[Invited] Recent Progress of Superconducting Induction Heater with HTS magnets in Korea

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Presenter : Ph. D. Jongho Choi, CTO

Supercoil Co., Ltd. in Korea
I. Development history of Superconducting induction heater

II. Introduction of the superconducting induction heater (SIH)

III. Design process of the HTS magnets and the 300 kW SIH

IV. Fabrication process and test results of the HTS magnets with the conduction cooling system

V. Manufacturing process and heating test results of the SIH

VI. Conclusions
Development history of Superconducting induction heater

10 kW SIH (Prototype)

300 kW SIH (Superconducting induction heater) (The first product)

MFD type 10 kW SIH

Crystal grower Superconducting Magnet

Big science (Superconducting magnets for accelerator & fusion reactor)

Defense industries (Coil and rail guns)

Incorporation of Supercoil

Power devices (Motor and generators)

Company History

Incubating in Techsteel Co., Ltd.

2012  2013  2014  2015  2016  2017
Supercoil Technologies & Business model

Superconducting magnets for Big-science

For accelerator
For research

Biz-M3

Top Technologies

Superconducting technologies (Zero resistance; No losses)

Basic technologies and principles

Superconducting Magnet

Superconducting technologies (Zero resistance; No losses)

World best Technology

Manufacturing technologies

Numerical analysis

Engineering technologies

Biz-M1

Superconducting Induction Heater

Superconducting magnet 300MZR (Monster Zero R)

Biz-M2

Crystal grower

Superconducting magnet for 18-inch 18MGB

Biz-Others

Defense Industries

Electric power industries

Future magnets industries

Owning the world best engineering technologies

Manufacture of the magnets based on the engineering technologies for applied superconducting devices
About the superconducting induction heater (SIH)
**Current Status of Superconducting Application Industries**

- **Superconductor has ‘Zero’ resistance → Energy loss is ‘Zero.’**
- **Superconducting wire has 100 times of the current density than a copper wire → Lightening devices and raising market competitiveness**

### Industrial fields?

- It is not any more future technology!!

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**Resistivity vs. Temperature Graph**

- **Normal conductor**
- **Superconductor**

- **Medical business: MRI**
- **Big sciences: Fusion reactor, High field magnet**
- **Transportation business: Large-sized magnets**
- **Power transmission, and network: cables**
Conventional Furnaces in industries

- These are available for the preheating process of the metal billets, in order to producing parts for the airplanes, automobiles, and electric power machineries.

▲ Aluminum extrusion plant

▲ Forging company with iron metals using Gas furnace and electric furnace

➢ Major products

▲ Lightening frame structures of airplanes, ships and automobiles

▲ Forging parts for automobiles
Necessities of the development on SIH

- **Superconducting Induction Heater**: It is expected as 30~70% Energy efficiency improvement than conventional furnaces.

Atmosphere furnace (Gas furnace)
- System efficiency: 20~30%
  - Electrical or Chemical energy
  - Heating elements
  - Gas ($N_2$, $CO_2$, $Ar$) in room
  - Heating energy for billets

AC induction heater
- System efficiency: 50~60%
  - Electrical energy (Grid power)
  - Magnetic energy
  - Copper coil
  - Heating energy for billets
  - 60Hz AC current

Superconducting induction heater
- System efficiency: 80~90%
  - Mechanical energy (Motor power)
  - DC current
  - No Loss!!
  - Magnetic energy
  - Superconducting coil
  - Heating energy for billets

System efficiency: 20~30% (High copper losses)

(System efficiency: 50~60% vs. System efficiency: 80~90%)

- Electrical or Chemical energy
- Heating elements
- Gas ($N_2$, $CO_2$, $Ar$) in room
- Heating energy for billets

- Electrical energy (Grid power)
- Magnetic energy
- Copper coil
- Heating energy for billets
- 60Hz AC current

- Mechanical energy (Motor power)
- DC current
- No Loss!!
- Magnetic energy
- Superconducting coil
- Heating energy for billets

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Energy transfer relations of SIH

\[ Q = M \cdot C_p \cdot \frac{dT}{dt} \]
Heat transfer energy from the aluminum billet

\[ = R_{Al} \cdot I_{ind}^2 \cdot t \]
Electrical energy in the aluminum billet

\[ = k \cdot T \cdot \omega \cdot t \]
Mechanical energy by induction motor
Advantages 1: Energy efficiency improvement!

- AC induction heater has a copper heat loss of about 40%.
- We can save the energy by using superconducting magnet to generate the magnetic field.

**Energy-saving effect**

<table>
<thead>
<tr>
<th>AC induction heating types</th>
<th>HTS DC induction heating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Power (kW)</td>
<td>1,588</td>
</tr>
<tr>
<td>Overall efficiency[%]</td>
<td>51.7</td>
</tr>
<tr>
<td></td>
<td>913</td>
</tr>
<tr>
<td></td>
<td>90 (Expected)</td>
</tr>
</tbody>
</table>

- AC induction heater has a copper loss of about 40%.
- We can save the energy by using superconducting magnet to generate the magnetic field.

**High efficiency**

Superconducting coil loss: ‘0’

- Heating energy
- Copper loss: about 40%
- Heating energy
- 51.7%
Advantages 2: Heating quality improvement!

- The quality of the metal billet is depended on the penetration depth of heating power.
- The penetration depth is related to the frequency of the induced current inside of the metal billet.
- SIH makes the quality better by controlling the rotating speed.

\[ \delta = \sqrt{\frac{2 \rho}{\omega \mu}} \]

\( \rho \): Relative resistivity
\( \omega \): Angular frequency
\( \mu \): permeability

- Frequency (Aluminum billet) in SIH: 1.83 Hz, Penetration depth: 100 mm
- Frequency (Aluminum billet) in AC induction heater: 60 Hz, Penetration depth: 19 mm
Advantages 2: Product quality improvement!

- Applying new magnetic displacement control unit ➔ Control the billet temperature along the length direction ➔ Higher extrusion performance ➔ The product quality improvement

  - When it extrudes, the deviation along the longitudinal temp. is controlled by the angle of iron yoke shape to get the best product quality

- 10 kW SIH operation test for the new magnetic displacement control

- Development of the simulation model of the 300 kW SIH operation for the new magnetic displacement control
These pictures show the change of the factory environments through the comparison between the before and after the installation of the superconducting induction heater.

- Lower sized transformer
- Lower room temperature of the factory
- Full automation available
- Simple structure and layout
- Lower Installation space
- Lower operation cost
About the design process of the SIH
We are convinced about the commercialization possibility through this results.

**You tube link:** Operation of a 10 kW HTS DC induction heating machine

- Efficiency reached at 99%
- Target temp.: 500°C
- Start: 19 s
- Expected heating time: 338 s
- Total heat energy of Aluminum
- Total input electrical energy
- Real heating time: 400 s
- Loss: 357 s
- 419 s

**Results of the 10 kW-class superconducting induction heater developed**
We finally adapted the candidate 2, racetrack and iron cored type, because of the highest magnetic field we could get at the center of the billet.

**Target : 300kW class SIH**
- Metal billet type: Aluminum Billet
- Average temperature: 540 (°C)
- Temperature deviation: below ±5 (°C)
- Magnetic flux density at the center of the billet: 1 (T)

**Determination of the size**
- Decide radius (mm), length (mm), weight (kg)

**Determine the resistive heating and operating range for heating with FEM tool**
- Rotating speed (rpm)
- Mechanical torque (N·m)

**Determine the specification of the magnet to generate the uniform magnetic field**
- Maximum magnetic field
- Type of HTS wire
- Shape of HTS magnet
- Considering the perpendicular magnetic flux density

**Design completion of an 300 kW-class SIH**
Specifications of the HTS magnets and the 300kW SIH

We set the billet size of the diameter, 9 inch, and the length, 700mm. It requires the magnetic flux density of 0.83 T at the rotating speed of 300 rpm. Total heating time would be 193 s.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTS tape maker</td>
<td>SuNam, Korea</td>
</tr>
<tr>
<td>HTS tape (Width×Thickness)</td>
<td>W12.1 (±0.1) mm×T150 (±15) μm</td>
</tr>
<tr>
<td>Minimum Critical current (77 K)</td>
<td>≥600 A (copper laminated)</td>
</tr>
<tr>
<td>HTS magnet type</td>
<td>MI, racetrack, a double pancake, iron cored type, metal tape co-wound</td>
</tr>
<tr>
<td>Size(Radius×Length)</td>
<td>H622 mm×L1247 mm</td>
</tr>
<tr>
<td>Number of turns</td>
<td>300 turns</td>
</tr>
<tr>
<td>Total length of the HTS tape</td>
<td>3,407 m</td>
</tr>
<tr>
<td>Inductance of a DPC magnet</td>
<td>560 mH without an iron core</td>
</tr>
<tr>
<td>Estimated critical current at 30K (I_c)</td>
<td>520 A calculated by only perpendicular magnetic flux density</td>
</tr>
<tr>
<td>Operating current (I_op)</td>
<td>440 A (I_op/I_c =0.85)</td>
</tr>
<tr>
<td>B_norm at the center of the magnet</td>
<td>2.755E-3 (T/A)</td>
</tr>
<tr>
<td>Position of the magnetic field sensor</td>
<td>(x,y,z) = (0,0,0) ; (unit: mm)</td>
</tr>
<tr>
<td>B_norm at the center of the magnet</td>
<td>1.08E-3 (T/A)</td>
</tr>
</tbody>
</table>

Development of the electromagnetic FEM analysis model

- We developed the electromagnetic FEM model of 300kW-class HTS DC IF.
- We designed the HTS magnet with the magnetic flux density of 1.1 T at the center of the billet.

FEM results of a 300 kW HTS DC IF

- Design of the magnet system
  - GM-cryocooler with 2nd stages

Current direction
Magnetic flux density direction

I_{\text{op}}(4)=440  
Volume: Magnetic flux density norm (T)  
Arrow Surface  
Arrow Surface: Current density

Magnetic flux density at the iron yoke: 2.5 T
Magnetic flux density at the center of the billet: 1.1 T

Iron core
Aluminum billet
Heat invasion loads analysis

- We need to analyze heat loads of the conduction cooling system for HTS magnet operation. There are three conditions, such as conduction, convection and radiation.

- Heat invasion loads

- Conduction
  ① Metal current leads
  ② Supporters (300K → 1st stage)
  ③ Supporters (1st stage → 2nd stage)
  ④ HTS current leads

- Convection
  ① From metal billet

- Radiation
  ① Metal billet → Outer cryostat
  ② Outer cryostat → Inner radiation shield
  ③ Inner radiation shield → HTS magnets
**Lorentz forces and their directions**

We calculated Lorentz forces of the HTS magnets for mechanical structure design.

- \( F_x \) is caused by the attracting force between iron core and HTS magnet

\[ |F_x| \]

Self-weight of a DPC of HTS magnet: about 150 kg

The volume integral of Lorentz force by each component according to the operating current

<table>
<thead>
<tr>
<th>( I_{op} (A) )</th>
<th>( F_x ) (ton)</th>
<th>( F_y ) (ton)</th>
<th>( F_z ) (ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>-0.20</td>
<td>0.0030</td>
<td>0.00075</td>
</tr>
<tr>
<td>200</td>
<td>-0.82</td>
<td>0.012</td>
<td>0.0030</td>
</tr>
<tr>
<td>300</td>
<td>-1.76</td>
<td>0.027</td>
<td>0.0068</td>
</tr>
<tr>
<td>440</td>
<td>-2.40</td>
<td>0.057</td>
<td>0.015</td>
</tr>
<tr>
<td>500</td>
<td>-2.28</td>
<td>0.073</td>
<td>0.019</td>
</tr>
<tr>
<td>600</td>
<td>-1.73</td>
<td>0.106</td>
<td>0.027</td>
</tr>
</tbody>
</table>

![Graph showing Lorentz forces and Target current](image)
Results of the heat transfer and mechanical analysis

- Total heat load was expected to 45 W at the 1st stage.
- 7 W was expected for the 2nd stage and HTS magnet.
- Expected heat loads of the 2nd stage cryo-cooler

**SRDK-415D Cold Head Capacity Map (60 Hz)**

- 1st stage temp.: 55.9 K
- 2nd stage temp.: 6.99 K
- Highest temp. in the HTS magnet: 9.65 K
- Highest temp. in the radiation shield: 91.3 K

**Maximum stress: 29.5 MPa**

**Mechanical analysis model**
About the fabrication process and test results of the HTS magnets
The 300kW induction motor was selected with 12 poles at 60 Hz.

Machine size: Length 7.4m X Height 2.9m X Width 4.7m

3 Phase 380V, 12 poles, 300 kW induction motor
(Weight: 6 tons, Torque: 484 kg\(\cdot\)m, Rated speed: 592 rpm, current 682 A)

HTS magnets and their conduction cooling system

Gripping system

Aluminum billet
(Length: 700mm, Diameter: 240mm)

Supporting system for Heavy weight parts

Loading/unloading machine of Aluminum billet
Winding composition of HTS magnet

- We fabricated the large-sized two HTS magnets for induction furnace in the world.
- The HTS magnet size: length 1.25m X height 0.62 m
We performed the critical current test and measured magnetic flux density. The critical currents were measured as the magnet A: 145 A@77K, magnet B: 165 A@77K. We fabricated the conduction cooling system including cryostat and radiation shield.

- Magnetic flux density measurement
- Total cryostat weight: 3.1 ton
- Module coil weight: 83 kg/1ea
- Iron cores: 1.72 ton
- Cryostat weight: 630 kg/1ea
- Inner radiation shield weight: 31 kg/1ea

We completed the experimental set-up.
Two type tests for the current flowing into two HTS magnets

- The **first** test of the HTS magnet with conduction cooling; it has 2 current leads in each cryostat with 1 cryo-cooler. It is called as Test A.

- The **second** test of the HTS magnet with conduction cooling; it has 2 current leads in a whole cryostat with 2 cryo-coolers. It is called as Test B.
System composition of the cooling down test A

- Cryostat B
- GM 2\textsuperscript{nd} stage Cryocooler
- Compressor
- Chiller
- 2 current leads in each cryostat with 1 cryo-cooler

We composed the system components for cooling down test of the HTS magnets with the conduction cooling.
Cooling down test results of Cryostat B in the test A

- The total cooling time took 3 days and 2 hours.
- The temperature at the 1st stage of cryo-cooler was saturated at 74K.
- Temperatures of the 2nd stage was cooled down and saturated at 5.3 K.

- Saturated temperature of the HTS magnet and conduction cooling system
Current flowing test results of two magnets connected in series

- When the current with 0.5 A/s ramping rate was supplied into the magnets, the terminal voltages increase with inductive voltage and the temperatures of HTS magnet increased at 6 K owing to AC losses.

- When discharging with (-) 0.5 A/s, the voltage variation occurs. It means that the magnet is unstable condition at that time. The current bypasses into the other turns.
Current flowing test results of two magnets connected in series

- Maximum magnetic flux densities were measured to 0.33 T of the cryostat A and 0.325 T of the cryostat B when the current of 360 A flew into the magnets in series connection. This result is almost the same as the FEM simulation results.

- Electromagnetic FEM analysis results:
  - 0.328 (T) at 360 A

Magnetic flux density on the cryostat A
- 0.33 (T) (Cryostat A)
- 0.325 (T) (Cryostat B)

Coil voltage on the cryostat A
System composition of the cooling down for test B

- Cryostat B
- Cryostat A
- GM 2nd stage Cryocooler
- Chiller
- Compressor
- Cryogenic connection with HTS magnet A and B

- 2 current leads in a whole cryostat with 2 cryo-coolers
Cooling down test results of Cryostat A and B in the test B

- The total cooling time took 2 days and 14 hours. It was 10 hours shorter than the results of Test A.
- The temperature at the 1st stage of cryo-cooler was saturated at 42.3K.
- Temperatures of the 2nd stage was cooled down and saturated at 5.2 K.
Current flowing test results in the test B

- When the current with 0.5 A/s ramping rate was supplied into the magnets up to 540A, the magnetic field increased as the current, proportionally.
- The magnetic flux density at the center of the magnet A was measured as maximum 1.02 T. And the magnetic flux density at the center between two HTS magnets was measured as maximum 0.69 T.
- All magnet temperatures are stable during the operation.
Current flowing test results in the test B

- When the current with 0.5 A/s ramping rate was supplied into the magnets as 40 A step, the terminal voltages increased with inductive voltage and the magnetic field at the center of the magnet A was saturated every ramps.
- The total inductance 560 mH without iron cores. Charging time was about 3 minutes. The characteristic resistance was 23.6 mohms of the HTS magnet A.
About the manufacturing process and operation test results of the SIH
Spindle units assembly

- Spindle units
- Supporting system for Heavy weight parts
- 300 kW 12 poles induction motor
Mounting HTS magnets on the base frame
The first superconducting induction heater was manufactured in Korea.
Current flowing test results in HTS magnets with iron cores

- When the current with 0.3 A/s ramping rate was supplied into the magnets up to 440A, the magnetic field increased as the magnetization characteristics of the iron yokes.
- The magnetic flux density at the center between two HTS magnets was measured as 0.75 T at the input current 140 A. And the maximum magnetic flux density was measured as 1.3 T.
- All magnet temperatures are stable during the operation.
Current flowing test results in HTS magnets with iron cores

- When the current with 0.3 A/s ramping rate was supplied into the magnets as 20 A step, the terminal voltages increased with inductive voltage and the magnetic field at the center between two HTS magnets was saturated every ramps. From the operating current of 200 A, the current step was reduced to 15 A. So, the terminal voltage was reduced.

- The total inductance 1.8 H with iron cores. Charging time was about 10 minutes.
The HTS magnets had a broad available range of the magnetic field to generate. As the result, we can heat up the various size billets in this heater.
Aluminum billet heating test movie is played in real-time.
Test completion for iron billet with 300 kW SIH (Aug. 19, 2017)

Iron billet heating test movie is played in real-time.
We developed the HTS magnet with the conduction cooling system for superconducting induction heater. The excitation test was successful.

We developed the rotating system for the superconducting induction heater. The performance of the spindle unit was demonstrated through the design parameters and real test results.

The first superconducting induction heater was manufactured. The aluminum and iron billet heating tests were successful.

Supercoil has a target to realize these superconducting induction heater technologies for industries.
Thank you for your attention.
Magnetic flux path consideration

- 20% magnetic field improvement

Operating current: 440 A, Multi-slice: Magnetic flux density (T), Streamline; Magnetic flux density

<table>
<thead>
<tr>
<th>Item</th>
<th>$B_{\text{edge}}$</th>
<th>$B_{\text{center}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Non-ferrous magnetic supporting frame</td>
<td>0.83 (T)</td>
<td>1.1 (T)</td>
</tr>
<tr>
<td>2 Ferrous magnetic supporting frame</td>
<td>0.99 (T)</td>
<td>1.33 (T)</td>
</tr>
</tbody>
</table>