Prospect of Liquid Hydrogen Cooled Superconducting Power Apparatus and Carbon Dioxide Emission Reduction

Yasuyuki Shirai*, Masahiro Shiotsu*, Hideki Tatsumoto**, Hiroaki Kobayashi***, Yoshihiro Naruo*** and Yoshifumi Inatani***

*Graduate School of Energy Science, Kyoto University, Kyoto 606-8501, Japan
** J-PARC center, Japan Atomic Energy Agency, Tokai, Ibaraki, Japan
*** Institute of Space and Astronautical Science, JAXA, Kanagawa, Japan
Contents

• Background (Prospects)
• Innovative Energy Infrastructure with low CO2 emission
  – Hydrogen & Electricity Hybrid energy system with
  – Hydrogen cooled superconducting power apparatus as key components
• Project Status
  – Experimental Set-up for liquid hydrogen cooling property and for electro-magnetic property of LH2 cooled superconductor
  – Some Experimental Results in Heat Transfer characteristics of LH2, Critical current test of MgB2 wire immersed in LH2 under external magnetic field
• Conclusion
• HTS (YBCO and BSCCO) superconducting wires: generally cooled by LN2(77K) or Conduction cooling.

However, it is considered that
• Excellent electro-magnetic properties are achieved with temperature of 15–40 K
• New superconductor MgB2 (Tc=39K) has been developed for actual wire

→
• LH2: 20 K is expected as a coolant for a HTS superconducting magnet because of its excellent cooling properties, such as large latent heat, low viscosity coefficient etc.

On the other hand,
• Hydrogen technology is one of the important solutions for CO2 reduction innovative energy infrastructure.
Innovative energy infrastructure for reduction of CO2 emission →
hybrid system (electric power system + hydrogen energy supply chain)

Liquid Hydrogen →
coolant of the superconducting power devices
energy storage for long period in power system

Synergy effect of hybrid energy system with electricity and hydrogen is expected using hydrogen cooled superconducting power apparatus as key components.
LH2 as a coolant

<table>
<thead>
<tr>
<th></th>
<th>LH2</th>
<th>LHe</th>
<th>LN2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiling Point (K)</td>
<td>20.3</td>
<td>4.22</td>
<td>77.3</td>
</tr>
<tr>
<td>density (kg/m^3)</td>
<td>70.8</td>
<td>125</td>
<td>808.6</td>
</tr>
<tr>
<td>latent heat (kJ/kg)</td>
<td>443</td>
<td>20.4</td>
<td>198.6</td>
</tr>
<tr>
<td>viscosity (uPa s)</td>
<td>12.5</td>
<td>3.2</td>
<td>142.9</td>
</tr>
<tr>
<td>critical pressure (MPa)</td>
<td>1.314</td>
<td>0.227</td>
<td>3.4</td>
</tr>
<tr>
<td>critical temperature (K)</td>
<td>32.97</td>
<td>5.19</td>
<td>126.19</td>
</tr>
</tbody>
</table>

Large latent heat and small viscosity

→ storage, transportation, coolant

Temperature → good property of (BSCCO,YBCO)
MgB2(39K)
Jc-B characteristics of superconductors

Critical current density $J_c$ (A/mm$^2$) vs. Magnetic flux density $B$ (T)

- YBCO (4.2K)
- YBCO (20K)
- NbTi (4.2K)
- Nb3Sn (4.2K)
- Bi2223 (4.2K)
- Bi2223 (20K)
- MgB2 (4.2K)
- Bi2223 (77.3K)
- YBCO (77.3K)
- Nb3Al (RHQT) (4.2K)
**Target:** hydrogen & electricity hybrid Carbon-free energy system with LH2 cooled superconducting devices

- H₂ Gas turbine driven: 20% CO₂ reduction
- LH₂ cooled superconducting generator (SCG): improve efficiency 2% CO₂ reduction
- (SCG+SMES+Fuel Cell+H₂-storage): improve power system stability, promote renewable energy introduction 5% CO₂ reduction
- Promote H₂ infrastructure: H₂ distribution

Hydrogen can be used as not only coolant of the superconducting power devices but also energy storage in electric power system.
Research Subjects

What is necessary to realize such an innovative energy infrastructure?

1. Heat transfer properties of LH2
2. Electro-magnetic properties of LH2 cooled superconductors
3. Design of LH2 cooled superconducting device
4. Development of LH2 cooling system, forced flow system and key components (LH2 pump, etc.)
5. Safety- design criteria of LH2 applied facilities
For these purposes, we have designed and fabricated an experimental setup for investigating heat transfer characteristics of LH$_2$ in a pool and also in forced flow for wide range of sub-cooling and forced flow velocity for evaluation of electro-magnetic properties of superconductors cooled by LH$_2$.

A Fundamental database of heat transfer in LH$_2$ has been preparing for pool-cooling and also for forced-flow-cooling.

Critical current under external magnetic field of MgB$_2$ wires cooled by LH2 were investigated using the experimental facility.

LH2 experiment has been safely carried out in 15 test-cools, about 400 test events/cool.
Experimental Set-up

Forced Flow Test

GH2 container

LH2 feed line

LH2 vent valve

For investigating heat transfer characteristics of LH2 in a pool and also in forced flow

Explosion-Proof Laboratory

Superconductor Test

Superconducting magnet

LHe feed line

LHe container

for evaluation of electro-magnetic properties of superconductors cooled by LH2 under external field
Thermal Hydraulic test system

Remote measurement / control

All measurement and control were carried out through optical LAN 170m away from test facility
Experimental Approach is undergoing…

• Pool cooling/ Forced Flow Cooling
  (flow velocity : 0 ~ 30 m/s)
• Saturated/ Sub-cooling (20 ~ 31 K: 0.1 ~1.1MPa)
• Supercritical (20 ~ 31 K: 1.32MPa~)
• Steady-state / transient state
  (exponential heat input)
Forced Flow cooling test samples

LH2 flow through heated SUS tube
(3~9mm diameter, 50-250mm length)

LH2 flow through FRP tube with heated PtCo thin wire
Forced Flow cooling Test Results
Heat transfer characteristics in subcooling condition

SUS-tube

\[ T_{\text{sat}} = 29.03 \text{ K} \]

- \( P = 0.7 \text{ MPa} \)
- \( \Delta T_{\text{sub}} = 5.0 \text{ K} \)

\[ q_{\text{DNB}} \]

\[ q (\text{W/m}^2) \]

\[ 10^{-1} \quad 10^0 \quad 10^1 \quad 10^2 \]

\[ 10^3 \quad 10^4 \quad 10^5 \quad 10^6 \]

\( \Delta T_L \) (K)

- Fully developed nucleate boiling
- Onset of nucleate boiling
- Dittus-Boelter equation

PtCo wire

\[ P = 700 \text{ kPa} \]

\[ \Delta T_{\text{sub}} = 6 \text{ K} \]

\[ 28.0 \text{ m/s} \]

\[ 20.9 \text{ m/s} \]

\[ 6.4 \text{ m/s} \]

\[ q \quad [\text{W/m}^2] \]

\[ 10^4 \quad 10^5 \quad 10^6 \]

\[ \Delta T_L \quad [\text{K}] \]

Excessive surface temp.

\[ \rightarrow \text{Correlation of} \]

DNB (Departure from nucleate boiling) heat flux with wide range of pressure, temperature, flow velocity

Kyoto University
International WorkShop
2016/03/09
14
LH2 cooled superconductor test system

- pressure: 2.0MPaG+0.1MPa
- capacity (LH2): 61 L
- ID=309mm/h=2218mm
- Power Lead ~500A covered by blanket with GN2(+5kPaG)

Main tank 2

Current Lead (blanket)
Transfer tube for LH2

LH2
LHe

- magnet 112 H (175A / 7T)
- Capacity (LHe): 175 L

2016/03/09 International WorkShop
Critical current test of MgB2 short wire under magnetic field

Illustrated test sample of MgB2 short wire and set-up
E-I characteristics of IMD-MgB2 short wire

\[ E \text{ [V/cm]} \]

10^{-6} \quad 10^{-5} \quad 10^{-4} \quad 10^{-3} \quad 10^{-2}

Turning point

Saturated condition

\[ T = 21 \text{[K]} \]

\[ B \text{[T]} \]

- 0
- 0.56
- 1.11
- 1.66
- 2.20
- 2.75
- 3.29
- 3.84
- 4.39
- 4.60
- 4.93
- 5.15

\[ 1.284 \times 10^{-10} \text{[Ωm]} \]
**Critical current density**

![Critical current density graph with data points for IMD wire and Li et al. in different temperature ranges (21 K, 24 K, 27 K, 29 K, 30 K).]

**n-value**

![n-value graph with data points for IMD wire and Li et al. in different temperature ranges (21 K, 20 K, 22.5 K, 25 K, 27.5 K, 30 K).]

**Open Symbol**: Conduction Cooling, Li et al., SUST, 25(2012)
LH2 Circulation Loop for Forced Flow Cooling Test

3000~63000rpm

By-Pass Valve

~43.7g/s

Heat Exchanger

Test Cryostat

Pump Unit

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)

(by-pass)
Top View of Facility

Test Cryostat

Pump Unit

Heat Ex.

Loop line & Valves
LH2 Circulation test

Critical Pressure

Revolution $\times 10^{-5}$ (rpm)

Pressure, Pump head (MPa)

Supply temperature

HX outlet temperature

Pressure

Pump head

Flow rate

Operation time (hr)

Critical Pressure

Pump starts

Pump stops

Temperature (K), Flow rate (g/s)

Flow rate
Conclusion

- The experimental setup for investigating heat transfer characteristics of LH2 in a pool and also in forced flow for wide range of sub-coolings, flow velocities and pressures up to supercritical condition, have been designed and fabricated.
- The additional test facility was designed and made for evaluation of electro-magnetic properties of super-conductors cooled by LH2 under external magnetic field.
- Fundamental data of heat transfer in LH2 are introduced which has been preparing for pool-cooling and also for forced-flow-cooling.
- Critical current test of MgB2 short sample under external magnetic field was carried out.
- LH2 circulation test loop was designed, made & successfully operated.
- LH2 experiment has been safely carried out in 15 test-cools, about 400 test events/cool.
Thank you for your kind attention!