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Design of the Conduction-cooled YBCO Magnet for a MW Class Induction Heating System

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ABSTRACT

Abstract—High efficiency HTS induction heating equipment has been regarded as a promising application for thermal processing of metal material, in which HTS magnet generates high magnetic field to form the background field in the iron core and the rotating billet is heated by eddy current to process temperature. Efficiency analysis and multiple structures are studied in this paper. Calculation models for induction heating system electromagnetic field and billet region temperature field analysis are established. The MW class conduction-cooled YBCO magnet system is designed. The magnet consists of an iron core and HTS coils wound with the spliced YBCO-coated conductors. The magnet system is cooled by two AL325 GM refrigerators with the pluggable structure and the operating temperature is 20~30 K. Furthermore, the prototype YBCO coils with the same thickness are fabricated and tested to evaluate the performance of conduction-cooled YBCO magnet. In this paper, test of the prototype magnet are presented.

INTRODUCTION

HTS induction heater has the potential of being the most effective way to realize the high efficiency and large capacity heating treatment for the non-ferromagnetic metal material because the non-resistance superconductor is used to be the main magnet conductor. Compared with the conventional induction heater that have the same power capacity, HTS induction heater can be higher efficiency with nearly no loss produced in the main magnet and the efficiency can be increased to reach 80~90% from less than 50%. In addition, HTS induction heater has better heating uniformity and repeatability. In the future, large-capacity high-efficiency HTS induction heater will play an important role in the field of non-ferromagnetic metal material through heating treatment.

INDUCTION HEATING TOPOLOGY AND EFFICIENCY

The heating efficiency could be:

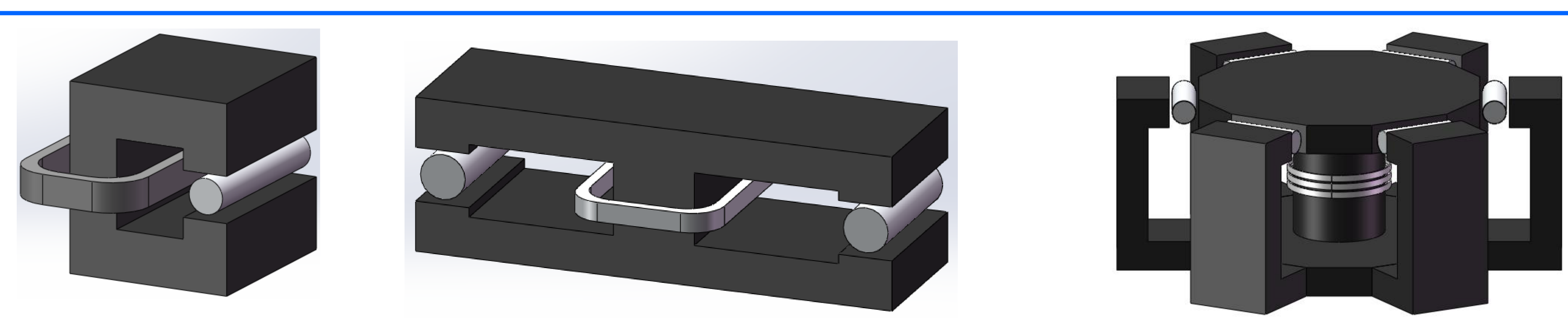
$$\eta = \frac{1}{1 + \frac{1}{n}\frac{l_w}{l_c}\sqrt{\frac{\rho_c \mu_c \omega_c}{\rho_w \mu_w \omega_w}}\left(\frac{r_c+\delta_c}{r_w-\delta_w}\right)}$$

the influencing factors on improving the efficiency could be concluded as the following:

1. More turn number of solenoid coil can improve the efficiency.
2. The length of the billet is shorter than that of the coil.
3. The resistivity, permeability, frequency of the coil decrease, the efficiency can be increased.
4. The greater resistivity, greater permeability, greater frequency of the billet can induce the greater efficiency.
5. The smaller the gap between the billet and the coil, the higher the efficiency.

Therefore, for the low resistivity and non-ferromagnetic billet, such as copper, aluminum, reducing the coil resistance can increase the heating efficiency.

The innovative induction heating adopt the DC background magnetic field and the rotating billet topology. The rotation of the billet cutting magnetic field lines and the change of magnetic flux generate the eddy current which heating the billet to the process temperature. The background is generated by the HTS DC superconducting magnet and the magnetic conducting core. Meanwhile the rotation of the billet is driven by the motor. Thus, when the output power is higher enough compare with the cryogenic loss and the other stray losses, this induction heating topology could greatly increase the heating efficiency for the low resistivity and non-ferromagnetic billet. The topology of main magnet with iron core can be one magnet correspond to one background and one billet, which can referred to in this paper as one drag one. For the superconducting magnet with high power density can output the high magnetic field, this topology can be extended to one drag two, three or multi-split according to the background magnetic field and the magnetic field saturation vale of iron core.



ELECTROTHERMAL MODELING AND ANALYSIS FOR THE MAGNET SYSTEM

Equations for electromagnetic field

In the eddy current area V1:

$$\nabla \times (1/\mu \nabla \times \dot{A}) - \nabla \cdot (1/\mu \nabla \cdot \dot{A}) + \sigma \partial \dot{A}/\partial t + \sigma \nabla \dot{\varphi} = 0$$

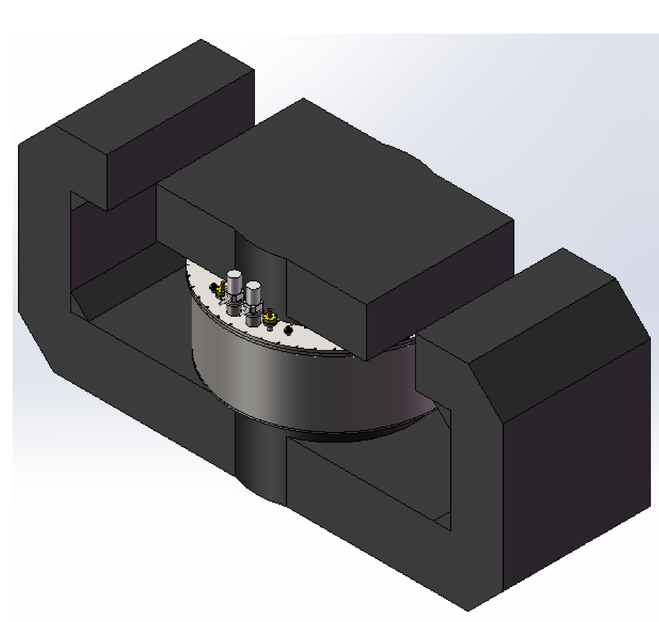
$$\nabla \cdot (-\sigma \partial \dot{A}/\partial t - \sigma \nabla \dot{\varphi}) = 0$$

In the non-eddy current area V2:

$$\nabla \times (1/\mu \nabla \times \dot{A}) - \nabla \cdot (1/\mu \nabla \cdot \dot{A}) = \dot{J}_s$$

Equation for temperature field

$$\frac{J_e^2}{\sigma} = \frac{\partial}{\partial t}(\rho c(T)T) - \nabla \cdot (\lambda(T)\nabla T)$$



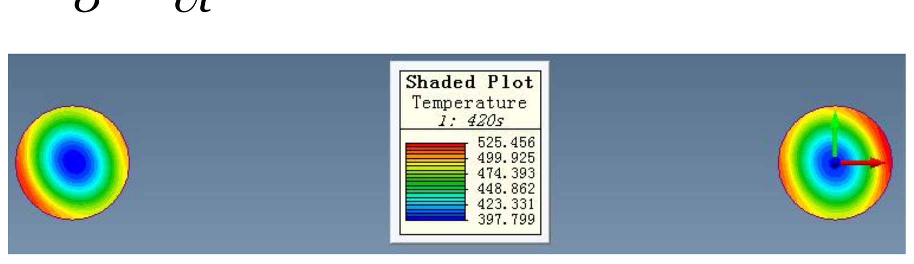


TABLE I. Induction Heating Description

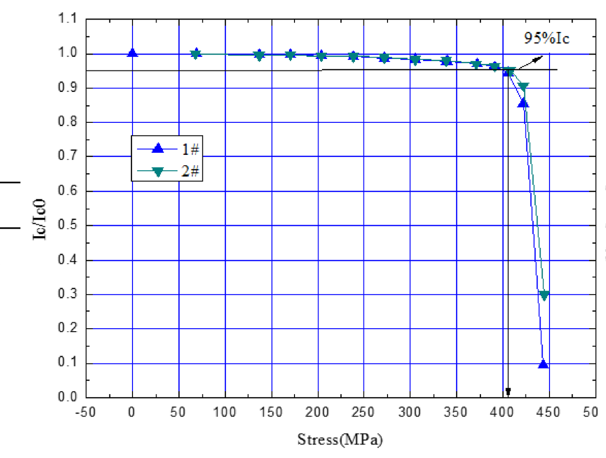
Parameters	Value
Output power	~1 MW
Output frequency	4～12 Hz
Billet	Φ446×1.5m
Heating beat	<10 min

DESIGN OF YBCO MAGNET

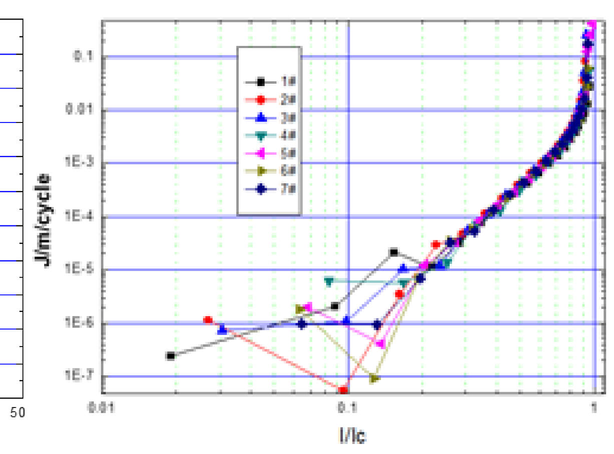
HTS Wire

TABLE II. Specification of YBCO Wires

Parameters	Value
Average thickness	4.75 mm
Average width	0.35 mm
Critical double bending diameter	≤30 mm
Min. average critical current@77K	200 A
N value@77K	40



Stress of the YBCO wires



AC losses of the YBCO wires

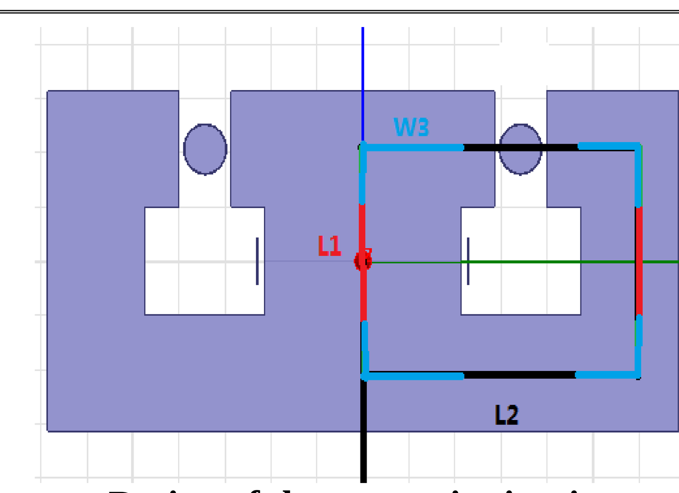
YBCO Magnet

Parameters of the YBCO magnet is shown in Table III. The essentials of optimum design can be generalized as follows:

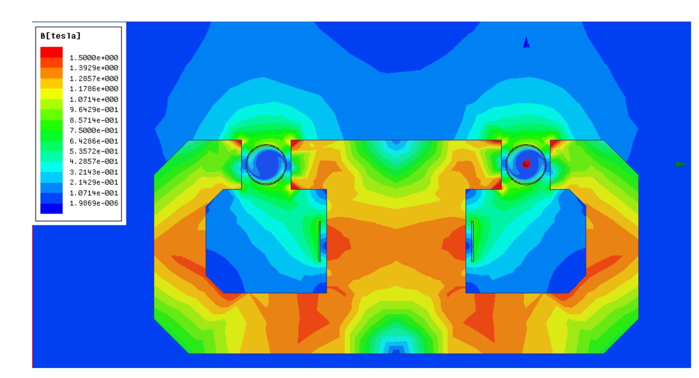
1. To determine the MMFs according to the design of magnetic circuit and mechanical properties of YBCO wires.
2. To determine the rated current and the number of turns according to the equivalent MMFs.
3. To determine the magnetic field distribution of the magnet according to the output power. The magnetic field acting on magnet should be minimized to reduce Ic degradation.
4. By iterative calculation from step 1 to 3 to gain the optimum operating current, the number of turns.
5. Both Ic and n values should be used as criterion of the selected HTS wires to ensure good performance of magnet.
6. The current distribution among conductor layers should be as uniform as to gain most efficient use of YBCO wires.
7. The strains experienced by YBCO wires due to thermal contraction and bending must be limited in order to minimize the Ic degradation of magnet.
8. The electrical and thermal conductivity varies with temperature, so the thermoelectric coupling and calculations should be a closed-loop calculation.

TABLE III. Induction Heating YBCO Magnet Description

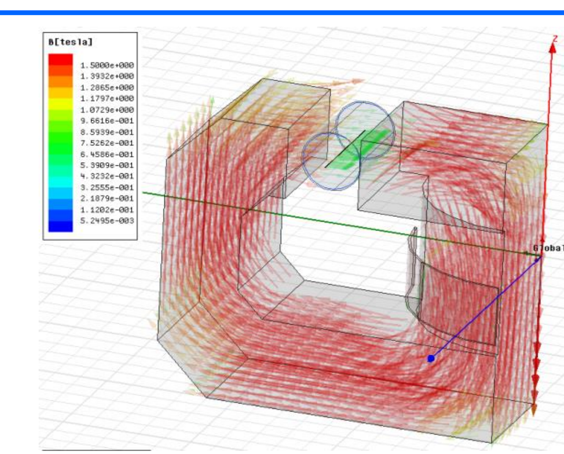
Parameters	Value
Inner Diameter	1960 mm
Outer Diameter	2009 mm
High	468 mm
Rated Current	130 A
Magnetic field in the middle of the billet	0.75 T



Design of the magnetic circuit



Optimization design of 2D solution region



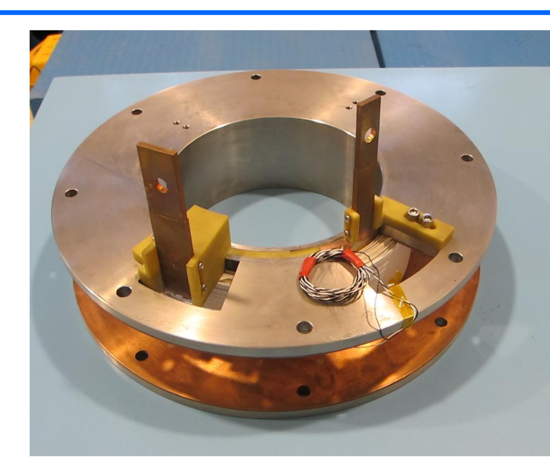
Optimization design of the iron core thickness

TABLE IV. Specification of YBCO Wires

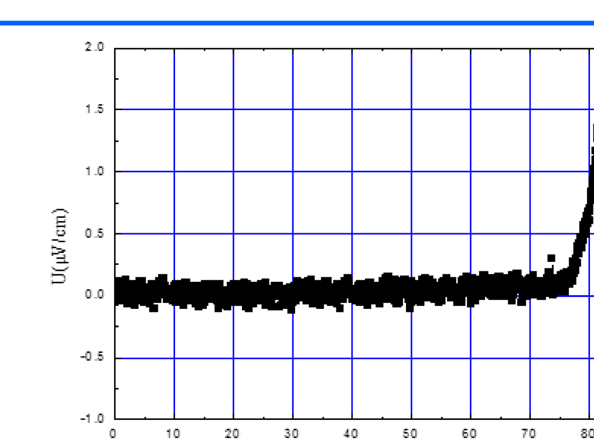
Parameters	1.6m	1.7m	1.8m
Magnetic field in the middle of the billet（mT）[1]	750.3	750.5	750.5
Magnetic field of the billet end face（mT）[2]	693.3	728.1	741.6
Difference between 1 and 2	7.6%	3.0%	1.2%
Magnetic field of the iron core end face（mT）[3]	660.6	687.4	736.6
Difference between 1 and 3	12.0%	8.4%	1.9%

FABRICATION AND TEST FOR THE PROTOTYPE MAGNET

The prototype YBCO magnets are fabrication to test the design, stability of conduction-cooled magnet. The I-V curve at 77K are got as shown in the following figure and the critical current is 81 A.



Fabrication of the prototype YBCO magnets.



The I-V curve of the prototype YBCO magnet

CONCLUSIONS

In this paper, the following conclusions are presented.

1. A design scheme of a MW class conduction-cooled YBCO magnet system for the induction heating application has been presented.
2. The stress and the AC losses of the YBCO wires are measured. No performance degradation occurred in the cooling cycle test.
3. The optimization design of electromagnetic design and the mechanical structure design have been presented. The output power can reach to MW class and the heat cycle is less than 7 minutes.
4. The prototype YBCO magnets are fabricated and the Ic is 81 A at the 77K.

The future work including the following:

1. The prototype YBCO magnet will be tested with cooled by the cryocooler and the stability will be assessed by the conduction-cooled experiment.
2. The components of the MW class induction heater will be developed.