ELSEVIER

Available online at www.sciencedirect.com

SciVerse ScienceDirect

Physics Procedia 27 (2012) 368 – 371

Physics Procedia

ISS2011

# Observation of the thermosiphon effect in the circulation of liquid nitrogen in HTS cable cooling system

Yury Ivanov[a*], Hirofumi Watanabe[a], Makoto Hamabe[a], Toshio Kawahara[a], Jian Sun[a], Satarou Yamaguchi[a,b]

[a]*Center of Applied Superconductivity and Sustainable Energy Research, Chubu University, Kasugai, Aichi 487-8501, Japan*
[b]*Department of Electric Engineering, Chubu University, Kasugai, Aich, 487-8501, Japan*

**Abstract**

It is traditionally considered that superconducting technology is just the way that will help to overcome the energy crisis and improve the environmental safety of the electricity production. However, real achievements in this field still insufficient to build commercial long power transmission lines. In particular, cooling systems constructed using expensive coolant circulation pumps have to be improved. Our previous calculations show that the use of a thermosiphon effect may reduce both the heat load and the required coolant circulation pump power and, ideally, would completely abandon the forced circulation. Direct experimental verification of this approach has been carried out at the new 200-meter HTS DC experimental facility of the Chubu University. The thermosiphon effect was clearly observed in satisfactory agreement with theory, although the change in elevation of the cryopipe was small. Our results will be used to design an effective HTS cable cooling system based on natural circulation of the coolant.



*Keywords*: power transmission; high-temperature superconducting cables; liquid nitrogen; cooling system; thermosiphon effect

## 1. Introduction

According to current concepts, future power delivery and distribution systems will be based on superconducting technology. Widely discussed "Smart Grids" are very important to reduce energy losses and improve resistance against natural and technological disasters. Despite the fact that superconductivity was discovered a century ago and superconducting power transmission (SC PT) lines are being developed for a long time, but their industrial application has not yet begun. Recently, DC SC PT lines have begun to attract more and more attention due to their significant advantages over traditional AC ones [1, 2]. Although energy dissipation is negligible in the real DC HTS cables, the power is required to remove heat incoming through thermal insulation in order to keep temperature below critical value. The creation of the high-performance heat insulation can be attributed as main technological problem now. Moreover, SC PT lines are very expensive apparatuses that slow down their development and implementation.

A new scheme that allows to address both issues was proposed several years ago. Namely, it was suggested to use natural circulation of coolant which may arise due to its density difference along the circulation loop if the system has elevation change. Therefore, it is possible to reduce the capacity of the coolant circulation pump or even completely abandon the forced circulation of the coolant and consequently reduce the heat load and save cost. The feasibility of

* Corresponding author. Tel.: +81-568-51-9286 ; fax: +81-568-51-9413 .
*E-mail address*: ivanov@isc.chubu.ac.jp .

1875-3892 © 2012 Published by Elsevier B.V. Selection and/or peer-review under responsibility of ISS Program Committee
Open access under CC BY-NC-ND license. doi:10.1016/j.phpro.2012.03.487

this approach was shown by theoretical calculations for different configurations of the system [3, 4]. Since all existing experimental facilities are characterized by use of corrugated cryopipes with high coefficient of hydraulic resistance and the difference of elevation of circulation circuit is usually small, the thermosiphon effect could not be seen against the background of a large pressure drop and did not attract attention of researchers.

**Nomenclature**

| | |
|---|---|
| $g$ | gravitational acceleration, 9.81 m/s$^2$ |
| $H$ | difference in elevation between highest and lowest points of cryopipe, m |
| $h_{HT1}$ | difference in elevation between heater HT1 and lowest point of cryopipe, m |
| $J$ | volume flow rate, l/min |
| $\Delta p$ | pressure drop, Pa |
| $TP_1...TP_7$ | average temperatures measured by pairs of thermometers TP11/TP12...TP71/TP72, K |
| $\Delta T_{eff}$ | effective temperature difference, K |
| $\alpha_{HT1} = h_{HT1}/H$ | relative difference in elevation between heater HT1 and lowest point of cryopipe |
| $\gamma$ | thermal expansion coefficient of liquid nitrogen, 4.4 kg/m$^3$ K |

## 2. Experimental

An experimental study was undertaken using 200 meter test facility at the Chubu University. This is DC SC PT line built in 2009-2010, having a number of significant differences from other similar devices designed to achieve a record length of the cable and the minimum cost of the apparatus. In particular, straight cryopipes are applied to reduce to a minimum hydraulic resistance instead of commonly used corrugated ones [5, 6]. The elevation difference of the cable route is about 2.6 m which allows to appear thermosiphon effect. Liquid nitrogen ($LN_2$) flows through a fairly narrow space between the cable of the diameter of 35 mm and the inner surface of the cryopipe with the diameter of 57.2 mm. The actual temperature distribution can be estimated by 7 pairs of platinum resistance thermometers located at different positions. In order to simulate heat load and vary $LN_2$ density the cryopipe was equipped with three compact heaters with capacity of up to 350 W, two of which are located at the downstream and upstream sections of the cryopipe. The pressure drop was measured between termination cryostats by means of two pressure gages (see Fig. 1). Automated measurement system reads data from more than 500 sensors with a period of 3 s [7].

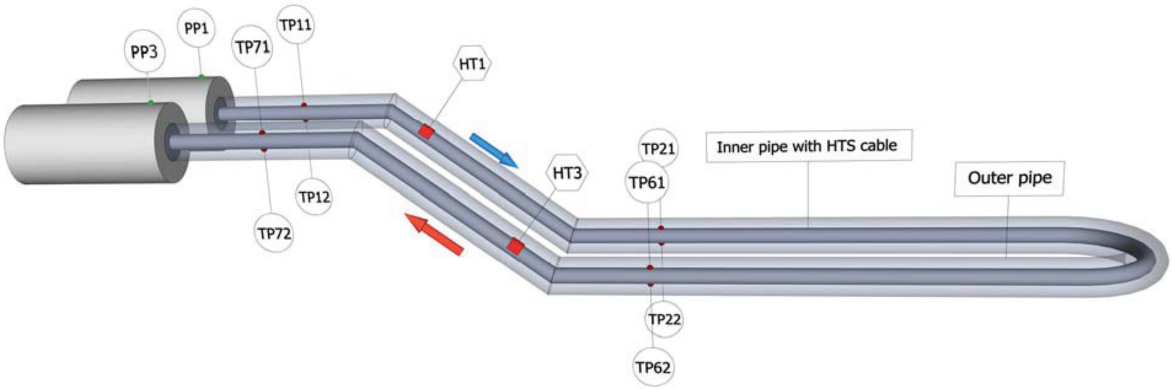


**Fig. 1.** Sketch of the HTS cable experimental facility at the Chubu University. Only terminal units, cryopipes, several thermometers (TP), pressure gages (PP), and heaters (HT) are shown in the picture. Level difference is 2.6 m.

The single-phase thermosiphon effect is very weak accounting for 44 Pa per 1 m elevation difference per 1 K temperature difference of $LN_2$. Therefore, a minimum circulation rate should be used to achieve a large temperature difference in order to reveal the effect.

## 3. Results

The experiments described were carried out during the third cooldown of the system (February-March 2011). The dependence of the pressure drop on the circulation rate of $LN_2$ was determined at first. The results are shown in Fig. 2. The measurements were made under the ambient heat load of about 240 W distributed between the inclined segments of the cryopipe. Data were collected by varying the $LN_2$ flow rate within 4.4-13.3 l/min that corresponds to the flow velocities within 0.045-0.14 m/s and Reynolds numbers within 4700-14200 (turbulent flow). The temperature difference was from 2.0 to 0.7 K. Points represent data averaged over 10 min (200 samples). The upper (blue) curve shows the design pressure drop obtained by the method described in [7]. The bottom (orange) curve shows the same curve corrected for the thermosiphon effect. It can be seen that the experimental points at lowest flow rates correspond to the second curve well.

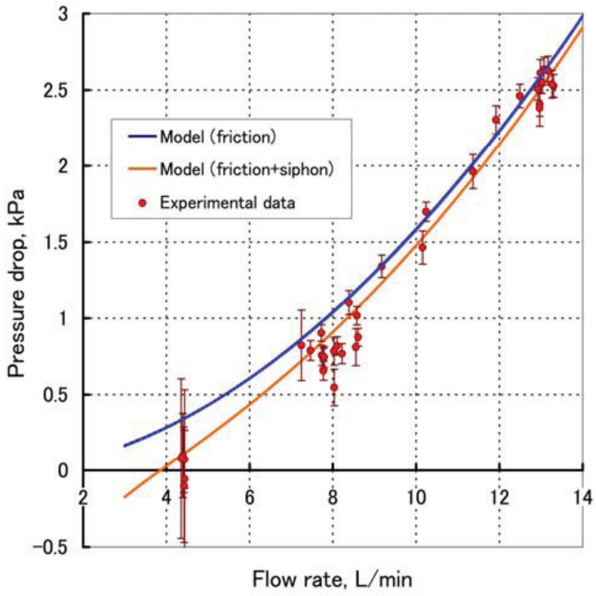


**Fig. 2.** Pressure drop as a function of $LN_2$ flow rate at constant heat load. Design curve is shown in blue. Orange curve is the design curve corrected for the natural thermosiphon effect. Experimental points represent averaged over 10 min data.

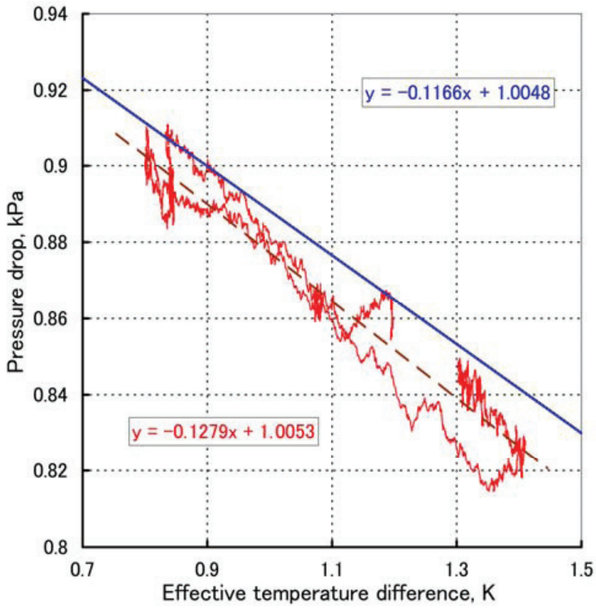


**Fig. 3.** Pressure drop as a function of the effective temperature difference between the inclined segments of the cryopipe varied by the heater HT1. Flow rate is fixed at 7.85±0.05 l/min. The data are smoothed over 4 min.

The second series of the experiments was carried out to study the behavior of the pressure drop as a function of the temperature difference between the inclined sections of the cryopipe at the constant $LN_2$ flow rate. The presence of the heater HT1 at the downstream section allows rapid heating of $LN_2$ to create up to a negative temperature difference that expands the range of the measurements. The actual temperature distributions inside the inclined sections of the cryopipe were estimated from the readings of pairs of the thermometers TP11/TP12, TP21/TP22, TP61/TP62, and TP71/TP72 with consideration for the flow velocity. Fig. 3 shows the results obtained by using the heater HT1 at $J$ = 7.85±0.05 l/min. If HT1 temperature changes slowly, the pressure difference due to the thermosiphon effect can be described by a linear expression

$$\Delta p = A \Delta T_{eff} + B \qquad (1)$$

where

$$\Delta T_{eff} = (TP_7 - TP_1) - \alpha_{HT1}(TP_2 - TP_1)$$
$$A = gH\gamma \qquad (2)$$
$$B = A(1.77\alpha_{HT1} - 1.1)/J$$

Complex form of the effective temperature difference, $\Delta T_{eff}$, is due to the heater HT1 is in an intermediate position. Numerical coefficients in Eq. 2 give the experimentally determined correction for the additional heating of the $LN_2$ that occurs at sites between inclined segments of cryopipe and thermometers. Heater power was varied trapezoidally from 0 to 250 W at the rate of 2 W/min. The total duration of the experiment was 5 hours. The data are smoothed over 4 min in order to reduce noise. The solid line exhibits the calculated pressure drop. The dashed line fits unsmoothed full set of the experimental points. Fig. 3 can be easily interpreted. The efficiency of the thermosiphon is characterized by the slope of the line. A point of intersection with the vertical axis ($\Delta T_{eff} = 0$) gives the net pressure drop without the influence of the thermosiphon effect. A point of intersection with the horizontal axis ($\Delta p = 0$) defines effective temperature difference at the given total heat load when the pump can be switched off and the natural circulation of $LN_2$ will occur. The observed behavior of the pressure drop is in satisfactory agreement with the calculated one. Deviations are caused by the inability to take into account accurately the temperature distribution in the inclined sections of the cryopipe, as well as some unreported slope of the horizontal part of the cryopipe.

## 4. Conclusions

We investigated experimentally the thermosiphon effect arising in the real HTS cable cooling system in the presence of elevation difference which can be used to save coolant circulation pump power. The study was carried out using 200 m DC SC PT line at the Chubu University. Experimental facility was not adapted to utilize natural circulation, but because we have achieved record low values of the pressure drop, it was allowed direct observation both the natural effect (caused by the heat penetrating through the insulation) and effect due to intentional local heating of $LN_2$. The obtained results show that by using bypass between termination cryostats the natural circulation can occur at the flow rate of about 4 l/min.

## Acknowledgements

The authors thank Dr. Atsuo Iiyoshi, the Chairman of the Board of Trustees and the Chancellor of Chubu University, for his encouragement during the course of this work. The authors acknowledge financial support from Dr. Hiroshi Fujiwara, the professor of Keio University and the president of Nano-Opt Energy Corporation.

## References

[1] Hirose M, Masuda T, Sato K, Hata R. High-Temperature Superconducting (HTS) DC Cable. *SEI Tech Rev* 2006;61:29-35.

[2] Hassenzahl W, Gregory B, Eckroad S, Nilsson S, Daneshpooy A, Grant P. *A superconducting DC cable. EPRI Report 1020458*. CA: Palo Alto: EPRI; 2009.

[3] Ivanov Yu, Watanabe H, Kawahara T, Hamabe M, Sun J, Yamaguchi S. Superconducting power transmission line cooled with naturally circulating $LN_2$. *Proc 23 Int Cryog Eng Conf Int Cryog Mater Conf 2010* 2011;1017-22.

[4] Ivanov Yu, Radovinsky A, Zhukovsky A, Sasaki A, Watanabe H, Kawahara T, et al. Compact counter-flow cooling system with subcooled gravity-fed circulating liquid nitrogen. *Physica C* 2010;470:1895-8.

[5] Yamaguchi S, Hamabe M, Yamamoto I, Famakinwa T, Sasaki A, Iiyoshi A, et al. Research activities of DC superconducting power transmission line in Chubu University. *J Phys Conf Ser* 2008;97:012290.

[6] Yamaguchi S, Kawahara T, Hamabe M, Watanabe H, Ivanov Yu, Sun J, et al. Design and construction of 200-meter high temperature superconducting DC power cable test facility in Chubu University. *Proc 23 Int Cryog Eng Conf Int Cryog Mater Conf 2010* 2011;1041-7.

[7] Ivanov YV, Watanabe H, Hamabe M, Sun J, Kawahara T, Yamaguchi S. Circulation pump power for 200 m cable experiment. *Physica C* 2011;471:1308-12.