Highly Efficient Liquid Hydrogen Storage System by Magnetic Levitation Using HTS Coils

Toshiyuki Mito, Akifumi Kawagoe, Nagato Yanagi, Shinji Hamaguchi, Suguru Takada, Naoki Hirano, Yoshiro Terazaki

Abstract—**Highly efficient liquid hydrogen storage system is studied with magnetic levitation using High-Temperature Superconducting (HTS) coils. The system also has high safety in case of emergency, such as an earthquake, with a seismic isolation to absorb vibrations provided by HTS levitation coils set up on the ground side. In such an emergency case, it is considered that a large amount of AC losses are generated in HTS coils, and the winding temperature may rise to lead to a coil quench. In this study, the self-oscillation-type heat pipe (OHP), whose thermal transport property is much greater than that of solid thermal conduction, is used to cool the coil windings. As a result, an HTS coil equipped with an OHP cooling system can be realized, supporting both low heat loads in the usual operation and high heat loads in an emergency.**

Index Terms—**hydrogen storage, magnetic levitation, HTS magnet**

I. Introduction

THE research for realizing the "hydrogen society", where hydrogen is widely used in place of fossil fuels, is to be prompted today. Hydrogen is gentle to the global environment without CO_2 emission. In the present-day technology, hydrogen can be stored in the form of liquid to provide electric power using fuel cells at disaster prevention bases in case of an emergency. It is expected that in the future, a large amount of hydrogen will be used as an energy resource that replaces fossil fuels. The merit to store hydrogen in the form of liquid is that the density (70.8 kg/m^3 at the boiling point of 20.3 K, 0.1 MPa) is much higher by 866 times than that of hydrogen gas (0.0818 kg/m^3 at 300 K, 0.1 MPa). Thus, a large amount of hydrogen can be stored equivalent as hydrogen gas at very high pressure over 80 MPa at 300 K. It is not necessary to worry about the aged determination of the container material because it is under an environment at a cryogenic temperature. This becomes an additional advantage. Here, the issue is how the heat load in the liquid hydrogen container is reduced while keeping the safety. In this paper, we propose magnetic levitation of a liquid hydrogen container using High Temperature Superconducting (HTS) coils operated in a persistent current mode. The heat load to a liquid hydrogen storage container can be greatly decreased by using HTS coil pair of the floating coil and the ground levitation coil in a thermal insulating vacuum. In addition, to maintain the storage system safely even when an earthquake occurs, a seismic isolation to absorb vibrations is provided by HTS levitation coils set up on the ground side. The floating position of the liquid hydrogen storage container is kept constant by controlling the current in the ground levitation coil even when an earthquake occurs.

Automatically generated dates of receipt and acceptance will be placed here; authors do not produce these dates. Acknowledgement of financial support goes here: This work was supported in part by the JSPS KAKENHI No. 25289343, the NIFS UFAA004, and the Iwatani Naoji Foundation.

T. Mito, N. Yanagi, S. Hamaguchi, S. Takada are with the National Institute for Fusion Science (NIFS) of NINS, Toki, Gifu, Japan (e-mail: mito@nifs.ac.jp, yanagi@LHD.nifs.ac.jp, hamaguchi@LHD.nifs.ac.jp, takada @LHD.nifs.ac.jp).

A. Kawagoe is with Kagoshima Univ., Kagoshima, Japan (e-mail: kawagoe@eee.kagoshima-u.ac.jp),

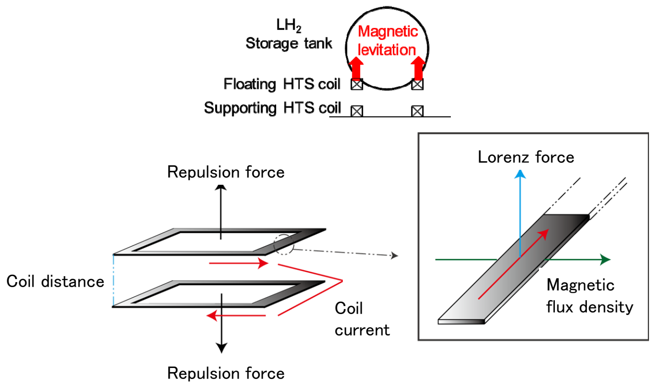
N. Hirano, Chubu Electric Power, Co., Inc., Nagoya, Japan (e-mail: Hirano.Naoki@chuden.co.jp),

Y. Terazaki, SOKENDAI (The Graduate University for Advanced Studies), Toki, Gifu, Japan (e-mail: terazaki@nifs.ac.jp).

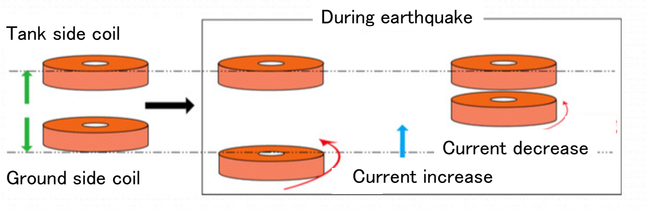
II. Magnetic Levitation Using HTS Coils

As for the liquid hydrogen, it is generally thought not to be adequate for economical long-term storage as the cryogenic liquid, because of the low boiling point of 20.3 K and also the small evaporative latent heat of 31.5 kJ/L. We note that the heat input from the support part by conduction is decreased by the use of the thermal insulated support structure. Moreover, the radiation heat load can be decreased by setting up the radiation shield with the multilayer insulator at the intermediate temperature in the insulated vacuum. The storage device (cryostat) that suppresses the amount of evaporation of the cryogenic liquid each day to 0.05 % or less can be designed by making adequate use of these appropriate thermal insulation technologies. However, the installation of a complex structural radiation shield that lowers the heat input, with the insulated support structure in the vacuum space is difficult coexisting with safety, because it requires a mechanically delicate structure.

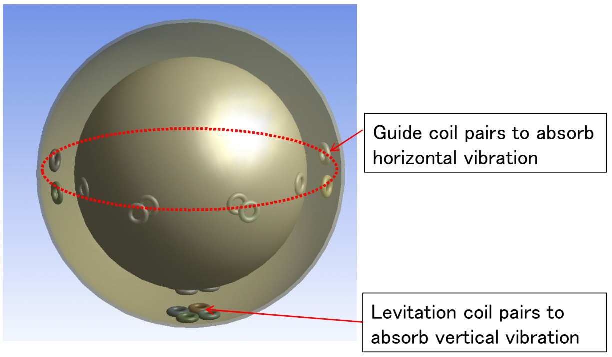
The HTS coil that can generate a high magnetic field at the liquid hydrogen temperature (20 K) can be fabricated using the HTS tapes (for instance, the commercially available Bi2223 tapes). Fig. 1 shows the basic arrangement of the HTS coils pairs for magnetic levitation. It is composed of a floating coil installed in the liquid hydrogen storing container and a levitation coil set up on the ground. The heat input by conduction from the support structure can fundamentally be close to zero by the magnetic levitation in the insulated vacuum. Moreover, the heat input by radiation can be reduced by installing a radiation shield with the multilayer insulators ideally set up in the insulated vacuum space. In the steady-state operation, AC losses are not generated in the floating coil operated in the persistent current mode. The levitation coil is connected to a power supply, and the coil current is controlled to keep the position of the floating coil to be constant.



F ig. 1 Principle of magnetic levitation using an HTS coil pair



F ig. 2 Base-isolated control using an HTS coil pair



F ig. 3 Magnetic levitation image of a 40-m-diameter LH_2 storage tank

The magnetic levitation systems using superconducting coils have already been realized as the internal conductor type plasma experiment devices such as LDX [1, 2, 3] , Mini-RT [4, 5, 6] and RT-1 [7, 8]. The supporting levitation coil was in the upper part and the floating superconducting coil was in the lower part, which was opposite position as shown in Fig. 1.

The distance between the floating coil (attached to the storage tank) and the levitation coil (on the ground) changes when an earthquake occurs. In such a situation, it is necessary to control the current in the levitation coil as illustrated in Fig. 2 to keep the floating position constant. In this case, the HTS coils that should be designed to endure high heat load because large AC losses should occur in the levitation coils during an earthquake. As for the levitation coil, a thermally insulated support is done from the ground side at the room temperature, the decrease of AC losses in addition to the heat input from the ground support will decide the total balance of the thermal loading by the magnetic levitation.

To store a large amount of liquid hydrogens, a large-scale magnetic suspension system that uses two or more HTS coils is needed. Fig. 3 shows an example of magnetic levitation of a 40-m-diameter spherical tank, which is widely used for LNG tankers. The capacity of such a tank is 33,500 m^3 where 2,000 tons of liquid hydrogen can be stored. Since the empty weight of the tank is 1,000 tons, the gross weigh that should support by the magnetic levitation is 3,000 tons. Here, four pairs of HTS coils for magnetic levitation are arranged at the bottom, and additional HTS coils for a roll prevention are arranged at the equatorial plane.

TABLE I
SPECIFICATIONS OF THE COMMERCIAL BI2223 TAPE

Item	Specification
HTS material	Bi2223
Manufacture	Sumitomo Electric Industries
Type	DI-BSCCO, HT-NX
Width	4.5 ± 0.2 mm
Thickness	0.31 ± 0.03 mm
Reinforced material	Nickel alloy (30 μm)
Ic (77 K, Self field)	190 A
Critical tensile strength (77 K)	< 500 MPa
Critical double bend diameter (RT)	40 mm

The storage tank of liquid hydrogen is covered to the upper part with a radiation shield in an insulated vacuum. It is thus considered that the heat input by radiation is uniform over the whole tank surface. Therefore, we can keep the low temperature even at the upper part of the tank.

III. HTS COIL CONCEPTUAL DESIGN

The magnetic levitation of a liquid hydrogen storage tank of a 40-m-diameter and the total weight of 3,000 tons is considered to be realistic or not by the concept examination using the specifications of the commercial Bi2223 tape as listed in Table 1. How the distance of the floating coil and the levitation coil changes here by a vertical shaking at an earthquake becomes an important parameter in the HTS coils design. It was a southern part of Hyogo Prefecture earthquake to record the maximum of vertical shaking due to an earthquake that occurred in the past of Japan. It was the earthquake directly above its epicenter under the hypocenter, and was recorded the vertical shaking of the amplitude ± 0.0545 m that became the maximum in the history of the observation. Here, the seismic ground motion of ± 0.1 m in maximum value of the displacement of the vertical shaking was assumed, and the magnetic levitation HTS coils were designed.

The result of design study of the HTS coil pair is listed in Table 2. The HTS tape is wound in the double pancake coil shape. Each double pancake coils are accumulated by six layers and finally one coil is composed. The outside diameter of the coil winding is 0.98 m, the inside diameter is 0.2 m, and the length of the axis is 0.054 m. The winding number per one coil is 15,600 turns and inductance is 115 H. The nominal distance of the levitation coil pair is 0.3 m and the maximum vertical shaking when earthquakes occur is ± 0.1 m. The floating coil attached to the LH_2 storage tank is operated at a fixed current of 200 A in the persistent current mode. The load factor (ratio between the operation current and critical current) is 66 % with a critical current of 305 A. The normal operating current of the levitation coil attached to the ground side is 159

TABLE II
CONCEPTUAL DESIGN OF THE HTS COILS FOR 40 Mϕ LH_2 STORAGE TANK.

Item		Specification
HTS levitation coils		4 pair
Position		Bottom
One coil parameter		
Outer diameter		0.98 m
Inner diameter		0.20 m
Length		0.054 m
Winding turn number		15,600 turns
Inductance		115 H
Normal distance of levitation coil pairs		0.3 m
Maximum vertical shaking		± 0.1 m
Operating current of floating coil / critical current (load factor)		200 A (fixed at persist current) / 305 A (66 %)
Normal operating current of levitation coil / critical current (load factor)		159 / 320 A (50%)
Operating current of levitation coil / critical current at earthquake	+ 0.1 m	258 / 270 A (96 %)
	- 0.1 m	90 / 380 A (24 %)
Maximum parallel field		12.6 T
Maximum vertical field		5.7 T
Maximum hoop stress		420 MPa
Total HTS tape length		231 km

A and the load factor is 50 % with the critical current of 320 A. The operating current of the levitation coil will change depending on the distance of the levitation coil pair when the earthquake occurs. At the coil position of +0.1 m, the operating current is 258 A and the load factor is 96 % with the critical current of 270 A. At the coil position of −0.1 m, the operating current is 90 A and the load factor is 24 % with the critical current of 380 A. During such operation, the maximum parallel field in the coil is 12.6 T and the maximum vertical field is 5.7 T. The maximum hoop stress in the coil is 420 MPa which is less than the critical tensile stress of the Bi2223 tape as listed in Table 1. The total HTS tape length is 231 km.

The amount of HTS tapes required for the magnetic levitation of LH_2 storage is not large compared to that for the fusion reactor magnets. For instance, the helical-type fusion reactor which is under the conceptual design phase at NIFS requires a superconducting conductor of the nominal current of 100 kA with a length of 115 km. In contrast, the four pairs of the superconducting coils used for the magnetic levitation of a 40-m-diameter LH_2 storage tank require a HTS wire of an operating current of 200 A with a length of 231 km. The ratio is 250 between the above two. Note that the liquid hydrogen of 2,000 tons that can be stored in a 40-m-diameter LH_2 storage tank produces electricity of 40 GWh on the assumption of power generation efficiency of 45 % using fuel cells. This could become a mass energy storage facility that is equivalent with a 40-hour-operation of a fusion reactor of 1 GW output. Note also that a NAS battery system needs a vast area of 14,000 m^2 for the installation of a 0.3 GWh storage [9].

If all the electric power consumption in the present world is supplied by fusion, about 2,000 fusion reactors of each 1 GW class are necessary. If the same amount of HTS wires required for these fusion magnets is also applied to LH_2 storage tanks, 500,000 units can be set up. This also means that 10,000 hours, or one year, of electricity storage becomes possible in the world. These design values are showing feasibility of the commercial HTS tape applicable to the magnetic levitation of 40-m-diameter LH_2 storage tank. A detailed design work is necessary for actual coils production, for examples; the large current capacity conductor design that bundles two or more HTS tapes, the coil protection method, the mechanical reinforcement, and the coil cooling method, etc.

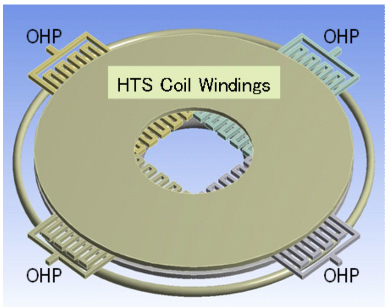
When an earthquake occurs, the large AC losses are induced by changing the current in the levitation coil to keep the floating position of the LH_2 storage tank to be constant. The AC losses generated in one levitation coil are calculated to 11 kJ. The AC loss power of 22 kW is generated during an earthquake. For this large AC loss occurrence, it is difficult for the HTS coil cooling to achieve it, and the development of the HTS tape that decreases the AC loss to at least 1/5 is necessary. It is also an important research item how to remove large AC loss that occurs inside the HTS coil windings.

IV. ENHANCEMENT OF COOLING PROPERTY OF HTS COIL

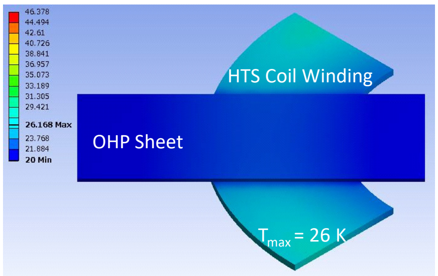
It is simply misunderstood that it becomes easy to cool for the HTS coil compared with the LTS coil. However, the generated heat in the coil windings will take time to diffuse to outside, and it is not removed easily if it relies only on solid heat conduction. This is because the thermal diffusivity of materials that composes the coil decreases along with a temperature rise. Therefore, the generation of a hot spot or thermal runaway in the winding may occur. As a result, it is easy to fall the damaging of the HTS coil.

Here, it relies on the Oscillating Heat Pipe (OHP) as an efficient heat transportation element built in the coil windings. The excellent thermal transport property is achieved corresponding to the high heat load, and the quick response can be achieved at the same time by the high thermal diffusivity of the OHP. The cooling the HTS coil using the OHP is a situation that is gradually spreading to the world from our research proposals. [10] The OHP is a heat transportation element that uses the self-induced oscillation generated in the heat pipe. The OHP filled with the working fluid of liquid and vaper (two phase) has the structure turned repeating between the heating edge and the cooling edge. The self-induced oscillation is generated by temperatures fluctuate on the heating edge and the cooling edge because the bubble of the vapor phase and the stopping of the liquid phase expand, and shrink. Then the mixture of the striped pattern of the working fluid moves repeatedly, and heat can be transported from the heating edge to the cooling edge quickly and efficiently. To build it in in the HTS coil windings, the OHP of the flat plate shape with high mechanical strength was needed. Four stainless steel sheets were accumulated and brazed, and the OHP with a three-dimensional passage structure was developed. It was confirmed that the OHP sheet has an excellent thermal transport property by the experiments. The hydrogen was used as working fluid, and an equivalent thermal conductivity that averages all cross sections of the OHP sheet reached 1,000 W/m·K. [11, 12]

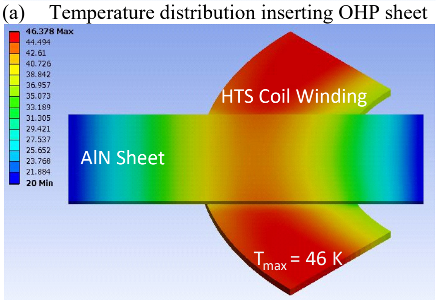
The cooling property of the element HTS coil was calculated by using the finite element method to confirm the effectiveness of the HTS coil that built in the OHP. Finally, it is planned to experiment on the element HTS coil, and to



F ig. 4 OHP built in element HTS coil



(a) Temperature distribution inserting OHP sheet



(b) Temperature distribution inserting AIN sheet

F ig. 5 Calculation results of temperature distribution in the element HTS coil.

TABLE IV
SPECIFICATIONS OF BI2223 TAPE USED FOR ELEMENT HTS COIL

Item	Specification
HTS material	Bi2223
Manufacture	Sumitomo Electric Industries
Type	DI-BSCCO, HT-Hi
Width	4.4 ± 0.3 mm
Thickness	0.28 ± 0.03 mm
Reinforced material	None
Critical current (77 K, Self-field)	180 A
Critical tensile strength (77 K)	80 MPa
Critical double bend diameter (RT)	70 mm

TABLE V
SPECIFICATIONS OF ELEMENT HTS COIL

Item	Specification
Coil	Double pancake coil
Length	13.8 mm
Inner diameter	220 mm
Outer diameter	400 mm
Turn	320 ×2 turn
Inductance	160 mH
Tape length	623 m
Number of OHP sheets inserted in one element HTS coil	4

TABLE VI
SPECIFICATIONS OF OHP SHEET

Item	Specification
OHP sheet width	95 mm
OHP sheet length	225 mm
OHP sheet thickness	5 mm
Cross section of OHP sheet	95 × 5 = 475 mm^2
Length and number of heat pipe channels inside OHP sheet	200 mm × 22 parallel path
Cross section of a heat pipe channel	1.5 mm × 1.5 mm
Gross-sectional area of heat pipe	1.5 × 1.5 × 22 = 49.5 mm^2
Ratio of sectional area in OHP filled with working fluid (H_2)	10.4 %
Material of OHP sheet	Stainless steel
Operating temperature	20 K
Effective thermal conductivity	1,000 W/m·K

compare it with this numerical calculation. Therefore, the Bi2223 tape without mechanical reinforcement and not reduced AC losses, as listed its parameter in Table 4, was used in consideration of easiness to obtain now, and the element HTS coil with the parameter listed in Table 5 was calculated.

Fig. 4 shows the shape of the double pancake coil. Four OHP sheets were imbedded between two single pancake coils wound one layer with Bi2223 tape and make the HTS double pancake coil. In the calculation, it was confirmed that AC losses generated by the magnetic field change during the earthquake was added in the coil, and the temperature rise in the coil was suppressed with the excellent thermal transport property of the OHP sheets. Table 6 shows the parameter of the OHP sheet. The operational condition of the element HTS coil is decided as the operational current of 300 A 0-p and the frequency of 0.2 Hz, that can imitates AC losses generation becomes the same level when an earthquake occurs assuming the use of the improved HTS tape which has reduced AC losses of 1/5.

At this time, AC losses generated in the element HTS coil are 88 W. To compare differences with the solid heat conduction, the nitride aluminum sheet with the thermal conductivity of 100 W/m·K was imbedded between the pancake coils, that was the same size as the OHP sheet with equivalent thermal conductivity of 1,000 W/m·K. The calculation results are shown in Fig. 5. The maximum temperature in the element HTS coil with the built-in OHP as the cooling panel stays in 26 K with the cooling edge temperature of 20 K. However, when it uses the nitride aluminum sheet instead of the OHP, it becomes 46 K, and the maximum temperature in the element HTS coil exceeds the critical temperature (32 K) at the operating current of 300 A. Therefore, it is understood that the OHP built-in HTS coil has excellent cooling property that is applicable to magnetic levitation with an aseismatic control.

V. CONCLUSION

The possibility, that the liquid hydrogen container maintained keeping a low heat load and high safety by the magnetic levitation using the HTS coils, was examined. It is shown that the magnetic suspension system that endures the high heat load due to AC losses when an earthquake occurs, because of the adoption of the HTS coil with the enhancement of the cooling property equipped with a built-in OHP. The cooling property with the OHP built in element HTS coil was clarified by the numerical calculation.

REFERENCES

[1] D. T. Garnier, A. K. Hansen, J. Kesner, et al., "Design and initial operation of the LDX facility," Fusion Engineering and Design. Vol. 81, 2006, pp. 2371-2380.

[2] J. H. Schultz, G. Discoll, D. Garnier, et al., "High temperature superconducting levitation coil for the Levitated Dipole Experiment (LDX)," IEEE Transactions on Applied Superconductivity, Vol. 11, No. 1, 2001, pp. 2004-2009.

[3] A. Zhukovsky, D. T. Garnier, "Operation of the Levitated Dipole Experiment floating coil," IEEE Transactions on Applied Superconductivity, Vol. 16, No. 2, 2006, pp. 898-901.

[4] Y. Ogawa, J. Morikawa, T. Mito, N. Yanagi, M. Iwakuma, "Application of high-temperature superconducting coil for internal ring device," Fusion Engineering and Design. Vol. 81, 2006, pp. 2361-2369.

[5] T. Mito, N. Yanagi, Y. Hishinuma, Y. Ogawa, J. Morikawa, K. Ohkuni, M. Iwakuma, T. Uede, S. Nose, I. Itoh, S. Fukui, "Engineering design of the Mini-RT device," IEEE Transactions on Applied Superconductivity, Vol. 13, 2003, pp. 1500-1503.

[6] K. Natsume, Y. Terazaki, T. Mito, N. Yanagi, Y. Ogawa, J. Morikawa, K. Uchijima, Y. Hosaka, S. Nose, A. Tomioka, I. Itoh, E. Takada, M. Konno, M. Ohaku, "Experimental results of the HTS floating coil using REBCO tape for the Mini-RT upgrading," IEEE Transactions on Applied Superconductivity, Vol. 24, No. 3, 2014, 4601104, DOI: 10.1109/TASC.2013.2287706.

[7] S. Mizumaki, T. Tosaka, Y. Ohtani, M. Ono, T. Kuriyama, K. Nakamoto, M. Shibui, N. Tachikawa, S. Ioka, J. Morikawa, Y. Ogawa, Z. Yoshida, "Development of the magnetically floating superconducting dipole in the RT-1 plasma device," IEEE Transactions on Applied Superconductivity, Vol. 16, No. 2, 2006, pp. 918-921.

[8] T. Tosaka, Y. Ohtani, M. Ono, T. Kuriyama, S. Mizumaki, M. Shibui, K. Nakamoto, N. Tachikawa, J. Morikawa, Y. Ogawa, Z. Yoshida, "First experiment on levitation and plasma with HTS magnet in the RT-1 plasma device," IEEE Transactions on Applied Superconductivity, Vol. 17, No. 2, 2007, pp. 1402-1405.

[9] "The World's Largest NAS Battery Installation Commences Operation", http://www.ngk.co.jp/english/news/2016/0303.html

[10] T. Mito, K. Natsume, N. Yanagi, H. Tamura, T. Tamada, K. Shikimachi, N. Hirano, and S. Nagaya, "Achievement of high heat removal characteristics of superconducting magnets with imbedded oscillating heat pipes," IEEE Transactions on Applied Superconductivity, Vol. 21, 2011, pp. 2470-2473.

[11] T. Mito, K. Natsume, N. Yanagi, H. Tamura, Y. Terazaki, "Enhancement of thermal properties of HTS magnets using built-in cryogenic Oscillating Heat Pipes," IEEE Transactions on Applied Superconductivity, Vol. 23, No.3, 2013, doi: 10.1109/TASC.2013.2251393.

[12] K. Natsume, T. Mito, N. Yanagi, H. Tamura, "Development of a flat-plate cryogenic oscillating heat pipe for improving HTS magnet cooling," Physics Procedia, Vol. 45, 2013, pp. 233-236.