Performance of a 10-kJ SMES model cooled by liquid hydrogen thermo-siphon flow for ASPCS study

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Abstract. We propose a new electrical power storage and stabilization system, called an Advanced Superconducting Power Conditioning System (ASPCS), which consists of superconducting magnetic energy storage (SMES) and hydrogen energy storage, converged on a liquid hydrogen station for fuel cell vehicles. A small 10-kJ SMES system, in which a BSCCO coil cooled by liquid hydrogen was installed, was developed to create an experimental model of an ASPCS. The SMES coil is conductively cooled by liquid hydrogen flow through a thermo-siphon line under a liquid hydrogen buffer tank. After fabrication of the system, cool-down tests were carried out using liquid hydrogen. The SMES coil was successfully charged up to a nominal current of 200 A. An eddy current loss, which was mainly induced in pure aluminum plates pasted onto each pancake coils for conduction cooling, was also measured.

1. Introduction

To effectively use renewable energy sources such as wind and photovoltaic power generations, we propose a new electrical power storage and stabilization system, called an Advanced Superconducting Power Conditioning System (ASPCS), that consists of superconducting magnetic energy storage (SMES), a fuel cell-electrolyser (FC-EL), hydrogen storage, direct-current-to-direct current (DC/DC) and direct-current-to-alternating-current (DC/AC) converters, and a controller. The ASPCS compensates for fluctuating electrical power generation by combining the SMES with quick response and hydrogen energy storage with unlimited capacity [1], [2]. Similar concepts for an energy buffering system have recently been considered by M. Sander et al. [3] and H. Louie et al. [4].

Figure 1 shows, the proposed ASPCS is to be built beside a liquid hydrogen storage facility for fuel cell (FC) vehicles. It is planned that there will be more than 3500 such storage facilities by 2030 [5], and we expect that some of them will use liquid hydrogen tanks to store hydrogen. The SMES coil in the ASPCS is cooled by liquid hydrogen that is transferred from a storage tank at approximately 20 K. This means that the ASPCS effectively uses the cooling capability of liquid hydrogen, which is dumped out through an evaporator in the present design of vehicle stations.
Liquid hydrogen has cooling properties that are favorably comparable to those of popular cryogens, such as liquid helium and liquid nitrogen, as shown in Table 1. However, liquid hydrogen, which has a high flammability range, requires special handling methods for storage and transport to avoid critical accidents. Sparks from electrical equipment, static electricity, open flames, or extremely hot objects need to be prevented to ensure human safety. Therefore, use of liquid hydrogen as a cryogen has been avoided for many years.

These safety measures for dealing with liquid hydrogen have to be applied for ASPCS cryogenic design criteria. All high current circuits for the SMES coil, including the electrical lead lines, have to be indirectly cooled across electric insulators. So, the coil cooling scheme is based on the design concept for the cryogen-free magnets or the particle detector magnets [6]. According to these thermal design concepts, pure aluminum strips with a high thermal conductivity of about 6000 W/m·K at 20 K, which adhere to the coil layers and the liquid hydrogen pipe, play a role of the thermal conductors.

On the other hand, this thermal design concept has two disadvantages in comparison to the pool boiling method, in which a superconducting coil is dipped directly into liquid hydrogen. One disadvantage is that a solid thermal conducting path through pure aluminum strips requires a temperature gradient. The other disadvantage is that eddy current loss in pure aluminum strips is induced by field fluctuation due to SMES operation and can amount to a large heat load.

The former disadvantage can be addressed by arranging cooling pipes near the coil, and the latter can be addressed by creating slits in the pure aluminum strips to prevent eddy current circuits. Eddy current loss is one of the important issues to be taken into consideration in ASPCS development.

Of course, there is another approach to secure handling of liquid hydrogen, which is based on the fact that pure hydrogen is inflammable. In some R&D studies, superconducting cables and devices have been put directly into liquid hydrogen baths or flows [7], [8]. However, additional control measures may be required to ensure the safety of the general public.

Table 1. Cooling properties of liquid hydrogen and other popular cryogens.\(^a\)

| Cryogen | Boiling Temp.(K) | Density (kg/m\(^3\)) | Viscosity (µPa·s) | Kinematic Visc. (mm\(^2\)/s) | Latent Heat (kJ/ℓ) | Sensible Heat (kJ/ℓ) |
|---------|----------------|----------------------|------------------|-----------------------------|-------------------|----------------------|
| Hydrogen | 20.28          | 70.8                 | 13.4             | 0.19                        | 31.4              | 248.5                |
| Helium   | 4.22           | 124.8                | 3.2              | 0.03                        | 2.6               | 192.4                |
| Nitrogen | 77.3           | 804.2                | 142.9            | 0.18                        | 160.6             | 188.0                |
| Neon     | 27.1           | 1204.0               | 125.2            | 0.10                        | 105.0             | 341.3                |

\(^a\) These are the values of these properties at 1 atm.
\(^b\) Sensible heat is the difference between the enthalpy at the boiling temperature and that at 300 K.
2. Design and fabrication of 10-kJ SMES model for ASPCS R&D

Many engineering studies and development efforts are required to produce an ASPCS. The most important topics are (1) establishment of combined input/output power control loops and sequences of both SMES and FC-ELs for ASPCS operation and (2) confirmation of the feasibility of the liquid hydrogen-based cooling scheme. A small model of the ASPCS was developed to demonstrate the ASPCS’s effects and to study these topics. The ASPCS model, which handles 1-kW power generated by a solar cell system, consists of a 10-kJ SMES, an FC unit, an EL unit, a hydrogen storage tank, and a control system, as shown in figure 2.

2.1. Design of 10-kJ SMES coil

The parameters of the SMES coil are summarized in table 2. Although, from an economic perspective, we are interested in an SMES coil wound with MgB₂ superconducting cable [1], the coil’s critical current density of 104 A/cm² at 5 T is still lower than the applicable level. Therefore, a BSCCO tape conductor [9] was initially chosen for the coil to permit an experimental study of cooling using liquid hydrogen.

A stack of eight double pancakes with 134 × 2 turns, with a nominal current of 200 A and a stored energy of 10 kJ, made up the coil. Unfortunately, the tape conductor in the seventh pancake was torn when a voltage tap was soldered onto its outermost surface. Therefore, a bus connection in the coil was used to bypass the seventh and eighth coils temporarily. Table 2 also summarizes the parameters of a coil composed of six double pancakes.

Two semicircular aluminum sheets 0.2 mm thick were laminated onto each upper and lower surface with a gap between them, so that a large induced circular current does not flow. Each semicircular sheet was formed with radial slits positioned approximately every 10 mm, leaving a 10-mm-wide outer edge portion, as shown in figure 4, to restrain eddy current. Four strips 10 mm wide extend from the outer edge portion to a heat exchanger.

Table 2. Model coil parameters.

| Parameter                      | Design | Fabricated |
|--------------------------------|--------|------------|
| No. of Double Pancake          | 8      | 6          |
| Superconductor                 | DI-BSCCO-HT-SS[9] |            |
| Ic at 77 K                     | 180 A (Self field) |          |
| Stored Energy (kJ)             | 10     | 6.22       |
| Coil I.D. (mm)                 | 100    |            |
| Coil O.D. (mm)                 | 193.8  |            |
| Coil Height (mm)               | 75.4   | 56.6       |
| Inductance (H)                 | 0.494  | 0.311      |
| Nominal Current (A) at 20 K    | 200    |            |
| B central (T) @ 200 A          | 3.32   | 2.63       |
| B max (T) @ 200 A              | 4.32   | 3.81       |
2.2. 10 kJ SMES model cryostat design

Figure 4 shows the cryostat assembly, which consists of a liquid hydrogen buffer tank with a capacity of 7 ℓ, a thermo-siphon (TS) loop pipe, a heat exchange (HEX) plate, and a BSCCO coil. One end of the TS pipe is connected to the bottom of the buffer tank, and the other end reaches the upper vapor phase part. The HEX plate, which is made of a copper (C1200) plate, is brazed onto the rising part of the TS loop line. Pure aluminum strips, which extend from each pancake, are attached to the HEX plate and are thermally face-contacted to it by tightening the screws for the push plates.

Consequently, the coil heat load is transferred through the pure aluminum plates to the HEX plate, creates vapors in the TS and drives TS flow in the pipe.

The entire electrical apparatus, except for a liquid hydrogen level sensor [10], is isolated from a hydrogen atmosphere. A set of current leads run from a vacuum vessel to the coil, which is made of phosphorous-deoxidized copper bar with dimensions of 5×10 mm². The current leads are attached to the outer surface of the liquid hydrogen tank and is indirectly cooled by liquid hydrogen thorough the tank wall.
2.3. Apparatus at atmosphere and safety interlock

The SMES model cryostat was set up in a laboratory at the IWATANI R&D Center [11], where safety research studies dealing with hydrogen are conducted. Liquid hydrogen is supplied continuously from a 2000-ℓ pressurized tank through a vacuum-insulated transfer tube to the model cryostat during tests to maintain the liquid hydrogen level in the buffer tank between appropriate values.

Both a pair of power cables for magnetic excitation and multi-core signal cables at the laboratory are lined inside a nitrogen jacket pressurized at a positive pressure of approximately 105 kPa to isolate them from hydrogen leakage in the laboratory. Once the nitrogen jacket pressure decreases to 101 kPa, a pressure switch interlocks both the coil current and the signal monitoring equipment.

3. Experimental results and discussion

3.1. Cooling down period and steady state

A cold mass at room temperature is cooled down using a thermo-siphon flow of liquid hydrogen. As figure 5 shows, the cooling down of the buffer tank occurs most rapidly. It takes approximately 8 hours for the coil to be cooled to a temperature below 26 K.

The temperature distribution in the cold mass after precooling is shown in figure 4. Temperature observations at precooling and steady-state cooling indicate that there may be substantial thermal resistance between the aluminum thermal conductor and the coil.

3.2. Evaluation of thermo-siphon flow and heat transfer

The heat load from the model coil has to be transferred by a hydrogen flow through the thermo-siphon line, and two-phase heat transfer and the fluidity of saturated hydrogen play an important role in this process. The heat transfer ability of the cooling system was measured empirically, with the input power provided by a set of film heaters laminated onto the HEX. The temperature distribution along the thermo-siphon line, is plotted with respect to the heater load in figure 6. It took for about 30 minutes that the temperature distribution by a constant heater load became steady. The temperature in the supply region is maintained at a constant low level with a maximum heater load of 230 W, which means that the thermo-siphon flow is continuous. On the other hand, the temperature at the heater rises suddenly at 230 W, which means that a departure from nuclear boiling (DNB) occurs at the surface of the pipe in the heat flux range of 1.8–2.7 W/cm². This measured critical heat flux (CHF) is close to the value of 1 - 10 W/cm² indicated in previous research [12].

![Figure 5](image.png)

Figure 5. Precooling trend curve. Liquid hydrogen was filled into the buffer tank at room temperature.
3.3. DC and AC excitation

The model coil was successfully charged up to a nominal current of 200 A. AC excitation was then performed with a sinusoidal current with ±9 A peaks and a maximum frequency of 1 Hz to measure the induced AC loss in the coil. Figure 7 is a trend on measured temperatures during AC excitation. Charging and discharging of the SMES model coil is performed by the ASPCS control system with a 10-A current and 0.1-Hz frequency. Although the peak current of 9 A is limited by the performance of the power amp purchased, the induced AC loss covers the future SMES operations. The measured AC loss at the highest frequency of 1 Hz was 10 W, and the temperature of the coil rose to near 26 K. The heat load was calculated from the temperature of the aluminum strip using the calibration curve shown in figure 8, which was obtained using a simulation heater firing on the coil.

The estimated eddy current loss due to the self-field of the SMES coil was estimated to be 0.14 W at ±9 A peaks and 1 Hz. The measured AC loss of 10 W was much larger than the estimated loss because two sets of semicircular aluminum sheet in the pancakes were connected with between 0.1 and 5 Ω as a result of assembly errors. This could induce the AC loss of between 1 and 50 W. Fortunately, however, the temperature margin of the conductor was large enough to accommodate the measured temperature rise. We can therefore identify as the next research step an examination of the combined control of the SMES with an FC/EL hydrogen energy buffer and solar panel power generation. Rearrangement of the pure aluminum sheets to reduce AC loss is also planned.

**Figure 6.** Thermo-siphon driven & DNB.

**Figure 7.** Temperature rise due to AC loss. Heat loads are calculated according to fitting results in figure 8. HEX and AL strip temperature became constant after about 10 min.
Figure 8. Calibration line for AC loss analysis. A calibration heater, which is laminated on the coil bottom, simulates heat loads of AC loss. Then temperatures rise at the HEX and AL strips become scales for AC loss.

4. Conclusions
In this paper, a design and performance evaluation for a BSCCO SMES model coil for an ASPCS experimental study—specifically, the safe use of its liquid hydrogen-based cooling scheme—is presented. In the system evaluated, a two-phase thermo-siphon loop supplies liquid hydrogen flow from a buffer tank near the coil, to which pure aluminum sheets are thermally connected. To prevent large AC losses in the thermal conductors themselves due to SMES operation, many slits and one-turn-cuts were made in the aluminum sheets. The coil was successfully cooled down and charged up to a nominal current of 200 A. The measured AC loss induced in the pure aluminum sheets was considerably greater than the predicted value, but the temperature increase was small enough to permit continuous AC excitation.

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