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Numerical analysis of heat transfer and fluid characteristics in long distance HTS cable

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Abstract

Japanese national project, called “Materials & Power applications of Coated Conductors (M-PACC)”, started in FY2008. In this project, high temperature superconducting (HTS) cable using REBCO tapes has been developing. These HTS cables are expected as a compact size with large capacity and low loss power transmission. In the future, it is supposed that these cables will be installed in power grid for replacing existing power cables. Under the operating HTS cable in the power grid, it is necessary that the REBCO tapes in the long distance cable are kept cooling at low temperature stably and efficiently by liquid nitrogen (LN2).

In this paper, the flow characteristic, such as pressure drop of LN2 flowing in the long distance HTS cable, and the heat transfer characteristic against heat generation, such as AC loss, and heat leak from cryostat-pipes were analytically estimated with varying the volumetric flow and the diameter of outer pipe wall which are parameters easy to control in cable system design. As a result, it was confirmed that the volumetric flow increasing is affective to extending the maximum distance which can be transmitted but it required increasing discharge pressure too. This increasing discharge pressure can be restricted without affecting the longitudinal distribution of the HTS temperature by expanding of the diameter of outer pipe wall.

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Keywords: HTS power cable; Liquid nitrogen; pressure drop; heat transfer

1. Introduction

High-temperature superconducting (HTS) power cables are compact and have a large power carrying capacity. In addition, they make it possible not only to reduce power transmission losses significantly but also alleviate global environmental problems and allow more efficient use of energy resources. In the future, these cables are expected to be installed in the power grid as replacements for existing power cables. A high-voltage cable (HV cable, 275 kV/3 kA) have been developed using rare-earth barium copper oxide (REBCO) superconducting tape in the Japanese national project “Materials & Power Applications of Coated Conductors” which started in FY2008 [1]-[2]. Referring to this HV cable design, we analytically estimated the cooling characteristics in long distance HTS cable in this paper.

2. Analysis model

The design specifications of referring HV cable for analysis model are listed in Table 1 [2]. In this HV cable design, LN2 flows through inner pipe and annulus in the same direction, as shown in Fig 1. The inner pipe is designed in order to efficiently cool HTS conductor layer which is inside a thick electrical insulation layer. The cable core is housed in a double corrugated stainless steel cryostat-pipe and positioned on bottom of the cryostat-pipe. However, in analysis model of this paper for estimation of fundamental heat transfer characteristics of HTS cable, it is assumed that the cable core is housed in straight cryostat-pipe and positioned on center of the cryostat-pipe, as shown Fig. 1 (b). In this model, two types of heat source are considered: one is the heat inflow at the cryostat-pipe wall, and the other is the AC
losses and dielectric loss of the cable core. In this HV cable design, the sum of AC loss of HTS conductor and HTS shield is 0.2 W/m and the dielectric loss of electrical insulation layer is 0.6 W/m [2]. In this analysis model, it is assumed that the sum of losses, which is 0.8 W/m, is distributed uniformly in HTS conductor, electrical insulation and HTS shield. The heat inflow at the cryostat-pipe wall is defined as 1 W/m. The cable core consists of many layers whose thermal resistance values are different each other. In this analysis model, the cable core is divided into Cu former, HTS conductor, electrical insulation, HTS shield and Cu shield, as shown in Fig. 1(b). The thermal resistances of these layers are given as equivalent thermal resistance of various materials included in each layer. With this analysis model, the pressure drop ($\Delta P$) and temperature rise ($\Delta T$) in steady-state conditions are provided as following sections.

### Table 1 275 kV high voltage cable specification

| Layer              | Construction       | Diameter, mm |
|--------------------|--------------------|--------------|
| Inner pipe         | LN$_2$ flow        | 14           |
| Former             | Cu stranded hollow 400mm$^2$ | 30.6         |
| HTS conductor      | 2 layers YBCO tape | 34           |
| Electrical insulation | PPLP 22 mm thick | 79.4         |
| HTS shield         | 1 layer YBCO tape  | 80           |
| Cu shield          | 3 layers Cu tape 310m$^2$ | 85           |
| Annulus (Outer pipe) | LN$_2$ flow     | 98.5         |

![Fig. 1. (a) Structure of the 275 kV high voltage cable, (b) Radial and longitudinal cross-section of the cable](image)

### 3. Analytical method

#### 3.1. Estimation of pressure drop

Pressure drop is caused by friction in the fluid boundary layer on pipe wall. In this cable design, there are two pipes of LN$_2$ flow: one is inner pipe and another is annulus. To calculate the pressure drop of LN$_2$ per unit length ($\Delta P/\Delta L$), it is necessary to obtain flow velocities in inner and annulus, respectively. Total volumetric flow rate in the cable ($W$) is divided into inner pipe ($W_1$) and annulus ($W_2$). If it is assumed that the $\Delta P/\Delta L$ of inner pipe and annulus are equal, $\Delta P/\Delta L$ is given by Darcy Weisbach equation [3] as,

$$\frac{\Delta P}{\Delta L} = f \times \frac{2}{d_{h1}} \times \frac{1}{2} \rho v_1^2 = f_2 \times \frac{2}{d_{h2}} \times \frac{1}{2} \rho v_2^2,$$

where $f$ is the dimensionless friction factor, $d_h$ is the hydraulic diameter as shown in Fig.1 (b), $\rho$ is LN$_2$ density and $v$ is mean flow velocity. The subscript numbers 1 and 2 indicate inner pipe and annulus, respectively. $f$ is friction factor, which is function of Reynolds number. This coefficient can be obtained by Prandtl-Karman formula [4] which is applicable in a wider range of Reynolds number for turbulent flow. The Reynolds number of inner pipe is defined as $\rho v d_h / \mu$, where $\mu$ is viscosity. That of annulus is defined similarly as $\rho v d_h / \mu$. Flow values of inner pipe and annulus, $W_1$ and $W_2$ are given as,

$$W_1 = A_1 v_1 = \pi r_1^2 v_1 = \frac{C}{1+C} W, \quad W_2 = A_2 v_2 = \pi (r_2^2 - r_2^2) v_2 = \frac{1}{1+C} W,$$

respectively, where,

$$C^2 = \frac{f_2 d_{h1} A_1^2}{f_2 d_{h2} A_2^2},$$

(3)
where \( A \) is the cross-section area of each flow path, and \( r \) is radius as shown in Fig 1 (b). In this study, it is assumed that same pressure difference between inlet and outlet, \( \Delta P \), is applied to both inner pipe and annulus. Furthermore, it is assumed that the LN\(_2\) viscosity is constant because the temperature dependence of LN\(_2\) viscosity hardly affects the pressure drop at around 65 to 77K which is expected as HTS cable operating temperature. Therefore, flow velocities, \( v_1 \) and \( v_2 \), can be obtained by using Eq 1-3.

### 3.2. Calculation method of temperature

The LN\(_2\) temperature variation per unit length, \( \Delta T/\Delta L \), is determined by energy conservation of LN\(_2\) and given as,

\[
\frac{\Delta T_1}{\Delta L} = \frac{Q_1}{\rho C_p W_1}, \quad \frac{\Delta T_2}{\Delta L} = \frac{Q_2 + Q_b}{\rho C_p W_2},
\]

where \( C_p \) is the specific heat of LN\(_2\), \( Q_b \) is the heat inflow at the cryostat-pipe wall. \( Q_i \) and \( Q_o \) are heat from cable core into inner pipe and annulus, respectively. Heat generation from cable core \((Q_s)\) was shared with \( Q_i \) and \( Q_o \) as shown in Fig 1 (b). The \( Q_i \) and \( Q_o \) can be given as,

\[
Q_i = \frac{Q_s}{r_2^3 - r_1^3} \left( r_1^2 - r_2^2 \right) + \frac{2\pi \rho \left( T_s - T_o \right)}{ln(r_2 / r_1)} = 2\pi K_1 (T_i - T_o)
\]

\[
Q_o = \frac{Q_s}{r_2^3 - r_1^3} \left( r_2^2 - r_1^2 \right) + \frac{2\pi \rho \left( T_s - T_o \right)}{ln(r_2 / r_1)} = 2\pi K_2 (T_o - T_2)
\]

where \( K_1 \) is equivalent thermal resistance of Cu former and heat transfer coefficient of LN\(_2\) flow in inner pipe, and \( K_2 \) is that of Cu shield and heat transfer coefficient of LN\(_2\) flow in annulus. \( k_s \) is equivalent thermal conductivity of HTS conductor, electrical insulation and HTS shield. \( T_{si} \) and \( T_{so} \) are temperature at HTS conductor and HTS shield, respectively. The heat transfer coefficients of LN\(_2\) flow can be calculated with Nusselt number. The Nusselt number of inner pipe is given by Petukhov equation [6]. That of annulus is calculated by Dalle-Donne equation with interference factor of the turbulent heat transfer in annuli [6].

When \( Q_i \) and \( Q_o \) are obtained, \( \Delta T/\Delta L \) of the inner pipe and annulus can be calculated with Eq 4 in steady-state conditions. Furthermore, radial temperature distribution of the cable can be obtained with expanding Eq 5-6.

### 4. Results and discussion

The pressure drop and temperature variation in various conditions can be calculated analytically as described above. These characteristics in the long distance cable were calculated with varying the volumetric flow and outer diameter of annulus which are parameters easy to control in cable system design, and the extensibility of the maximum distance which can be transmitted in allowable temperature 65 to 77 K was estimated.

First, these characteristics were calculated on various volumetric flows between 10 and 50 liter/ min and shown in Fig 2 (a) and (b). As shown in Fig 2 (a), the pressure drop was increased significantly with the volumetric flow increasing, because the pressure drop is proportional to square of velocity which is varied by volumetric flow as described in Eq 1 and 2. As shown in Fig 2 (b), the temperature variation was decreased with the volumetric flow.

![Fig. 2. (a) Longitudinal distribution of pressure drop for the various volumetric flow of LN\(_2\); (b) Longitudinal distribution of temperature of HTS conductor for the various volumetric flow of LN\(_2\)](image-url)
increasing, because the temperature variation is inverse proportional to volumetric flow as described in Eq 4. These results indicate that the increase volumetric flow is effective to extend of the maximum distance which can be transmitted in the allowable temperature but required discharge pressure for circulating LN₂ is increased significantly.

Next, these characteristics were calculated on 20 liter/min volumetric flow if the outer diameter of annulus is varied from 98.5 mm to 93.5 mm or 103.5 mm and shown in Fig 3 (a) and (b). When the outer diameter of annulus is varied as described above, the volumetric flow rate in annulus against total is varied from 87 % to 66 % or 93.4 % respectively. As shown in Fig 3 (a), it was confirmed that the expanding outer diameter is effective for decreasing discharge pressure, because the velocity is decreased with expanding of cross section area of LN₂ flow with volumetric flow fixed as described Eq 2. As shown in Fig 3 (b), it was confirmed that outer diameter of annulus has little dependence on longitudinal distribution of the HTS temperature. It indicates that longitudinal distribution of HTS temperature is not affected by volumetric flow ratio of each flow path but by sum of volumetric flow.

By these results the extensibility of the maximum distance which can be transmitted in allowable temperature was estimated as an example. If the 1500 m long cable is operated in allowable temperature, required minimum volumetric flow is approximately 10 liter/min as shown in Fig. 2 (b) and the required discharge pressure for circulating LN₂ to this length cable is under 0.05 MPa as shown in Fig 2 (a). When the 3500 m long cable is needed, required minimum volumetric flow is increased from 10 liter/min to 20 liter/min but the required discharge pressure is increased to approximately 0.2 MPa, too. However, if it is possible to expand the outer diameter from 98.5 mm to 103.5 mm, the discharge of pressure can be restricted as 0.07 MPa without affecting longitudinal distribution of the HTS temperature as shown in Fig 3 (a) and (b). It was confirmed that the maximum cable length can be extended saving the required discharge pressure by increasing volumetric flow and expanding diameter of annulus.

![Fig. 3. (a) Longitudinal distribution of pressure drop for the various outer diameters of annulus; (b) Longitudinal distribution of temperature of HTS conductor for the various outer diameters of annulus](image)

**5. Summary**

The allowable transmission length and required discharge pressure for circulating LN₂ can be obtained roughly in the various cases by using this analytical model. These characteristics were estimated with varying the volumetric flow and outer diameter of annulus. As a result, it was confirmed that the volumetric flow increasing is effective to extending the maximum distance which can be transmitted but it required increasing discharge pressure too. This increasing discharge pressure can be restricted without affecting the longitudinal distribution of the HTS temperature by expanding of outer diameter of annulus.

For estimating to cooling characteristics of the real cable design, it is necessary to discuss the effects of positioning cable core on bottom of cryostat-pipe and the corrugated form of cryostat-pipe. These effects to cooling characteristics of cable have been simulated by Computational Fluid Dynamics (CFD).

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