Cryogenic Fluid Dynamics for DC Superconducting Power Transmission Line

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***Abstract*—Distributions of the velocity, the temperature and the pressure of a liquid nitrogen (LN2) flow are analyzed at hydraulic cross-sections on two types of superconducting power transmission lines (SC PT). One is on a DC-SC PT, the other is on a three phase AC-SC PT. Inflow heat from the pipe wall and the cables to LN2 are evaluated, however the heat flux from the DC cable is zero. The channels are straight, and hydraulic cross-sections are 3.77×10^{-3} m2 and 4.27×10^{-3} m2 on the DC and AC-SC PT lines, respectively. The increased temperature and the pressure drops on the DC-SC PT lines are lower than those of the AC-SC PT. The fluid velocity dependence on the distance between two cooling stations and on the pump power are estimated. When cooling stations are installed every 10 km, the flow velocity of the DC and AC system are 0.10 and 0.25 m/s, respectively. The pump power of the DC system is dramatically lower compared with the AC system. Therefore, minimizing the SC PT by using DC systems is much more practical.**

***Index Terms*—Computational fluid dynamics, DC power transmission, HTS power cable, pressure drop.**

I. Introduction

THERE are several known projects of the power transmission line using high temperature superconducting (HTS) power cable [1]–[4]. Most of these projects develop the AC power transmission lines (AC-SC PT), including both single phase and three phase systems. In order to complete the superconducting power transmission line, we must solve many technical and economical issues. One of the technical issues is related to the fluid mechanics. We must find the actual structures and operations that keep the pressure drop low enough for the circulation of the coolant. The key technical issues are how to reduce the heat inflow to the coolant and to save the pump power of the cooling stations, and these were not discussed so much at the present phase. There are two types of heat inflow: one is the heat through the pipe wall, and the other is the AC losses of the power cable. The magnitude of the AC losses was 2.0 W/m for the current of 1.0 kA in three-phase AC cable systems operated at the temperature of 77 K [3]. The magnitude of the AC losses was 0.98 W/m for the current of 1.26 kA in a single phase AC system at the same temperature [4].

Computational Fluid Dynamics (CFD) were used to design a cooling system for the ACSC-PT and ITER cables [5], [6]. In [6], R. Zanino *et al.* used FLUENT for CFD modeling. However, CFD has not been used for the design of the DC power transmission lines (DC-SC PT). In this paper, we are using FLUENT to obtain the distributions of the velocity, the temperature and the pressure of the liquid nitrogen (LN2) flows. The pressure drops for DC-SC PT and AC-SC PT have been estimated. We compare these distributions on a case by case basis. The computational results of the pressure drops are compared with theoretical values. The distances between cooling stations and the pump power are calculated.

II. Numerical Formulation

A. Turbulence Model

Flow of the LN2 in the HTS cables is typically turbulent because of high Reynolds numbers of $\mathrm{Re} > 10^4$. The flow, however, is also influenced by the laminar viscosity, particularly close to the walls of the pipe and cables where the Reynolds numbers are low. In order to find these solutions of fundamental flows inside the HTS cables, we choose $k-\varepsilon$ turbulence model which is described by one of the Reynolds-Average Navier-Stokes (RANS) equations and has been widely used in [6]–[8]. In this approach, the Navier-Stokes equation is evaluated by the averaging on a period of time longer than the actual time scale of turbulence fluctuations, which are filtered away.

The viscous sub-layer in a boundary layer is so thin that it is difficult to use many grid points to resolve it for the models of high Reynolds number. This problem can be avoided by using the wall functions, which rely on the existence of a logarithmic region in the velocity profile; the velocity profile of turbulent boundary layer is shown in Fig. 1. In the logarithmic layer, the model of the profile is given by:

$$u^+ = \frac{\overline{v_t}}{u_\tau} = \frac{1}{\kappa} \ln y^+ + B, \tag{1}$$

where v_t is the mean velocity parallel to the wall, u_τ is the shear velocity given by $u_\tau = \sqrt{|\tau_w|/\rho}$. Here, τ_w is the shear stress at the wall, κ is called the von Karman constant ($\kappa = 0.41$), B is an empirical constant related to the thickness of the viscous

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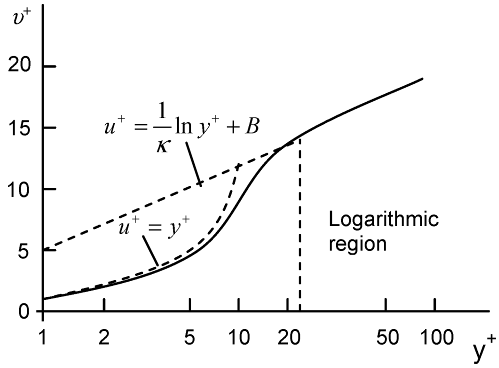

Fig. 1. The velocity profile of turbulence boundary layer as a function of distance normal to wall (dashed lines are from corresponding equations, solid line represents experimental data).

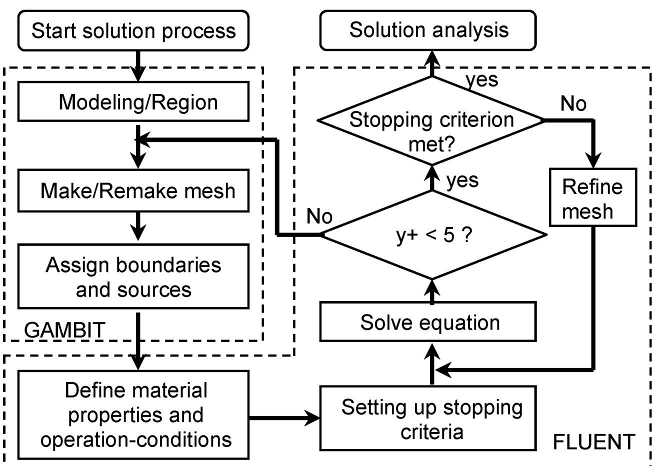

Fig. 2. Flow chart of the fluid analysis for the DCSC-PT system.

sub-layer and y^+ is the dimensionless distance from the wall [8]:

$$y^+ = \frac{\rho u_\tau y}{\mu}, \tag{2}$$

where ρ is the density of fluid, y is distance from wall.

FLUENT is used in the present study and has three different methods for the wall functions [9]. One of them is named Enhanced Wall Treatment, which is used to solve the flow near wall. By using the function, the first mesh of the fluid from a wall must be made when y^+ is less than 5 or from 30 to 300.

B. Solution Process

Fig. 2 shows the process of numerical calculation, two software packages named GAMBIT and FLUENT, are used to resolve the solutions. The geometries and meshes are made by GAMBIT [9]. The mesh size varies by the each step of the calculation depending on the thickness of boundary layer and the flow velocity. Boundary conditions, material properties and operation conditions are defined by the FLUENT.

The mesh geometries are remade by GAMBIT, when the magnitude of y^+ is smaller than five or to thirty from three hundreds. FLUENT solver will stop when the calculation criteria is satisfied. The value of the criteria is set initially, and usually it is around 1.0×10^{-4}, and this also means the error of the calculation. FLUENT has the default values of 1.0×10^{-3} as the criteria for the mass continuity, the velocities for all directions, such as x, y and z axis, the kinetic energy k, and the dissipation of energy ε, but the accuracy of the energy balance is high as 1.0×10^{-6}. User can change these values in the subroutine.

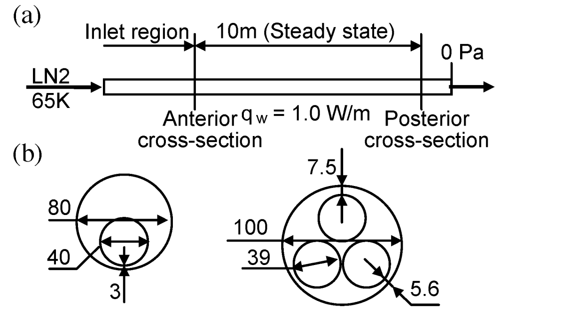

Fig. 3. Models of the geometries of pipe. (a) The parameters of the calculations along LN2 channel. (b) The hydraulic cross-sections of a single cable and three cables.

III. Numerical Result

A. Fluid Analysis

Fig. 3 shows the calculation model of the pipes for HTS power cables. In order to keep the low pressure drop, we avoid the corrugate tubes or bellows for the AC-SC PT and for simplicity use straight pipes for all cases considered in this paper.

The turbulence is developed in the inlet region for the flow of LN2, and continues all over the rest of the pipe region. This part is indicated by the steady-state region in Fig. 3. The parameters of the model for the single phase cable are the pipe diameters of 80 mm, and the cable diameter of 40 mm, respectively. Therefore, the hydraulic diameter is $3.77 \times 10^{-3}\ \mathrm{m}^2$. These specifications are the same as the DC-SC PT project in Chubu University at the present time. The parameters of the AC-SC PT model are defined as the pipe diameter of 100 mm, and cable diameter of 40 mm, respectively. The magnitude of the AC losses is 2.0 W/m, and the heat influx comes from the surface of the cable. The heat influx from the pipe wall is 1.0 W/m. The hydraulic diameter is $4.27 \times 10^{-3}\ \mathrm{m}^2$. These specifications are referred from [3]. The cables are located on the bottom of the pipe. The inlet temperature is 65.0 K and the boundary pressure is 0.1 MPa, the pressure is 0.0 Pa at the outlet, and these are the same for both AC-SC PT and DC-SC PT. The distributions of the velocity, the pressure and the temperature of LN2 flow at each cross-section have been calculated for the inlet flows of 0.1, 0.3, 0.5 m/s, respectively. Finally, we compare both results.

Fig. 4 shows the computational results as cross-sectional contours of the velocity, the temperature and the pressure in the region of the steady state. Depending on the pressure and velocity, they are strongly related with each other. The hot temperature areas are localized around the surface of the pipe for the single cable, and in the center of three cables and around the inner surface of the pipe for the three-cables system. However, the temperatures of the hot regions are almost the same as 65.2 K for

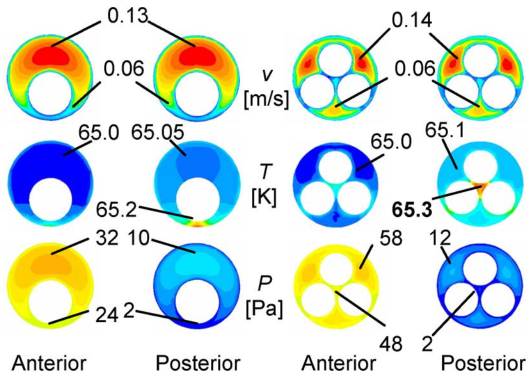

Fig. 4. The distributions of the fluid velocity, temperature and pressure at the anterior cross-sections and posterior cross-sections for the DC-SC and AC-SC cables.

both cases even for different distances between the cable surface and the inner surface of the pipe. The pressure drops are 22 Pa for $v = 0.1\ \mathrm{m/s}$, 170 Pa for $v = 0.3\ \mathrm{m/s}$, and 430 Pa for $v = 0.5\ \mathrm{m/s}$ in the case of a single cable. The pressure drops are 46 Pa for $v = 0.1\ \mathrm{m/s}$, 340 Pa for $v = 0.3\ \mathrm{m/s}$, and 840 Pa for $v = 0.5\ \mathrm{m/s}$ in the case of three cables.

B. Accuracy of Software

The accuracy of FLUENT solver has been examined by the comparison of the analytical calculations with theoretical solutions. The formulae for the theoretical solutions of the friction factor and the turbulent pressure drop are given by (3) and (4) [10], [11]:

$$f = \frac{0.0791}{\mathrm{Re}^{0.25}}, \tag{3}$$

$$-dp_f = \frac{2fG^2L}{\rho D_h} = \frac{2f\rho v^2 L}{D_h} \tag{4}$$

where Re is the Reynolds number, D_h is the hydraulic diameter, G is the mass velocity, L is Length of straight pipe, ρ is the density and v is the velocity of flow. The result of the comparison of pressure drop is in shown in Fig. 5. The plot and curve of theoretical solution are similar with the results of FLUENT. The computational results are between fifteen and thirty percent smaller than the theoretical ones.

IV. Estimation for Cooling Station

A. Distance Between Cooling Stations

In this section, the cooling station interval is estimated for the real constructions. The heat capacity of the LN2 in cables is given by (5):

$$Q_{LN2} = \rho C_p v t A_h, \tag{5}$$

where Cp is thermal capacity of liquid, t is the time when LN2 inflows to a power line and A_h is the hydraulic cross-section. The energy, E_{LN2}, to absorb a temperature difference, ΔT, of refrigerant fluid is expressed as:

$$E_{LN2} = \Delta T Q_{LN2} = \rho C_p v t A_h \Delta T. \tag{6}$$

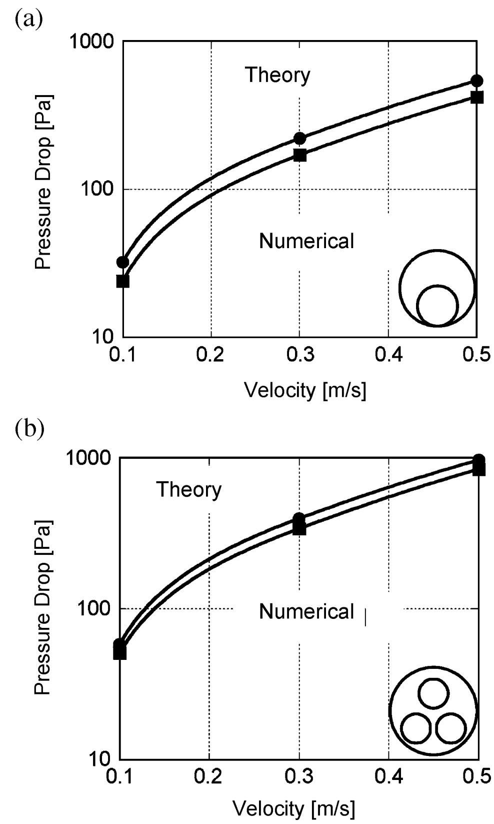

Fig. 5. Comparisons of the analytical results with theoretical results on fluid velocity dependence of the pressure drop. (a) For the single phase DC-SC cable. (b) For the three phase AC-SC cable.

The total inflow heat, Q_w, from the wall of power cables and a pipe over the time, t, is:

$$Q_w = t q_w L, \tag{7}$$

where q_w is the heat load per the second per meter. To decide the locations of cooling stations, the total heating has to be smaller than the energy, E_{LN2}. Therefore, the distance between two cooling stations should satisfy the following relation:

$$Q_w < E_{LN2}, \tag{8}$$

$$L < \frac{\rho C_p A_h \Delta T}{q_w} v, \tag{9}$$

where the temperature difference is 20 because it is assumed that the temperature of LN2 in conduit increases from 65.0 K to 85.0 K.

Fig. 6 shows the dependence of the fluid velocity on the distance between two cooling stations on a single phase DC power line and a three phase AC power line, the velocities are 0.05, 0.1, 0.2 and 0.3 m/s. Other flow conditions and properties of LN2 for the numerical calculation are the same as in analytical calculation. For DC-SC power transmission lines placing cooling stations every 10 km it is enough for pumping LN2 at 0.1 m/s. For AC lines, the velocity has to be larger than 0.2 m/s.

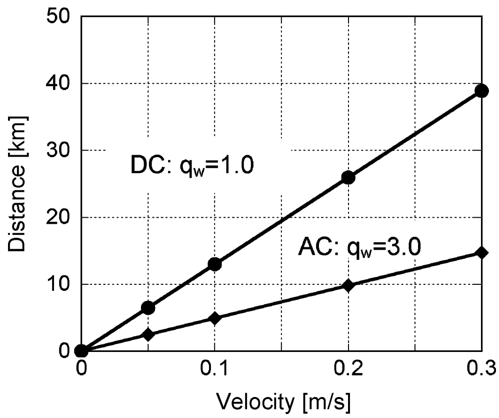

Fig. 6. The velocity dependence of distance between cooling stations. The distance for a DC-SC system is twice longer than that for a AC-SC system.

TABLE I
VALUES OF PUMP POWER TO CIRCULATE LN2 WHICH ARE CALCULATED BY USING THE ASSUMED DISTANCES, FLUID VELOCITIES AND PRESSURE DROPS

Cable	Distance [km]	Velocity of flow [m/s]	Pressure drop [Pa]	Pump Power [kW]
DC	10	0.10	$3.2\times10^{+4}$	0.13
q_w: 1.0 W/m	15	0.15	$9.9\times10^{+4}$	0.23
	20	0.20	$2.2\times10^{+5}$	0.39
AC	10	0.25	$2.9\times10^{+5}$	0.63
q_w: 3.0 W/m	15	0.35	$7.8\times10^{+5}$	1.6
	20	0.45	$1.6\times10^{+6}$	3.7

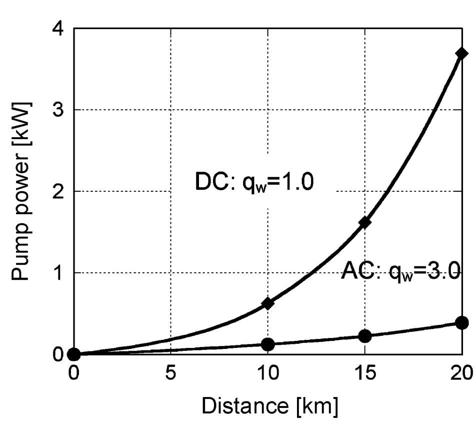

Fig. 7. The distance dependence of pump power to circulate LN2. When the cooling station interval is 10 km, the pump powers of a DC-SC PTL and AC-SC PTL are 0.13 kW and 0.63 kW, respectively. When the distance between cooling stations are 20 km, the pump power for the DC systems is one order lower than that of the AC systems.

B. Pomp Power

The pump power necessary to circulate the coolant is defined as [12]:

$$W_{pump} = vA_hP, \tag{10}$$

where P is total pressure. The specifications to circulate LN2 are shown in Table I. Fig. 7 shows the distance dependence of the pump power on the LN2 flow. In the DC-SC PT and AC-SC PT, the cooling stations can be built every 10 km, and if the velocities are 0.10 m/s or 0.25 m/s, the pump power is estimated to be 0.13 kW and 0.63 kW.

V. CONCLUSION

In a DC-SC and AC-SC power cables, the pressure drops and temperature increases of coolant are compared by fluid analysis. The real pressure drops in a three cables system are much higher than the calculated values because we did not consider the wall structure of the pipe and did not include the effect of twisting the three cables. High temperature spots exist in the LN2 conduit. The pressure drop of DC-SC PT is half of that of AC-SC PT. The analytical results are from 15% to 30% smaller than the theoretical results.

Distance between the cooling stations and the pump power required to circulate LN2 are estimated for the cooling system design. When the distance between the cooling stations is 20 km, the pump power of the DC-SC PT is one order lower than that of the AC-SC PT.

Using DC-SC PT saves the coolant by taking advantage of no AC losses, and it makes the pump power smaller, and the distance between cooling stations longer, which minimizes the cooling systems.

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REFERENCES

[1] Y. F. Fan, L. H. Gong, X. D. Xu, L. Zhang, L. F. Li, and L. Y. Xiao, "Cryogenic system for 75 M three-phase AC HTS cable," *Adv. Cryog. Eng.*, vol. 51, pp. 798–803, 2006.

[2] D. H. Kim, C. D. Kim, I. S. Kim, I. S. Park, H. M. Jang, C. Y. Lee, and D. W. Kim, "Thermomechanical properties of 30 M HTS power cable in DAPAS project," *Adv. Cryog. Eng.*, vol. 51, pp. 811–817, 2006.

[3] M. Hirose, Y. Yamada, T. Masuda, K. Sato, and R. Hata, Sumitomo Electric Industries, Ltd., Osaka, "Study on commercialization of high-temperature superconductor," *SEI Tech. Rev.* no. 62, June 2006 [Online]. Available: http://www.sei.co.jp/tr_e/t_technical_e_pdf/62-03.pdf

[4] J. Cho, J. H. Bae, H. J. Kim, K. D. Sim, S. Kim, H. M. Jang, C. Y. Lee, and D. W. Kim, "Development of a single-phase 30 m HTS power cable," *Cryogenics*, vol. 46, pp. 333–337, 2006.

[5] H. S. Yang, D. L. Kim, W. M. Jung, S. Cho, H. S. Ryoo, and J. W. Cho, "Cryogenic design of termination cryostat for HTS power cable," *IEEE Trans. Appl. Supercond.*, vol. 14, no. 2, pp. 1750–1753, June 2004.

[6] R. Zanino, S. Giors, and R. Mondino, "CFD modeling of ITER cable-in-conduit superconductors. Part 1: Friction in the central channel," *Adv. Cryog. Eng.*, vol. 51, pp. 1009–1016, 2006.

[7] B. E. Launder and D. B. Spalding, *Mathematical Models of Turbulence*. London and New York: Academic Press, 1972, pp. 90–109.

[8] J. H. Ferziger and M. Peric, *Computational Methods for Fluid Dynamics*, 3rd ed. : Springer, 2002, ch. 6.

[9] J. H. Ferziger and M. Peric, *Fluent 6.2 User's Guide*. Lebanon Pennsylvania: Fluent Inc., 2005.

[10] Y. Nakayama and R. F. Boucher, *Introduction to Fluid Mechanics*. , Great Britain: Arnold, 1999, ch. 7.

[11] W. H. McAdams, *Heat Transmission*, 3rd ed. , Florida: Robert E. Krieger Publishing Company, 1985, ch. 6.

[12] M. Oomachi, *Pump Design*, 7th ed. Tokyo: Power Company Ltd., 1993, ch. 2.