Conceptual Design of 1 GW Class Hybrid Energy Transfer Line of Hydrogen and Electricity

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Abstract. Applicability of 1 GW class hybrid energy transfer line of hydrogen and electricity is investigated in this report. Hydrogen refrigeration station is placed on every 10 km of the unit section. The rated current is 10 kA, and operation voltage is 100 kV (+50 kV and -50 kV for ground). Delivery capacity of the liquid hydrogen is 100 tons per day. The HETL consists of the SC cable, electrical insulation layer, channel for liquid hydrogen, inner corrugated tube, vacuum space for thermal insulation and outer corrugated tube. The special multi-filamentary MgB₂ wire was developed to improve the \( I_c \) performance against bending strain. When the pressure of liquid hydrogen increases, boiling temperature of liquid hydrogen becomes high. Pressurization of liquid hydrogen enables to expand operation temperature region of the MgB₂ cable, and to absorb the head loss of the installation route. To obtain the operation temperature from 20 K to 25 K, pressure of liquid hydrogen from 0.4 to 0.6 MPa was chosen. When the heat leak into the liquid hydrogen is 1.0 W/m (expected value), the temperature at the outlet becomes 21.8 K. It was confirmed that this HETL is one of the attractive energy transportation system which combines hydrogen fuel and SC power transmission.

1. Introduction

Thermo-nuclear fusion is recognized to be a clean and unexhausted energy resource because the fuel can be extracted from sea water unlimitedly. It also has a big advantage of less CO₂ emission, of which character would contribute to avoiding green house effect on the earth. Integrated energy transportation system will be necessary for the hydrogen society in near future.

The force-free helical-type fusion reactor, FFHR, can produce the current-less steady-state plasma with no dangerous disruptions [1]. This is one of great advantages for the force-free helical-type D-T reactors. To allow the flexibility in operation, co-generation system of electricity and hydrogen is one of potential candidates. In this system, hydrogen is made from the steam electrolysis, in which thermal energy of the steam can be obtained from the waste heat of the divertor and/or the radiation shield components outside of the breeder blanket [2]. Hydrogen has to be packaged by compression or liquefaction, transported by trailer or pipeline, stored, and transferred to the end users.

The Energy Supergrid that delivers electricity and hydrogen in the integrated energy pipelines in the USA was proposed [3]. World Energy Transmission System is also discussed to assess the global network of the SC power cables and fuel pipelines [4]. One GW class hybrid energy transfer line
Table 1. Design parameters of hybrid energy transfer line.

| Items                                      | Target values |
|--------------------------------------------|---------------|
| Total length to end user                   | 100 km        |
| Length between the cooling stations        | 10 km         |
| Unit length of a HETL                      | 500 m         |
| Operation voltage to ground                | +50 kV and -50 kV |
| Operation voltage between the lines        | 100 kV        |
| Maximum operation current                  | dc 10 kA      |
| Transportation capacity of each line       | 50 ton/day (1.6 kg/s) |
| Operation temperature                      | 17 – 24 K     |
| Pressure of liquid hydrogen                | 0.4 – 0.6 MPa |

(HETL) of hydrogen and electricity is proposed, and pressure loss and temperature rise of the 10 km long HETL are investigated on the basis of experiences of the SC bus-lines of the LHD [5-7].

This paper describes the conceptual design of the HETL. The design concepts for the bending strain of the HTS cable and thermal contraction of long cables are investigated. The efficiency of the HETL under the 100 km delivery is also discussed in this report.

2. Hybrid Energy Transfer Line

The characteristics of the HETL are, 1) low energy consumption system for long transportation, 2) power line of low-voltage high-current system, and 3) integrated energy transportation system. It is desired for the new needs which combine hydrogen fuel and SC power transmission. The total length of 100 km is selected to assess the engineering potential of the HETL.

The design concepts for the HETL are as follows. (1) The hydrogen refrigeration station is placed on every 10 km of the unit section. (2) The rated current and rated voltage of the dc power line are 10 kA and 100 kV (1 GW), respectively. (3) Delivery capacity of the liquid hydrogen is 100 tons per day. Design parameter of the HETL is summarized in Table 1.

2.1. Structure of the HETL

The HETL system requires high reliability and safety as well as the conventional power grid and natural-gas pipe line. The SC cable should have the large margins for the operation current in the
limited cross-section. The SC materials should have the requirements, (1) which can expect reduction in manufacturing cost, (2) which can be used in the liquid hydrogen temperature, and (3) which is simple for manufacturing and can keep seeing enlargements. BSCCO or YBCO tapes have excellent SC performances in liquid hydrogen temperature. However, they are expensive. On the contrary, magnesium diboride (MgB$_2$) wire is one of the potential candidates for 10 kA class cable, since the core $J_c$ of more than 1000 A/mm$^2$ under the liquid helium was observed in various MgB$_2$ wires [8-10]. The 10 kA class SC cable for the HETL was designed on the basis data of the MgB$_2$ wires with a diameter of 1.3 mm [8]. Operation current of an MgB$_2$ strand at liquid hydrogen temperature was determined to 20 A (core $J_c$=100 A/mm$^2$).

Schematic drawing of the HETL is shown in Fig. 1. Two types of the structure were investigated; one is bath cooling method, and the other is hollow type conductor [5]. The application of Type A leads to an easiness of the assembling work and an enlargement of the liquid hydrogen area. On the other hand, application of Type B leads to a decrease of the magnetic field in the cable and an increase of heat transfer between cable and liquid hydrogen. Both types of SC cable structures are acceptable for a cryogenic envelope of the HETL. Parameters of Type A and Type B cables are listed in Table 2.

### 2.2. Bending Properties of MgB$_2$ wires

It is important to understand the mechanical performance of the MgB$_2$ wire. To suppress the $I_c$ degradation for bending strain, multi-filamentary MgB$_2$ wires were investigated. The bending property of the 19 filamentary MgB$_2$ wire was made, and it awe tested in comparison with the mono-core MgB$_2$ wire [11]. Cross-sectional views of the MgB$_2$ wire applied to the HETL design and the samples of the bending test are shown in Fig. 2.

A relationship between the normalized $I_c$ and bending strain for MgB$_2$ mono-core wire and multi-filamentary wire is shown in Fig. 3. The bending strain $\varepsilon$ is defined as,

$$\varepsilon = \frac{\Delta L}{L_0}$$

where $\Delta L$ is the change in length and $L_0$ is the original length.

Figure 2  Cross-sectional view of MgB$_2$ wire applied to HETL design (a), and cross-sectional views of mono-cored MgB$_2$ wire (b) and multi-filamentary MgB$_2$ wire (c) used in bending test.

| Table 2. Parameters of Type A and Type B cables. |
|---------------------------------|-----------------|-----------------|
| Diameter of SC cable           | 34.5 mm         | 103/105 mm      |
| Thickness of electrical insulation | 13 mm           | 12 mm           |
| Number of strands              | 507             | 500             |
| Current of one strand          | 19.7 A          | 20 A            |
| Maximum Magnetic field in SC cable | 0.12 T         | 0.04 T          |
| Cooling method                 | Bath cool       | Hollow type     |
| Cross-section of liquid hydrogen | 103 cm$^2$    | 79 cm$^2$       |
| Velocity of liquid hydrogen    | 1.1 m/s         | 1.4 m/s         |

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\[ \varepsilon = \frac{d}{D} \times 100 \quad (\%) \]

Where the \( d \) is diameter of the wire, and \( D \) is diameter of the bend. The \( I_c \) degradation of both wires was observed. However, about 50% of \( I_{c0} \) is remained in the multi-filamentary MgB\(_2\) wire, even if the bending strain exceeds 2%. This may be that about half of the filaments of inside keep the \( I_{c0} \) value, whenever the filaments of outside are damaged by the large bending stress.

![Figure 3](image-url) Relationship between the normalized \( I_c \) and bending strain for MgB\(_2\) mono-core wire and multi-filamentary wire.

### 2.3. 10 kA Class MgB\(_2\) Cable

The MgB\(_2\) cable should be robust for the repetition of the bend and stretch of following manufacture process of; the heat treatment, transfer to the real, twist and bundle, transportation by cable drums and installation on site. As shown in Fig. 4 (a), a diameter of the cable dram has the restriction of the surface transportation. Diameter of the dram is determined to 3 m. When the cable is wounded to the cable dram, tensile stress and compressive stress are induced to the outside and inside of the bend, as shown in Fig. 4 (b). Structure of a coaxial stranded cable is suitable to relieve the bending stress for the large bore cable. The bending strain of the tight-twisted cable can be explained by the Eq. (1). In the loose-twisted cable, bending strain will decrease, because the slip among the strands to the axial direction will compensate the outside tensile stress with inside compressive stress. In a coaxial flexible stranded cable, total number of the strands, \( N \), and diameter of the cable, \( D \), can be expressed as

\[ N = 3n(l+n)+m(l+n) \quad (2) \]

and

\[ D = (k+2n)d \quad (3) \]

where, \( n \) is number of layers, \( m \) is number of strands of the core, \( k \) is constant and value related to \( m \). 

![Figure 4](image-url) Cable dram (a) and coaxial twisted MgB2 cable (b).
Table 3. Design parameters of 10 kA MgB2 cable of Type A.

| Items                                      | Target values                  |
|--------------------------------------------|--------------------------------|
| Operation Temperature                      | 17 K – 24 K                    |
| Material of the SC wire                    | MgB2                           |
| Diameter of the SC strand (core of MgB2)   | 1.3 mm (0.5 mm)                |
| Operation Current of strand (core Jc)      | 19.7 A (~100 A/mm²)            |
| Number of the SC wire                      | 507                            |
| Diameter of SC cable and MgB2 wire         | 26.5 : 1                       |
| Twist ratio (= P / d_c)                    | 30 (= 1035 mm / 34.5 mm)       |

Figure 5  Schematic illustration of HETL (a), and winding up process to the cable dram (b).

When m is 3, k becomes 2.155.

In the cable design of the Type A, parameters of m and n are selected to 3 and 12, respectively. The diameter of the strand, n, is 1.3 mm as shown in Fig. 2 (a). To decrease the bending strain, a twist ratio (= one pitch length / cable diameter) is also determined to be 30. Main parameters of 10 kA MgB2 cable of Type A are summarized in Table 3.

3. HETL System

3.1. Thermal Contract

When a 500 m long HETL is cooled down, the inner SC cable and inner corrugated tube will shrink about 1.7 m in the axial direction. This thermal contraction should be absorbed in the structure of the HETL. Following countermeasures are effective: 1) the inner SC cable and inner corrugated tube are made longer than the outer corrugated tube, as shown in Fig. 5 (a), and 2) the outer corrugated has a large diameter in which inner SC cable and inner corrugated tubes enables to move naturally.

On the winding-up process of the HETL to the cable drams, the SC cable was drawn into the corrugated tube as shown in Fig. 5 (b), since the both ends of SC cable is not fixed to the corrugated tube. This drawn length is important to relieve the thermal contraction. The clearance between the outer corrugated tube and inner corrugated tube are determined in consideration with this idea.

3.2. Pressure Loss of 10 km long HETL

Area of liquid hydrogen of type A is 103 cm² (equivalent diameter of 114 mm φ), and type B for 79 cm² (100 mm φ). We assume the inlet temperature for 17 K, and flow rate of each channel for 50 tons/d (0.58 kg/s). Friction factor in large flow rate regime \( \lambda \) is expressed by Nikuradse’s equation of,

\[
\lambda = 0.032 + 0.021 \text{Re}^{-0.237} \quad (4)
\]
Table 4. Calculation results of outlet temperatures for typical heat load cases.

| Temperature at inlet (K) | Temperature at outlet for each heat load (K) |
|--------------------------|-----------------------------------------------|
|                          | 0.5 W/m | 1.0 W/m | 1.5 W/m | 2.0 W/m |
| 17.0                     | 18.1    | 19.1    | 20.0    | 20.9    |
| 18.0                     | 19.0    | 20.0    | 20.9    | 21.7    |
| 19.0                     | 19.9    | 20.8    | 21.7    | 22.5    |
| 20.0                     | 20.9    | 21.8    | 22.6    | 23.4    |
| 21.0                     | 21.9    | 22.7    | 23.4    | 24.2    |

Figure 6  Pressure loss of 10 km long HETL as a function of temperature of pressurized hydrogen.

Where, Re is Reynolds number. By using the Eq. (4), pressure loss $\Delta P$ is expressed by following Fanning’s equation.

$$\Delta P = 4\rho \frac{v^2 L}{D}$$  \hspace{1cm} (5)

Where, $\rho$ is density of the fluid, and $v$ is velocity. The calculation result of the pressure loss as a function of pressurized hydrogen temperature is shown in Fig. 6. When the pressure of liquid hydrogen increases, boiling temperature becomes high. Density of liquid hydrogen is 0.071 g/cm$^3$ which is more than one order smaller than that of liquid nitrogen. Pressurization of liquid hydrogen enables to expand operation temperature region of the MgB$_2$ cable, and to absorb the head loss of the installation route. In order to obtain the operation temperature of MgB$_2$ cable from 17 K to 25 K, the pressure of liquid hydrogen from 0.4 to 0.6 MPa was chosen [5].

3.3. Heat Load and Cooling Station

Reduction of the heat load into the inner corrugated tube is one of the important subjects to realize the high-efficiency HETL system. Following are effective methods to reduce the heat leak, (1) high vacuum degree against heat leak due to convection, (2) increase in number of super-insulation (SI) sheet against heat leak due to radiation, and (3) slender and long spacer against heat leak due to conduction [12]. Purging with clean and dry gas before evacuation is also important to obtain a high vacuum degree for the long cryogenic tube. Taking into consideration of the above mentioned methods, the heat load of 1.0 W/m is realizable.

Temperature rise of liquid hydrogen after 10 km transportation is calculated as a function of heat load. Where, cross-section and flow rate of liquid hydrogen is 79 cm$^2$ (diameter; 100 mm) and 50tons/day for each tube, respectively. The calculation result is summarized in Table 4. When a heat load is 1
W/m, the temperature rise is 2 K. Even if the heat load is 2 W/m, the cryostable condition can be sustained, when the inlet temperature is less than 20 K.

4. Conclusions
Design studies of 1 GW class hybrid energy transfer line of hydrogen and electricity is performed. The results are concluded as follows;
(1) Power transmission capacity of the dc power line is 1 GW, and capacity of the liquid hydrogen transportation is 100 tons per day.
(2) The special multi-filamentary MgB$_2$ wire was developed to improve the $I_c$ performance against bending strain.
(3) To keep the liquid state of hydrogen anywhere in the unit section, the temperature and pressure of the inlet point were selected to 17 K and 0.4 - 0.6 MPa.
(4) When the heat leak into the liquid hydrogen is 1.0 W/m (expected value), the temperature difference between the outlet and inlet becomes about 2 K.

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