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Fluid characteristic of liquid nitrogen flowing in HTS cable

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Abstract. For long distance operation of High-temperature superconducting (HTS) cables, evaluations of heat transfer and fluid flow dynamics of liquid nitrogen (LN_2) flowing in the HTS cable is important. However, the LN_2 flow is complicated when the cable core is housed in a spiral corrugate cryostat-pipe and positioned at an eccentric position to the center of the cryostat-pipe. In this study, the effect of a configuration of a spiral corrugate cryostat-pipe on the pressure drop was evaluated using computer simulation. As a result, it was confirmed that the calculated pressure drop in the spiral corrugate pipe is 17 times larger than that in the straight pipe due to the shrinking and expanding of the LN_2 flow at the concave domain. This shrinking and expanding of LN_2 flow was assumed to be the flow in a gradual contraction pipe and a gradual expansion pipe respectively, so that the pressure drop was calculated by a theoretical arithmetic analysis. For verification of this calculation, the calculated value was compared with the measured value of a HTS cable system, which was constructed in NEDO project. As a result, these values were agreed well each other and it indicated that the pressure drop in the spiral corrugate pipe could be evaluated by this calculation.

1. Introduction

The HTS cables have significant merits of compactness and larger power transmission capacity. In the future, these cables are expected to be installed in a power grid as replacement of existing power cables. For operation of the HTS cables in the power grid, it is necessary that the HTS coated conductors in the long distance cable are maintained at the low temperature stably and efficiently by liquid nitrogen (LN_2). It is necessary that the HTS cable can be bended at winding on a drum or installating on varying condition so that configuration of a cryostat-pipe of the HTS cable is corrugated. However, the LN_2 flow is complicated when the cable core is housed in the spiral corrugated-cryostat-pipe and positioned at an eccentric position to the center of the cryostat-pipe. Therefore, evaluations of heat transfer and fluid flow dynamics of LN_2 flowing in the HTS cable are important for the HTS cable system design including both the cooling system and the circulating pump.

2. Previous work and Objective

For simulation of the LN_2 flow in the HTS cable, referring to the 275 kV/3 kA high-voltage cable (HV cable, shown in figure 1) which has been developed in the M-PACC project [1]-[3], the pressure drop and temperature rise were calculated by theoretical analysis for the case of the simple cable configuration which is assumed that the cable core was arranged in the centerline position of the straight cryostat-pipe [4]. In this analysis, the dependences of volumetric flow of the LN_2 on the pressure drop and the temperature rise were evaluated. As a result, it was confirmed that the temperature rise decreased and the pressure drop increased significantly with increasing the volumetric flow of LN_2. However, the LN_2 flow pattern is complicated such as the case of eccentric arrangement of the cable core. A computer simulation analysis is effective in evaluating these characteristics with

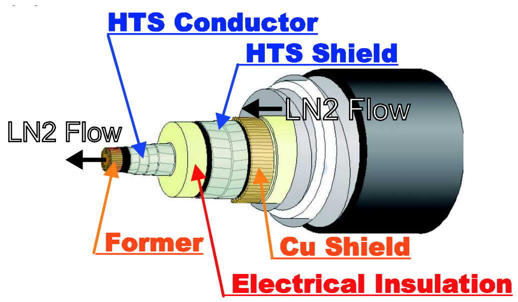

Figure 1. Structure of the HV cable.

the complicated LN_2 flow so that the accuracy of the computer simulation model was evaluated by comparison of the theoretical arithmetic analysis model for the simplified cable configuration [5]. As a result, the values of the computer simulation analysis showed a good agreement with that of the theoretical arithmetic analysis. Then, using this computer simulation model, the effects of the eccentric arrangement on the pressure drops and the temperature distribution of the cable core housed in the straight pipe were simulated [5]. As a result, the pressure drop of the eccentric arrangement became to about two-third as compared with that of the center configuration and no significant temperature difference of the HTS conductor of each configuration was confirmed due to the existence of a Cu outermost shielding layer of the cable which has high thermal conductivity.

In this study, the effect of a configuration of a spiral corrugate cryostat-pipe on the pressure drop was evaluated using this computer simulation. Furthermore, the calculated value was compared with the measured values of the HTS cable system, which was constructed in NEDO project [6].

3. Design of calculation model

The design specifications of referring the HV cable for calculation model are listed in Table 1 [2], [5]. In this HV cable design, LN_2 flows through both the inner pipe and the annulus as shown in figure 1. It is assumed that the pressure gradients for the inner and the outer (annulus) regions in the pipe are assumed to be equal. Total flow rate and the temperature of LN_2 at the cable inlet are assumed to be 20 liter/min and 65 K, respectively. The physical properties of LN_2 using in these calculations are listed in Table 2 [7]. In this model, the cable cross section is modeled as shown in figure 2 and two types of heat sources are considered; one is the heat intrusion from outer wall of the cryostat-pipe, and the other is the AC losses and the dielectric loss of the cable core. The heat intrusion is defined as 1 W/m

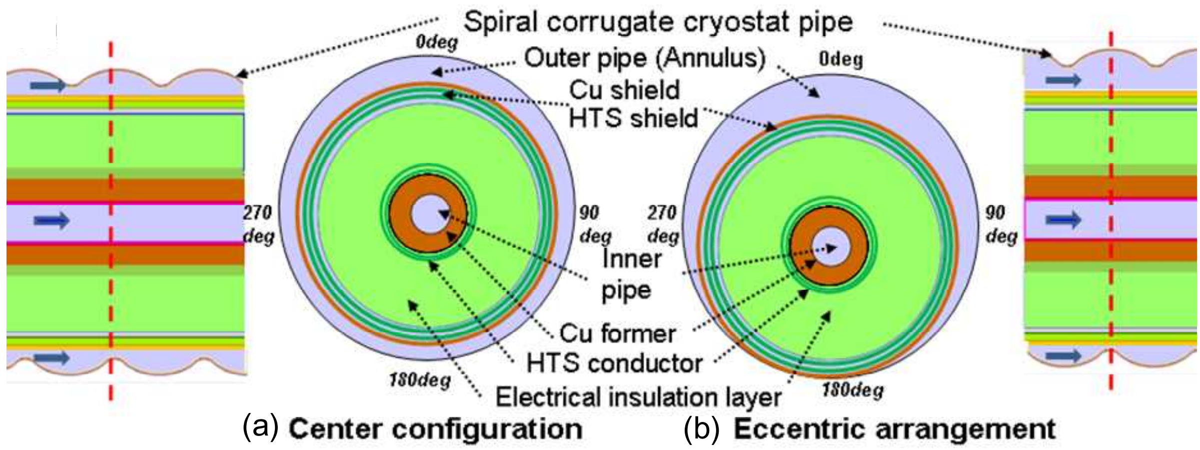

Figure 2. Calculation model for effect of corrugate pipe. (a) Center configuration (b) Eccentrici arrangement.

Table 1. HV Cable specifications

Cable component (Layer)	Architecture and materials	Outer diameter (mm)	Thermal conductivity (W/m·K)
Inner pipe	LN_2 flow	14	0.18
Former	Cu stranded	30.6	646
HTS conductor	2 layers YBCO tape	34	646
Electrical insulation	PPLP 22 mm thick	79.4	0.14
HTS shield	1 layer YBCO tape	80	646
Cu shield	3 layers Cu tape	85	646
Annulus (Outer pipe)	LN_2 flow	98.5	0.18

Table 2. Physical properties of LN_2

Items	Value
Specific heat C_p	2000 J/kg·K
Density ρ	860 kg/m^3
Viscosity μ	210 μPa·s
Thermal conductivity λ	0.18 W/m·K

[8]. The dielectric loss from the electrical insulation layer is 0.6 W/m, AC losses of the HTS conductor layer and the HTS shield layer are 0.13 and 0.07 W/m, respectively [2], [3]. The heat generation in each layer is assumed to be uniform. The pressure drop with the condition described above was calculated by the computer simulation analysis using the FLUENT, which is computational fluid dynamics simulation software, with coupling the equation of continuity, the Navier-Stokes equations and the advection thermal diffusion as described in (1), (2) and (3), respectively. The Finite volume method was applied and solved by the Semi-Implicit Pressure Linked Equations (SIMPLE) method. Furthermore, the k-ε model is used for the turbulence model in this simulation. The HTS cable was modelled three-dimensionally in 3.3 meters as shown in figure 3 (a). Figure 3 (b) shows a mesh cut of cross section at the modelled HTS cable. For long distance (axial) direction analysis, this simulation was calculated by periodic boundary condition.

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial (\rho u_j)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_i} = -\frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_i}\left[(\mu + \mu_t) \frac{\partial u_j}{\partial x_i} \right] + f_g \tag{2}$$

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u_j \frac{\partial T}{\partial x_i} = \lambda \frac{\partial^2 T}{\partial x_j \partial x_j} \tag{3}$$

where u is vector of flow velocity, μ is viscosity λ is thermal conductivity and f_g is mean buoyancy. With this calculation model, the pressure drop of LN_2 in the steady-state conditions are provided as following sections.

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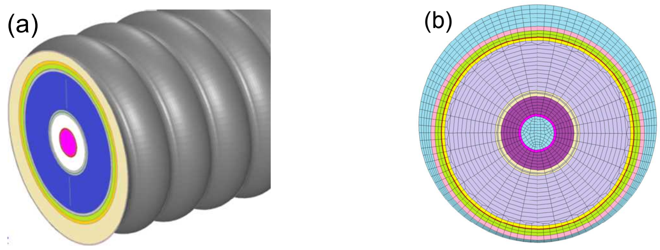

Figure 3. (a) 3-D modelling HTS cable (b) Mesh cut of HTS cable cross-section

4. Results of calculation and discussions

4.1. LN_2 fluid flow and pressure drop

The calculated pressure drop of the spiral corrugate configuration is 177 Pa/m and its value is 17 times larger than that of the straight pipe configuration, whose diameter assumed to be the equal to the hydraulic diameter of the spiral corrugate pipe. Even if the diameter of the straight pipe is assumed to be the equal to the inner diameter of spiral corrugate pipe, the value of the spiral corrugate configuration is 3 times larger than that of the straight pipe. The reason of this pressure drop increasing was discussed by simulated fluid flow in the pipe, as followings.

The simulated result of the LN_2 fluid flow in the corrugated pipe of the central core configuration is shown in figure 4. In this figure, it was confirmed that the simulated streamlines are divided into two different main flows. One is a spiral fluid flow, which is shown in the blue lines, in a convex domain in a corrugate pipe. Another is the slow spiral fluid flow, which is the shown in the yellow lines, through the long distance (axial) direction in a corrugate pipe. Figures 5 and 6 show the contour maps of LN_2 velocities of the circumferential flow and axial flow. As shown in figure 5, the spiral flow along the groove of the corrugation is confirmed. However, its velocity is about one-third of the axial flow which is shown in figure 6, so its influence on the pressure drop might be small.

As shown in figure 6, the stagnant flow region in a groove of the corrugation is confirmed. It indicates that the axial flow hardly flow into this groove. In this figure, at the concave domain by the corrugation of the pipe, the velocity is higher than that of the convex domain. This is due to the shrinking of LN_2 flow at concave domain, as shown in figure 7. Figure 8 shows the contour map of the LN_2 pressure. In this figure, it was confirmed that the pressure drop occurred this concave domain approximately 5 Pa by 1 pitch. Accordingly, it was confirmed that the pressure drop in the spiral corrugate pipe increased significantly at the concave domain of the corrugation due to the shrinking and expanding of the flowing LN_2.

In the case of the eccentric arrangement of the cable core, the calculated pressure drop is 143 Pa/m. The calculated pressure drop of the eccentric arrangement became to about four-fifth as compared with that of the center configuration. Accordingly, it was confirmed that the eccentric arrangement is effective for reduction of the pressure drop in the case of the spiral corrugate pipe as well as the straight pipe case [5].

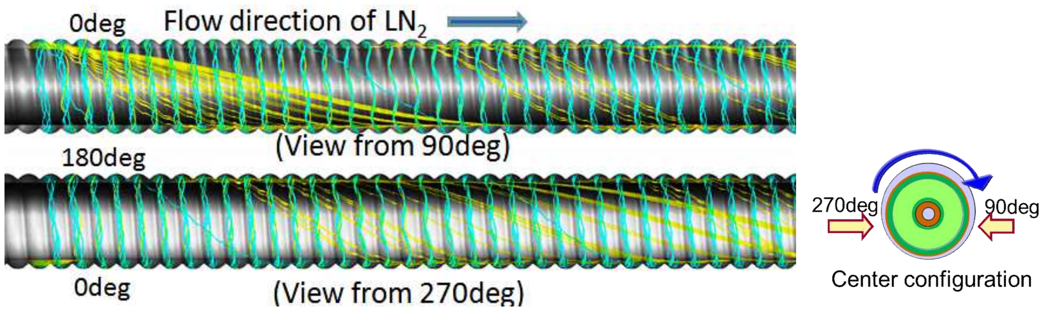

Figure 4. Streamline of LN_2 flowing in corrugated pipe.

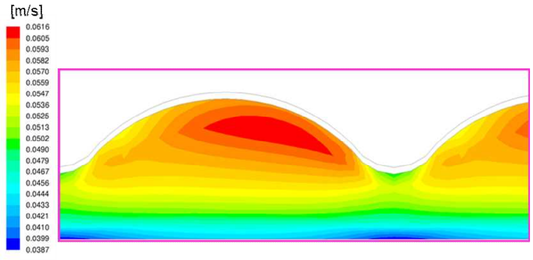

Figure 5. Contour map of LN_2 velocity of the circumferential flow.

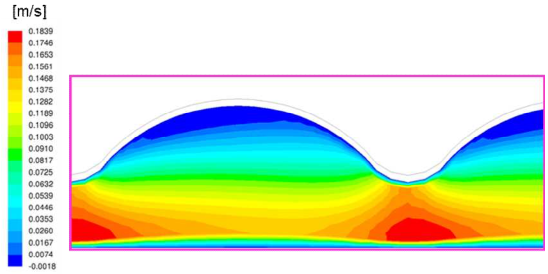

Figure 6. Contour map of LN_2 velocity of the axial flow.

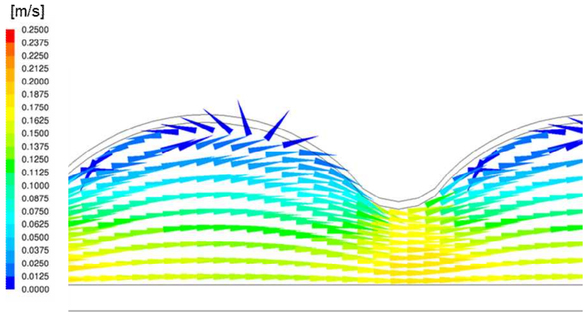

Figure 7. Vector of LN_2 velocity of the axial flow.

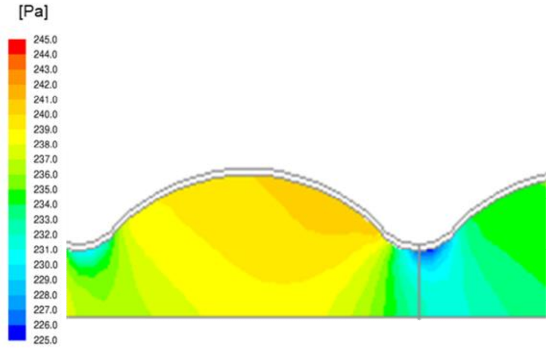

Figure 8. Contour map of LN_2 pressure.

4.2. Theoretical arithmetic analysis

As described in section 4.1, the pressure of LN_2 mainly reduced by the shrinking and expanding of the LN_2 flow path at the concave domains of this pipe. So, this flow was assumed to be consist of the two flows which are flowing in a gradual contraction pipe and a gradual expansion pipe. These pressure drops in each pipe were evaluated individually by theoretical arithmetic analysis, as followings.

In case of the gradual expansion pipe, the velocity of LN_2 decreases and the pressure increases generally. The energy of layers at the boundary is so small that the increased pressure may stop the flow there or even reverse it. As a result, eddies form and the flow separates from the pipe wall. The greater the angle of divergence of an expanding pipe the more pronounced these phenomena and the greater the turbulence loss. Therefore, the pressure drop of the LN_2 per unit length ($\Delta P/\Delta L$) can be given by (4) and (5) [9], as followings.

$$\frac{\Delta p}{\Delta L} = \frac{\xi}{s} \times \frac{1}{2}\rho v^2 \tag{4}$$

$$\xi = \left(0.011\theta^{1.22}\right)\left(1 - \frac{A_1}{A_2}\right)^2 \tag{5}$$

where s is pitch of the groove of the corrugation per unit length, v is velocity at outlet domain of the expansion pipe, ξ is loss coefficient, θ is the divergence angle of pipe and A is the cross-section area of LN_2 path. The subscript numbers 1 and 2 indicate intake and outlet of the expansion pipe. These are assumed to be the concave and convex domain of the corrugated pipe, respectively and the calculation model is shown in figure 9. As described above, the pressure drop values with varying the volumetric flow were calculated.

In case of the gradual contraction pipe, the velocity of LN_2 increases and pressure drops generally.

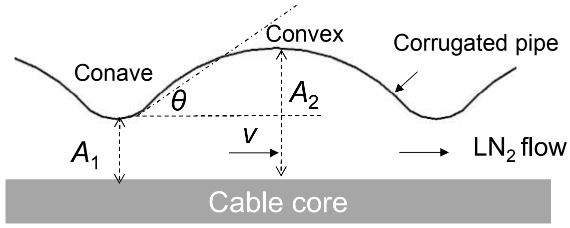

Figure 9. Calculation model for theoretical arithmetic analysis

The flow is from higher to lower pressure, which eliminates the causes of turbulence and separation.

Accordingly, the loss in a gradual contraction are due to friction only. The pressure drop caused by friction in the fluid boundary layer on pipe wall is calculated using friction factor, which is function of Reynolds number. However, as shown in figure 6, the axial flow hardly flow into the groove of pipe corrugation so that the domain of the friction by pipe wall is decreased signicantly. Accordingly, the loss caused by the pipe friction was ignored in this study.

Furthermore, in the case of the eccentric arrangement of the cable core, the pressure drop should be calculated with considering an empirical formula depends on eccentricity ratio which is the position of the cable core moved from the center to the bottom of the cryostat pipe [5], [10].

4.3. Comparison with measured value of HTS cable system

For verification of this calculation method described in section 4.2, the calculated value was compared with the measured value of a 20 meter long HTS cable system shown in figure 10, which was constructed by Furukawa electric at Shenyang in China in the NEDO project. The specifications of HTS cable in this system are different from that of table 1, as shown in table 3.

The calculated and measured values with varying the volumetric flow are shown in figure 11. As a result, these values were agreed well each other with varying the volumetric flow. It indicated that the pressure drop in the spiral corrugate pipe could be evaluated by these equations.

Table 3. Cable specifications for evaluating fluid flow.

Cable component	Architecture	Outer diameter (mm)
Inner pipe	LN_2 flow	14
Cable core	Dummy core	79
Annulus (Outer pipe)	LN_2 flow	104
Core position	Eccentric arrangement	-

Figure 10. 20-meter long HTS cable demonstration system at Shenyang in China.

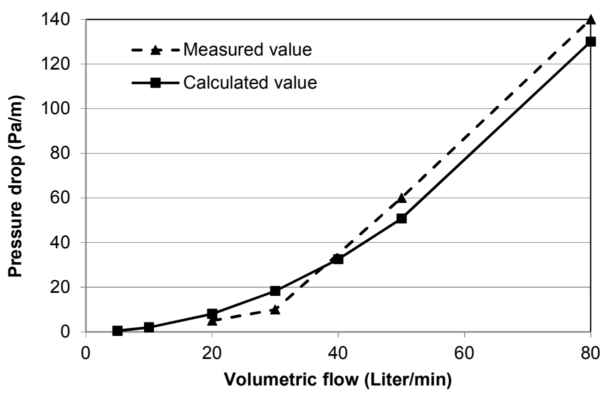

Figure 11. Pressure drop of LN_2 with varying the volumetric flow.

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5. Conclusion

The effect of a configuration of a spiral corrugate cryostat-pipe on the pressure drop was evaluated using computer simulation. As a result, it was confirmed that the calculated pressure drop in the spiral corrugate pipe is 17 times larger than that in the straight pipe due to the shrinking and expanding of the LN_2 flow at the concave domain. This shrinking and expanding of LN_2 flow was assumed to be the flow in a gradual contraction pipe and a gradual expansion pipe respectively, so that the pressure drop was calculated by evaluation equations theoretically. For verification of this calculation, the calculated value was compared with the measured value of a HTS cable system, which was constructed in NEDO project. As a result, these values were agreed well each other and it indicated that the pressure drop in the spiral corrugate pipe could be evaluated by this calculation.

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