## §12. Investigation of Low Loss Cryogenic Tube for Hybrid Energy Transfer Line

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The merits of hybrid energy transfer line (HETL) 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. Design parameter of the HETL is summarized in Table 1.

Reduction of the heat load into the cryogenic tube is one of the important subjects to realize the high-efficiency hybrid energy transfer line of liquid hydrogen fuel and electricity system. The SC bus-line of the LHD applied the conventional structure as shown in Fig. 1 (a). Following are effective methods to reduce the heat leak between the corrugated tubes, (1) high vacuum degree ($1 \times 10^{-5}$ 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 [1]. 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 as shown in Fig. 1 (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 2. 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 at 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,

$$P = W_L \frac{T_H - T_L}{T_L} \frac{1}{\eta} \qquad (1)$$

Table 1 Design parameters of 10 kA MgB$_2$ cable.

| Items | Target values |
|---|---|
| Target length | |
| total length to end user | 100 km |
| length btw cooling stations | 10 km |
| Power Transmission | |
| operation voltage | +50 kV and -50 kV (100 kV) |
| operation current | dc 10 kA |
| Hydrogen transportation | |
| Temperature | 17 – 24 K |
| capacity of each line | 50 tons/day (1.16 kg/s) |
| pressure of L-H$_2$ | 0.4 - 0.5 MPa |

The refrigerator operates between $T_H$ (=300 K) and $T_L$ (=17 K). $W_L$ 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 100 km length becomes 13.2 MW. This value is equivalent to 1.3 % to the energy transport capacity of 1GW [2]. Main parameters of the HETL of the unit section are summarized in Table 3. Structure of the peripheral terminal is shown in Fig. 2.

(1) Yamada, S, et al.; Journal of Physics: Conference Series **97** (2008) 012167.
(2) Yamada, S, et al.; Journal of Physics: Conference Series **234** (2010) 032064.

Table 2 Calculation results of outlet temperatures.

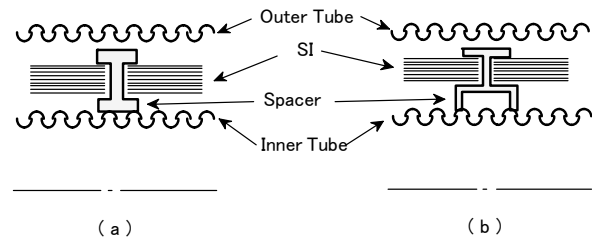| Inlet Temp. (K) | Outlet Temp. for each heat load (K) | | | |
|---|---|---|---|---|
| | 0.5 W/m | 1.0 W/m | 1.5 W/m | 2.0 W/m |
| 17.0 | 18.1 | 19.1 | 20.0 | 20.9 |
| 18.0 | 19.0 | 20.0 | 20.9 | 21.7 |
| 19.0 | 19.9 | 20.8 | 21.7 | 22.5 |
| 20.0 | 20.9 | 21.8 | 22.6 | 23.4 |
| 21.0 | 21.9 | 22.7 |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



Fig. 1 Cryogenic tube of (a) conventional structure and (b) low loss structure.
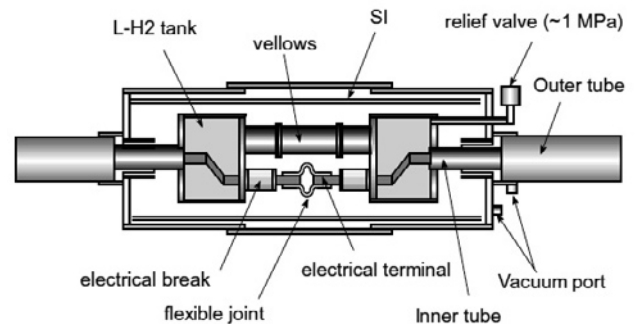


Fig. 2 Structure of the cryogenic tube (a) conventional structure and (b) low loss structure.

Table 3 Main parameters of the HETL of the unit section.

| Items | Target value |
|---|---|
| Length of a HETL | 10 km |
| Capacity of hydrogen refrigerator | 20 kW |
| Electrical power of the refrigerator | 1.32 MW |
| Inventory in one-war 10 km tube | 78.5 m$^3$ |