Cryogenics 51 (2011) 471–476

Contents lists available at ScienceDirect

Cryogenics

journal homepage: www.elsevier.com/locate/cryogenics

LN_2 circulation in cryopipes of superconducting power transmission line

A. Sasaki, Yu. Ivanov, S. Yamaguchi *

Chubu University, Kasugai, Aichi 487-8501, Japan

ARTICLE INFO

Article history:
Received 13 December 2010
Received in revised form 14 May 2011
Accepted 18 May 2011
Available online 7 June 2011

Keywords:
Superconducting power transmission line
Superconducting cable
High temperature superconductor
Liquid nitrogen
Bellows pipe
Pressure drop
Computational fluid dynamics
k–ε turbulence model

ABSTRACT

We propose and consider the application of superconducting power transmission lines (SC PTs) using high temperature superconductors (HTSs) for further reduction of the electricity losses. To keep HTS cable at low temperature it is usual to use liquid nitrogen (LN_2). Straight and bellows pipes used in SC PT have different hydraulic friction factors due to differences in the shape of the wall surfaces. Moreover, the decentering of the HTS cable, which is unfixed at the center of the pipeline, also influences the LN_2 flow. In the case of long SC PTs, high power must be expended to overcome hydraulic friction. There are two methods to evaluate pressure losses. One is based on empirical formulae and another is based on the algorithms of computational fluid dynamics (CFD). Empirical formulae can estimate pressure losses for long pipes, but the decentering of the cable is not considered. CFD computations describe flow behavior taking into account cable position inside the pipeline, though there is a limit to computable length due to the dependence on the number of mesh points and computation capacity. In this paper, circulation losses and pump power are estimated in straight and bellows pipes forming circulation channels by both methods. For a 40 mm diameter cable in an 80 mm diameter pipe, with the bellows pipe segments covering 2% of the length, and a heat loss of 1 W/m, the required flow rate and pump power for a circulation of 10 km are approximately 19 L/min and 10 W, respectively.

1. Introduction

Several projects of superconducting power transmission lines (SC PTs) have been developed in the world. Table 1 shows outlines of some research projects that use corrugated cryopipes and are an AC system [1–3,5,22]. There are different kinds of losses in SC PTs: some are from coolant circulation, others from radiation penetration into the cryopipe. These two kinds of losses, directly proportional to the cable length, are large compared to the conduction heat losses through current leads in long-distance systems. The radiation heat loss decreases together with the decrease of the cryopipe emissivity [6,7] and of the cryopipe diameter.

Before constructing SC PTs, it is necessary to design them in detail. As a part of the design procedure, circulation losses of liquid nitrogen (LN_2) should be realistically evaluated under various conditions in a cryopipe some kilometers in length. There are two methods to estimate circulation losses. One is the analytical computation using well-known empirical formulae obtained from experiments with straight pipes. This method allows a quick evaluation of long-distance circulation losses due to the simplicity of the models. Some experiments and empirical formulae were also reported on bellows and corrugated pipes [8,9,10,11]. However, these experiments did not take into account the presence of the cable inside the cryogenic pipe. Another way is the numerical computation by computational fluid dynamics (CFD) [12]. It is suitable for analyzing the flow under various conditions through the bellows/corrugated pipes. However, there is a maximum calculable length because the computer memory and CPU time limit the number of mesh points. Additionally, a long computation time is needed to calculate the fluid flow parameters of the entire length of a few kilometers. Therefore, neither of these two methods is sufficient on its own.

In our previous works we reported the differences of the pressure drop and the temperature rise of LN_2 flow obtained by both CFD and empirical formulae calculations [13,14]. It was assumed that a single HTS cable is placed in cryopipe (so called "one-in-one" design) of the DC system. Another considered configuration was the "three-in-one" AC system where three cables were placed together in one cryopipe [15]. Initial conditions refer to the experimental setups [14,15]. In these calculations, the cable of the DC system is decentered downward, while the three cables of the AC system are not twisted and parallel. However, the calculations were done only for straight pipes, not bellows or corrugated pipes. Consequently, we reported the pressure drop in the corrugated and bellows pipes by using the CFD and compared their pressure drops with that of straight pipes [13]. The pressure losses in bellows pipes were significantly lower than those in corrugated pipes. Based on this result, a structure combining straight and bellows pipes was proposed [16]. The straight pipe segments contribute

* Corresponding author.
E-mail address: yamax@isc.chubu.ac.jp (S. Yamaguchi).

0011-2275/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cryogenics.2011.05.002

Table 1
Specifications of several AC SC PT projects.[a]

	Length (m)	Flow rate (L/min)	Operating temp. (K)	Voltage (kV)	Current (kA)	Diameter cable/pipe (mm/mm)	Number of cables in pipe	Refs.
Albany project/USA	320 + 30	>50	67–77	34.5	0.8	39/–	3	[1]
LIPA project/USA	600	30	65.5–71.9	138	2.4	–/83	1	[2]
Super-ACE project/Japan	500	20–60	63–77	77	1	58/82	1	[3]
KEPCO project/Korea	100	>50	66–77	22.9	1.25	35/–	3	[22]
Project at Puji/China	33.5	10–15	70–76	35	2	∼38/30 + 43	1	[5]

[a] All pipes are corrugated pipes.

to reduction of friction losses and the bellows pipe ones absorb heat shrinkages and mechanical tensions (see Fig. 1). However, it is insufficient to consider the influence of the cable position and of the long-distance flow with empirical formula alone.

In this paper, we study the flow behavior in combined straight-bellows pipes and estimate the pressure drop and the friction factor as a function of cable decentering by the CFD computation. The results are applied to the evaluation of the pressure drop and the pump power to improve the accuracy of the analysis of LN_2 circulation through the combined straight-bellows pipes.

2. Calculation by CFD and empirical formulae

Long-distance SC PT needs cooling stations to be built at some interval to re-cool LN_2. Narrowing of the cross-section of the flow channel leads to increased pressure losses due to flux enhancement. For constructing long-distance SC PTs, it is necessary to intensify the circulation of LN_2, but the circulation loss increase is approximately equal to flow velocity squared. Therefore, some optimal cryopipe diameters provide minimum heat losses. Heat transfer along the cable is governed by a mass flow of LN_2. The mass flow of circulating LN_2, $\dot{m}$, is expressed by a following equation [13]

$$\dot{m} = L\frac{q_n}{C_p \Delta T} \tag{1}$$

where L is the cryopipe length in m; q_n is the heat load in W/m; C_p is the specific heat of LN_2 in J/(kg K); and ΔT is the temperature difference of LN_2 between the outlet and the inlet in K. Therefore, required mass flow rate can be easily obtained. For example, in case of a 10 km line the flow rate is 250 g/s, while ΔT is 20 K, q_n is 1 W/m, and C_p is about 2 kJ/(kg K).

The frictional pressure drop is described by a following Darcy–Weisbach equation [17]:

$$\Delta P = \frac{1}{2}\lambda\rho u^2 \frac{L}{D_h} = \frac{1}{2}\lambda\frac{\dot{m}^2}{\rho}\frac{L}{A^2 D_h} \tag{2}$$

where ρ is the density of LN_2 in kg/m^3; u is the flow velocity in m/s; D_h is the hydraulic diameter in m; A is the cross-sectional area in m^2; and λ is the dimensionless friction factor, which is typically expressed in the form of experimentally obtained correlations of Reynolds number, Re, pipe diameter and pipe wall roughness. A few correlations for λ depending on the flow regime are widely used.

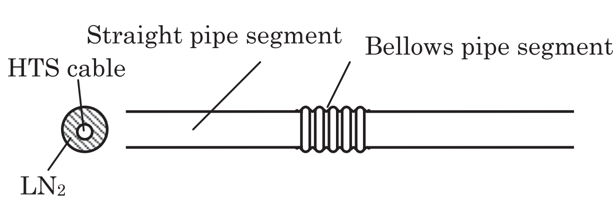

Fig. 1. Pipeline structure.

For example, in the case of laminar flow, it is given by the Hagen–Poiseuille formula

$$\lambda = 64/\mathrm{Re} \tag{3}$$

or, in case of turbulent flow, by the Blasius formula

$$\lambda = 0.3165/\mathrm{Re}^{0.25} \tag{4}$$

This adequately fits experimental results within the range of $3000 < \mathrm{Re} < 10^5$. The other one, the Prandtl formula, is applicable in a wider range of Re, but λ is expressed in implicit form [17]

$$\frac{1}{\sqrt{\lambda}} = 2\log(\mathrm{Re}\sqrt{\lambda}) - 0.8 \tag{5}$$

Nikuradse empirically found the correlation between λ, Re and relative roughness of the pipe wall ε/D. He showed that when Re is over 10^5, the λ depends only on ε/D. This behavior is expressed by Plandtl–Nikuradse formula as follows:

$$\frac{1}{\sqrt{\lambda}} = -2\log(\varepsilon/D) + 1.14 \tag{6}$$

The implicit Colebrooke–White general correlation can be used to evaluate λ in the general case

$$\frac{1}{\sqrt{\lambda}} = -2\log\left(\frac{\varepsilon}{D} + \frac{18.7}{\mathrm{Re}\sqrt{\lambda}}\right) + 1.14 \tag{7}$$

Several correlations were also proposed for bellows pipes, but their precision is poor. For example, as reported in Weisend and Van Sciver [18], a simple model of Hawthorne and von Helms is only accurate within ±30%. The range of applicability of an alternative Kauder's formula is narrow. Weisend and Van Sciver [18] also reported that, in accordance with the experimental results, the pressure drop of bellows pipes was about four times as high as that of the smooth pipes. However, their experiment had no cables. When these empirical formulae are applied to the analysis of LN_2

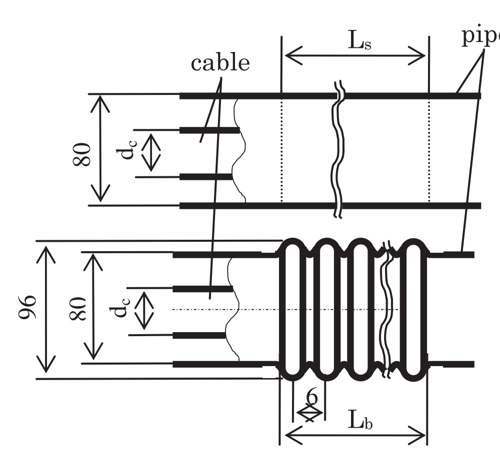

Fig. 2. Geometry of straight and bellows segments.