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Study on 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. Target distance of hybrid energy transfer line is 1000 km. Hydrogen refrigeration station is placed on every 10 km of the unit section. The rated current and withstand voltage of the dc power line are 10 kA and 100 kV, respectively. Capacity of the liquid hydrogen transportation is 100 tons per day. Transfer line consists of the superconducting (SC) cable, space for liquid hydrogen, electrical insulation layer, vacuum space for thermal insulation, and cryogenic envelopes. High Jc performance in a liquid hydrogen temperature requires for the SC cable. The MgB2 wire is one of the potential candidates for this system as well as BSCCO or YBCO tapes. 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 MPa, respectively. When the heat leak into the liquid hydrogen was 1.0 W/m (expected value), the temperature at the outlet became 18.1 K. Total power consumption of the 10 kW class refrigerator is estimated to 660 kW. The total power consumption for the hybrid energy transfer line of 1000 km length becomes 132 MW. This value is equivalent to 13.2 % to the transport capacity of 1GW.

1. Introduction

The conceptual design studies on force-free helical-type fusion reactor, FFHR, have been carried out with collaborations between the universities and National Institute for Fusion Science in Japan [1]. The SC helical coil system reduces the centering force by compensating with the hoop force. The FFHR can also produce the current-less steady-state plasma with no dangerous disruptions. These are 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]. These reports deal the qualitative analysis and/or principle proposals.
In this report, 1 GW class hybrid energy transfer line of hydrogen and electricity is proposed on the basis of experience of the SC bus-lines with total length of 500 meters [5, 6]. Total efficiency of the hybrid energy transfer line system under 1000 km delivery is also investigated in this report.

2. Fusion Power Plant with Electrolyzer

To assess the technical potential of the FFHR operation style, dedicated hydrogen production from electrolysis by the electric power of 1 GW have been investigated. Schematic illustration of co-generation of electricity and hydrogen is shown in Figure 1. Gaseous hydrogen of 700 tons per day can be produced. The steam of 6,354 tons per day at 150 °C is necessary in this case. In FFHR, about 450 MW of thermal power is delivered via the scrape-off layer plasma to the divertors.

The energy is necessary to compress and/or liquefy the hydrogen for packing and delivering it to the end users. The compression works depends on the thermodynamics of the compression process. The energy consumption of a multi-stage hydrogen compressor is about half-way between the two theoretical limits of an isothermal and adiabatic compression process. About 17.4 MW of electrical power is needed for the compression of 100 tons per day of hydrogen from 0.1 MPa to 50 MPa. Even more energy is needed to compact hydrogen by liquefaction. Required power of the helium compressors is about 2.7 times larger than that of the hydrogen compressors. The total power consumption of the hydrogen liquefaction system of 100 tons per day is 26 MW [2].

Figure 2 gives power flow diagram from fusion output to power generation and electrolysis. The four different styles of plant outputs are investigated: (A) pressurized hydrogen of 625 tons per day, (B) liquid hydrogen of 574 tons per day, (C) 1 GW of power generation, and (D) 0.824 GW of electricity production plus 100 tons per day of liquid hydrogen. Case (A) and case (B) are dedicated hydrogen production and these cases are desirable as the infrastructure for the future fuel cell society. Case (C) is suitable for a largely constant level of power demand as well as a nuclear fission power plant. Case (D) has the flexibility in plant operation. Electrical power to the grid can be modulated if the excess electricity were used for the hydrogen production, at the constant power generation. This fraction rate of case (D) is also appropriate for the levelization between on-peak and off-peak demand. In the following sections, transportation method of case (D) is investigated [2].

3. Hybrid Energy Transfer Line

The merits of hybrid energy transfer line (ETL) of hydrogen and electricity are, 1) low energy consumption system for long transportation, 2) power line of low-voltage high-current system (for downsizing ac/dc converter), 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 1000 km is selected to assess the engineering potential of the HETL.

The HETL should be flexible, because of the transportation by cable drums and installation on site. 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.

Schematic illustration of HETL is shown in Figure 3. Design parameter of the HETL is summarized in Table 1.

### 3.1. 10 kA Class Cable

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 temperature range of 17 K - 24 K, and (3) which is simple for manufacturing and can keep seeing enlargements. BSCCO and/or YBCO tapes have excellent SC performances in liquid hydrogen temperature. However, they are expensive, and some of them have mechanical weakness. On the contrary, magnesium diboride (MgB2) wire is one of the

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**Table 1.** Design parameters of hybrid energy transfer line.

| Items                        | Target values          |
|------------------------------|------------------------|
| Target distance              |                        |
| total length to end user     | 1000 km                |
| unit length between the cooling stations | 10 km               |
| Power Transmission           |                        |
| withstand voltage of each line | ±50 kV and -50 kV (100 kV) |
| rated current               | dc 10 kA               |
| Hydrogen Transportation      |                        |
| Transportation capacity of each line | 50 ton/day (1.6 kg/s) |
| Operation temperature       | 17 – 24 K              |
| Pressure of liquid hydrogen  | 0.4 MPa                |
potential candidates for 10 kA class cable, since the core Jc of more than 1000 A/mm² under the liquid helium was observed in various MgB2 wires [7-9]. The 10 kA class SC cable for the HETL was designed on the basis data of the MgB2 wires with a diameter of 1.3 mm [8]. Operation current of a MgB2 strand at liquid hydrogen temperature was determined to 20 A (core Jc=100 A/mm²).

Cross-sectional view of the HETL is shown in Figure 4. Main parameters of 10 kA MgB2 cable are summarized in Table 2. Two types of structure were investigated; one is bath cooling method (Type A), and the other is hollow type conductor (Type B). 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 3.

### 3.2. Structure of HETL

As shown in Figure 4, transfer line consists of the superconducting (SC) cable, space for liquid hydrogen, electrical insulation layer, inner corrugated tube, vacuum space for thermal insulation, outer

![Figure 3. Liquid hydrogen distribution in HETL system.](image)

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### Table 2. Design parameters of 10 kA MgB2 cable.

| 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) | 20 A (~100 A/mm²) |
| Number of the SC wire              | > 500             |

![Figure 4. Schematic drawings of 1 GW class cables: (A) twisted SC cable with 500 strands, and (B) hollow-type SC cable.](image)
Table 3. Parameters of Type A and Type B cables.

|                      | Type A          | Type B          |
|----------------------|-----------------|-----------------|
| Diameter of SC cable | 36.8 mm         | 103/105 mm      |
| Thickness of electrical insulation | 12 mm         | 12 mm           |
| Cross-section of liquid hydrogen | 103 cm²       | 79 cm²          |
| Maximum Magnetic field in SC cable | 0.12 T       | 0.04 T          |

Figure 5. Pressure loss of 10 km long HETL as a function of temperature of pressurized hydrogen.

corrugated tube and so forth. Here, the corrugated tubes of the same size as that of the SC bus-line of the LHD were applied and pressure loss of the liquid hydrogen was investigated as a function of the temperature.

Cross-section 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 (1.6 kg/s). Friction factor in large flow rate regime λ is expressed by Nikuradse’s equation of,

\[ \lambda = 0.032 + 0.021 \text{Re}^{0.237} \]  \hspace{1cm} (1)

Where, Re is Reynolds number. By using the Eq. (1), pressure loss ΔP is expressed by following Fanning’s equation.

\[ \Delta P = 4 \lambda \frac{v^2 L}{D} \]  \hspace{1cm} (2)

The calculation result of the pressure loss as a function of pressurized hydrogen temperature is shown in Figure 5. When the pressure of liquid hydrogen increases, boiling temperature 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. In order to obtain the operation temperature of MgB2 cable from 17 K to 25 K, the pressure of liquid hydrogen from 0.4 to 0.6 MPa was chosen.

4. HETL System

Reduction of the heat load into the transfer line is one of the important subjects to realize the high-efficiency HETL system. Figure 5 shows the internal structures of cryogenic envelopes. The SC bus-
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. Internal structures of cryogenic envelopes: (a) conventional structure, and (b) low loss structure.

lines of the LHD applied the conventional structure as shown in Figure 6 (a). Following are effective methods to reduce the heat leak between the corrugated tubes, (1) high vacuum degree (1 x 10^{-5} mbar) 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 [10]. 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 and shown in Figure 6 (b), 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 cm² (diameter; 100 mm) and 50 tons/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.

When the heat load is 1 W/m per one-way, refrigeration capacity of 20 kW @17 K is necessary. Cryogenic refrigeration is a complex process involving Carnot cycles and physical effects that do not obey the theoretical law. Nevertheless, the Carnot function is used as a reference for the process analysis. Power consumption of the refrigerator, $P$, can be estimated as shown in the following equation.

$$ P = W_c \frac{T_H - T_L}{T_c} \frac{1}{\eta} \quad (3) $$

The refrigerator operates between $T_H (=300 \text{ K})$ and $T_L (=17 \text{ K})$. $W_c$ is the refrigeration capacity, and $\eta$ is efficiency of the Carnot cycle. Here, 0.25 was assumed as a value of $\eta$. Required power of the 20 kW refrigerators is estimated to 1.32 MW. The total power consumption for the energy transfer system of 1000 km length becomes 132 MW. This value is equivalent to 13.2 % to the transport capacity of 1GW. Main parameters of the HETL of the unit section are summarized in Table 5.
Table 5. Main parameters of the HETL of the unit section.

| Items                                           | Target values |
|------------------------------------------------|---------------|
| Length of a HETL                                | 10 km         |
| Capacity of a refrigerator                      | 20 kW         |
| Electrical power of the refrigerator            | 1.32 MW       |
| Liquid hydrogen inventory in one-way 10 km tube | 78.5 m³       |

5. Conclusions
Applicability of 1 GW class hybrid energy transfer line of hydrogen and electricity is investigated. 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) 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 MPa.
(3) When the heat leak into the liquid hydrogen is 1.0 W/m (expected value), the temperature at the outlet becomes 18.1 K.
(4) The total power consumption for the energy transfer system of 1000 km long becomes 132 MW. This value is equivalent to 13.2 % to the transport capacity of 1GW.

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