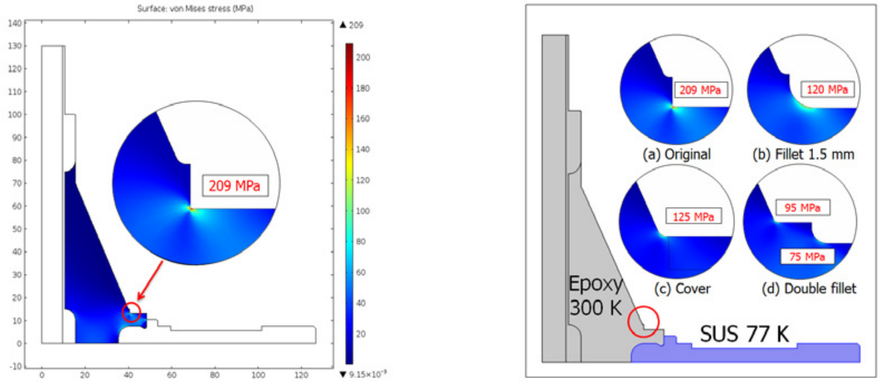

Fig. 9. Thermal stress for various shape of epoxy

4. Conclusion

We have studied optimal cooling time and shape of the epoxy insulator to minimize the thermal stress at the cooling step. As the cooling speed increases, large thermal stress is generated by the temperature gradient in the epoxy. It was found that this could be minimized when the cooling time was longer than 40 minutes. When the cooling time was more than 40 minutes, the maximum stress of the epoxy was about 90 MPa that was under the maximum tensile stress of the epoxy (100 MPa). The residual thermal stress is caused by coefficient of thermal expansion of different materials. In addition, it was confirmed that the thermal stress could be reduced more by changing the detail shape of the epoxy insulator.

Acknowledgements

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References

[1] J.G Kim, D.W. Kim, A.R. Kim, M. Park, I.K. Yu, S.H. Kim, K.D. Sim, J.W. Cho, “ Loss characteristic analysis of high capacity HTS DC power cable considering harmonic current ”, Physica C 470 (2010) 1592-1596.

[2] Kideok Sim, Seokho Kim, SeokJu Lee, Jeonwook Cho, and Tae Kuk Ko, “The Estimation of the Current Distribution on the HTS Cable by Measuring the Circumferential Magnetic Field”, IEEE Trans. Appl. Supercon., Vol. 20, No. 3 (2010) 1981-1984.

[3] Maziar Moradi, and Siva Sivoththaman, “Stain Transfer Analysis of Surface-Bonded MEMS Strain Sensors”, IEEE sensors journal, Vol. 13, No.2, (2013) 637-643.

[4] Li Ren, Yuejin Tang, Jing Shi, Liang Li, Jingdong Li, and Shijie Cheng Cheng, “Techno-Economic Feasibility Study on HTS Power Cable”, IEEE Transactions On Applied Superconductivity, Vol. 19, No. 3 (2009) 1774-1777.

[5] W.J. Kim, H.J. Kim, J.W. Cho, S.H. Kim, “The surface discharge and breakdown characteristics of HTS DC cable and stop joint box”, Physica C 504 (2014) 172-175.