Development and Test of One Commercial Megawatt Superconducting DC Induction Heater With Extra High Energy Efficiency

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ABSTRACT
Energy conservation and emission reduction is a critical task for China’s aluminum industry. During the last decade, the high temperature superconducting (HTS) technology has been successfully demonstrated to have great potential for energy conservation in this field. Different from the present AC induction heater, this HTS direct current (DC) induction heater is expected to significantly improve the energy efficiency of preheating aluminum billets before extrusion process. This paper thoroughly presents the development of the world’s first commercial megawatt HTS DC inducting heater based on 2nd generation HTS tapes. Firstly, the commercial design of this 1 MW HTS DC induction heater including design specifications, energy efficiency and commercial potential are analyzed carefully. Subsequently, the manufacture and operation of three core parts including HTS magnet with extra-large diameter, iron core structure and electrical driving system, are introduced. A low cost and practical driving system consisting of motors and gearboxes is developed to solve the problem of peak electromagnetic torque at low rotation. Meanwhile, the heating quality of aluminum billets (i.e., temperature distribution along the radial and axial direction) can be accurately controlled by an adjustable air gap structure. Finally, the present technique challenges and corresponding solutions of this commercial HTS DC induction heaters are summarized and proposed. Compared with an energy efficiency of 45 - 60% in the MW-class conventional heater, the energy efficiency of this HTS DC induction heater can achieve up to 80.6% based on test results. This work can also provide guidance for the design and optimization of HTS DC induction heaters.

INDEX TERMS
Energy conversation, induction heating, high temperature superconductor, energy efficiency.

I. INTRODUCTION
An endeavor to accomplish energy conservation and carbon emission reduction has always been a goal of China’s industrial manufacturing. As an energy- and CO2-intensive process, the aluminium industry in China is also unavoidably confronted with a challenge meeting both the new promise of greenhouse gas emissions peaks by 2030 and the expansive demand for aluminum consumption (such as aluminum profiles for automotive, transportation and industrial equipment) and export. To resolve this contradiction, it is necessary that the continuous innovation in energy-saving technology for improving energy efficiency in both aluminium electrolysis and deep processing, which are two of the most energy consumption processes in aluminium industry.

During the last decades, it has been successively demonstrated that the high temperature superconducting (HTS) technology has great potential and extensive benefits for energy conservation and emissions reduction in the aluminium industry [1]–[3] due to its nearly lossless and markedly high current carrying capacity. In 2014, Dai et al. accomplished successfully a 10 kA/362 m HTS DC cable to supply power for an aluminium electrolyzing plant (Henan Zhongfu Industrial Company, Ltd., Gongyi, China).
Compared with conventional copper cable, this HTS cable can reduce electricity consumption by 65% at the same capacity [4]. Meanwhile, most research has been aiming at improving energy efficiency in the aluminium deep processing, and a series of superconducting induction heaters (SIH) were developed and improved to preheat aluminium billets manufactured by extrusion and forging processes, and even melt aluminium pipe for diecasting process [5].

Conventional induction heaters utilize an alternating-current (AC) magnetic field to produce the induced eddy currents in the billets. For nonmagnetic metal billets (such as aluminium), the energy efficiency of the heaters is usually less than 50%, and more than half of the electric energy is dissipated on copper windings of the induction coils generating ac magnetic field [6], [7]. To improve the efficiency of the heating process, in 2002, Runde and Magnusson et al. have put forward an AC induction heater in the 1 MW class, in which nearly resistance-free BSCCO/Ag HTS windings directly replace copper windings to reduce the unwanted AC loss of the induction coils with 50-60 Hz AC [8]. However, the subsequent efficiency analysis indicated that the overall energy efficiency of this HTS AC induction heater for nonmagnetic metal billets does not exceed 60% and need to be faced with new problems because it is still unavoidable for HTS windings to suffer serious AC losses and the resulting quench of HTS coils from Joule heat. In addition, the problem of low heating depth along radical direction caused by skin effect is also unavoidable in electromagnetic induction heating process [9]–[11]. Reduce the frequency of alternating current (even as low as 3-7 Hz) to obtain large heat penetration depths may be a solution, but it is difficult to achieve under the premise of high heating efficiency.

In order to overcome the above problems, the HTS DC induction heater is developed, in which a lossless HTS DC magnet was considered to take place the AC induction coils in the AC case and provides a static magnetic field. Meanwhile, the metal billets rotate inside the magnetic field and the induced currents are caused on the surface of the billets. The resulting Joule heating can heat the billet to a desired temperature [12]–[17]. In an ideal case, the AC losses in the magnet is avoided and all the mechanical power generated from one motor is converted to the required thermal power of the billet. Therefore, the energy efficiency of a DC induction heater in the range of 1 MW is expected to be more than 90%, which is primarily determined by the high efficiency of conventional motors (more than 90% or even more than 95%) [18]. During the past decade, a series of research and engineering validation have been carried out to facilitate the commercial adoption of the DC induction heaters in Europe, Korea and China.

In Europe, the first industry-scale HTS DC induction heater with 360 kW motor power has been installed to preheat aluminium billets since 2008, and subsequently more heaters are put into practical use. For these DC induction heaters, HTS magnet coils wound with 1st generation HTS BSCCO tapes was operated at temperatures of 20 - 40 K and the central magnetic flux density of the billet was more than 0.5 T. Typically at Weseralu aluminium extrusion plant (Germany), the Ø152 mm × L690 mm aluminium billets were preheated to expected temperatures (450 - 500 °C) within 140 sec and the energy efficiency of the heating process was more than 80% [19], [20].

In Korea, a 300 kW-class HTS DC induction heater had been proposed since 2014 and commercialized by Supercoil Company Ltd. (South Korea) in 2017. The HTS magnet coils was wound with 2nd generation HTS ReBCO tapes and the magnetic flux density at the center of two HTS magnets is more than 1.0 T within 10 K. The heater showed 89.7% of the energy efficiency for aluminium billets with the maximum size of Ø240 mm × L700 mm [21], [22].

Considering MW-class HTS DC induction heaters have potentially a competitive advantage on energy saving and production cost reducing for the preheating process of nonmagnetic metal billets with large diameters, one 1 MW HTS DC induction heater, which can preheat the Ø446 mm × L1500 mm aluminium billets, was proposed and developed in China since 2012. A laboratory-scale heater prototype was built to validate the DC inducting heating method in 2014 [23]–[27]. However, a large diameter and length of billets will inevitably result in many serious challenges in the engineering and manufacturing process of the commercial prototype. Firstly, one large-diameter YBCO coil coupled with iron core is needed to produce at least 0.5 T DC magnetic flux density in the air gaps of induction heater. The large current and high-intensity magnetic field may bring a serious challenge to the electrical and mechanical properties of YBCO tapes. Meanwhile, the HTS coil need more reliable quench protection system. Secondly, large-size aluminium billets process a large weight, which might cause the torque of the mechanical driving system to exceed the rated load torque during start up. Thirdly, it will be difficult to control the uniform temperature distribution along the radiation and radial direction with the increasing radius and length of aluminium billets [28]–[32].

Here, it is reported that an industry-scale megawatt HTS DC induction heater is successfully commercialized to preheat the Ø446 mm × L1500 mm aluminium billets by the Jiangxi LIAN photoelectric Polytron Technologies Inc (China) by the end of 2019. To our knowledge, this is the world’s first MW-class HTS DC induction heaters with maximum capacity, maximum heating space and largest magnet system. However, it need overcome a series of new challenges inevitably. Firstly, a large inner diameter (about 2 meter) and coil turns (more than 2000) leads to a great challenge for the winding and vacuum pressure impregnation (VPI) of HTS coils, in which the inner stress produced by quick winding and VPI maybe aggravate the superconducting properties of YBCO tapes. At the same time, it is very difficult for ReBCO pancake coil with extra-large diameter to be cooled effectively. In addition, the total inductance of this HTS magnet with the iron core reaches almost 200 H and the magnet stores huge magnetic energy, which will be a great challenge for
The quench protection of HTS coils. Secondly, as one critical part of the induction heater, the mechanical driving system meets a critical challenge to drive one Ø446 mm × L1500 mm aluminium billet, in which it need overcome the peak load torque during the start-up process. Meanwhile, good economy is also a crucial issue for the design of mechanical driving system. Thirdly, considering the heat generation of the friction and deformation, certain temperature gradient along axial direction of aluminium billet is needed during the extrusion process to obtain uniform temperature distribution after the extrusion process. Obtaining an adjustable air gap is a new challenge. All above challenges need to be overcome to meet the need of commercial applications.

In this paper, the first commercial megawatt HTS DC induction heater will be presented thoroughly based on three main parts: HTS magnet, iron core structure and driving system. Furthermore, the heating quality of aluminium billets (i.e., temperature distribution along radial and axial direction) is confirmed to be accurately adjustable by some case studies. Finally, the present technique challenges and corresponding solutions of commercial HTS DC induction heaters are summarized and proposed. Presently, this MW-class superconducting DC induction heater can efficiently preheat aluminium billets with large size (Ø446 mm × L1500 mm) and adjust flexibly the temperature distribution along the axial direction of aluminium billets. Compared with an energy efficiency of 45–60% in the MW-class conventional heater, the energy efficiency of this HTS DC induction heater can achieve up to 80.6%.

II. COMMERCIAL DESIGN OF THE 1 MW HTS DC INDUCTION HEATER

A. OVERVIEW OF THE 1 MW HTS DC INDUCTION HEATER AND DESIGN SPECIFICATIONS

This 1 MW HTS DC induction heater is designed to preheat aluminium billets with a diameter of 446 mm and a length of 800 - 1500 mm from ambient temperature to 500 °C within 12 minutes before extrusion processing. Some core parts (such as HTS coils and iron core) of this heater are shown in Fig.1 except for some additional devices, such as a DC power supply and cooling system.

As shown in Table 1, this HTS DC induction heater was designed for MW-class heating power capacity. As well known, the power dissipations of the whole heating system mainly include the cooling power of HTS magnet, power dissipation of motors, and heat flux to air of the billet during the heating process. Considering that the efficiency of motors is generally more than 95% and the heat flux to air of billet can be minimized to a very small value by covering thermal insulation materials, the overall efficiency of this heater system mainly depends on the cooling power of the HTS magnet. Therefore, the overall energy efficiency of this system is expected to be more than 85%.

The excitation current of 130 A to the magnets coupled with iron core can generate a magnetic flux density larger than 0.45 T at the center of the air gaps. The HTS coils are wound with double pancake (DP) and have a large inner diameter (1.942 m), which leads to a great challenge for the coil winding. In addition, the iron core makes the total inductance of HTS magnet increase by 5 times and reach about 190 H. It is a great challenge for the quench protection of HTS coils because huge magnetic energy is stored in the magnet.

The induction motor with controllable rotating speed range from 240 to 720 rpm was used to drive the aluminium billets to rotate. Based on the above design, the surface temperature of aluminium billet can be heated from 20 to 500 °C within 12 minutes.

The whole heating system was manufactured and assembled as shown in Fig.2, and there are mainly three parts: HTS magnet with iron core (generating DC magnetic field), driving motors (rotating billets) and mechanical grippers (gripping billets), and its total size is as follows: length 14.0 m, height 2.5 m, and width 6.5 m. Due to the huge volume, most parts of the magnet are placed below floor and only the air gap part is placed up floor. Two independent motor systems are designed to rotate two aluminium products synchronously, and the rated mechanical output power of each system is about 0.5 MW. The weight of single aluminium billet reaches 650 kg so that each driving system is equipped with a main motor (560 kW) and an auxiliary motor (185 kW), and simultaneously assisted by main gear, auxiliary gear and grippers. During the start-up operation of the billets, the auxiliary motor provides extra torque for the main motor using an auxiliary gearbox with a high ratio (10:1) [31]. In the following section 4, the detailed description of driving system will be presented in detail. The grippers are used to fix and rotate aluminium billets. During operation, a large axial jacking force from grippers need to overcome the peak torque of the electromagnetic force on aluminium billets so that the maximum torque of the magnetic field and cylinder thrust is designed as 25000 N·m and 100000 - 188000 N respectively.

B. ENERGY EFFICIENCY

Compared with the conventional AC induction, the commercial potential of the HTS DC induction heater is determined by its significant improvement in energy efficiency. The efficiency ($\eta$) of HTS DC induction heater can be expressed as follows:

$$\eta = \frac{\eta_{motor}P_{motor} - P_{flux}}{P_{motor} + P_{cooling}}$$

(1)
where $P_{\text{motor}}$ is the input power of the motors and $\eta_{\text{motor}}$ is the efficiency of the motors, which is about 94.3\% for this heater. $P_{\text{flux}}$ is the heat loss of the billets through air heat flux and the gripper of stainless steel. The estimated value is less than 81 kW. $P_{\text{cooling}}$ is the power of the cooling system for the HTS coils, which is equal to the power of two refrigerators. Two CRYOMECH CP1110 with AL325 are applied to cool the magnet, and the total energy consumption is 22.4 kW. Therefore, the energy efficiency of this 1 MW heater should be 78 - 90\%.

Actually, the energy consumption of this heater during a heating operation process of aluminium billets was measured and the results is listed in Table 2. In one case, only one aluminium billet (Ø446 mm × L1500 mm) is rotated and heated. The initial central magnetic field at air gap is 0.3 T and the operated rotation speed is 350 rpm. Within a testing period of 19 minutes, the efficiency of this heater can be obtained by the following formulas:

$$\eta = \frac{Q_{\text{AL}}}{Q_{\text{motor}} + Q_{\text{cooling}}}$$

$$Q_{\text{AL}} = c_{\text{AL}} \cdot \rho_{\text{AL}} \cdot V_{\text{AL}} \cdot (T_{\text{heat_temp}} - T_{\text{ambi_temp}})$$

with: $Q_{\text{AL}}$ - electrical consumption of aluminium billet, $c_{\text{AL}}$ - specific heat capacity, $\rho_{\text{AL}}$ - mass density of the aluminium billet. As a result, the energy efficiency of this heat is 80.6\%, which is much higher than 40 - 50\% of traditional AC induction heater. In the actual testing process, the peak power output of main motor is only 318 kW, while its rated power is 560 kW. With the increase of power output, the efficiency of main motor will further lead to a considerable improvement. Especially in practical operations, two billets will be heated synchronously, and the overall efficiency will be improved again. In addition, there is no thermal insulation on the billets in the testing process, which can lead to a considerable convection heat transfer on the surface of the billet. If suitable low-temperature and medium-temperature insulation materials are installed around the heating zone to reduce heat loss, the overall efficiency of the heater will also be improved further. Above technology improvements will gradually be adopted in the future upgrade products.

### C. COMMERCIAL POTENTIAL

The cost of HTS DC induction heater is much higher than that of traditional AC induction heater. Table 3 shows the estimated cost of main parts in this HTS DC induction heater when it is produced commercially by an industry scale. The cost of a 1 MW traditional AC induction heater is about 2.27 million US $, while that of the traditional AC induction heater with the same heating power is only 0.53 million US $. Therefore, the economic advantage of HTS DC induction heater relies on whether the extra cost can be paid back in electricity conservation.

The economic parameters of this 1 MW HTS DC induction heater and traditional AC counterpart with same heating power were compared in Table 4. As well known, the heating power of one 1 MW HTS DC induction heater is the equivalent of the heating power of two 1 MW AC induction heaters. The rated power of AC induction heater multiplied by 2 is...
because the HTS DC induction heater can simultaneously heat two aluminium billets. Compared with AC induction heater, the 1 MW HTS DC induction heater can save 190 kWh electricity for heating per ton aluminium billets. Given that the average price of industrial electricity was 0.1 US $ per kWh in China, this HTS DC induction heater can save 0.65 million US $ per year. Therefore, the additional manufacture cost of the machine can be covered by energy saving within 2.68 year, which is called payback period (PBP) in this study. If the machine could work well for 20 years, it will generate profit of US $ 11.26 M in comparison to the AC induction heater, which is called total extra profit in this study. Considering the electrovalency difference of various countries, their dependence on the electricity price is illustrated in Fig.3. With the electricity price increasing, the payback period drops sharply and total extra profit increases linearly. Since the electricity price is higher than 0.05 US $/kWh in most countries, the additional cost of HTS DC induction heater can be covered within 5 years generally. Much better economic benefit is possible achieved in practical applications based on some changing trend, of which the electricity price increasing during the past three decades and the price of HTS tapes falling in the last decade continually. In view of this, it is predictable for this 1 MW HTS DC induction heater to have a great commercial potential.

III. HTS MAGNET FOR THE HEATER

A. HTS MAGNET DESIGN SPECIFICATION

As shown in Fig.1, the HTS magnet is designed to generate a 0.5 T magnetic field at the centre of the iron core, and its specifications is shown in Table 5. This magnet system consists of three HTS solenoid coils, iron core, vacuum Dewar and two cryocoolers, as shown in Fig.4. The HTS coils are wound by ReBCO tapes and have a special large inner diameter (2200 mm) (in Fig.4(a)). The desired operational temperature is 25 K, and a conduction cooling is applied on the HTS coils by using two cryocoolers (in Fig.4(b)).

A ring-shaped vacuum Dewar is designed for the HTS coils (in Fig.4(c)), which works as a thermal insulation between HTS coils and iron core. The iron core works at ambient temperature. The critical current of the HTS magnet is larger than 170 A at 30 K, and the operational transport current is 130 A. The total weight of the iron core is approximately 130 tons, and the embedment depth is 1.5 m (in Fig.4(d)). The iron core is composed of 7 blocks and assembled on site, which are joined by soldering. The weight of each part is less than 30 tons. The block of centre column uses a central iron core as shaft, and 0.5 mm thick silicon steel sheets are in the middle of block. The outer layer is 2 mm thick pure iron coating. Thermal sensors are put on the HTS coils to measure temperature and Hall sensors are put in the air gap to measure magnetic fields.
The achievement of this HTS magnet suffers from four key technical challenges:

1) Winding technology for ReBCO pancake coil with extra-large diameters. ReBCO pancake coil in this magnet has the largest diameter so far, which has an extremely high demand on the mechanical strength of coil former and winding machine. A special copper former with enhanced mechanical strength was built, and the coil winding system has been modified to meet the technical requirements of solenoid ReBCO coil with a diameter of 2200 mm.

2) Low-resistance joint technology. The longest length of single ReBCO tape is reported to be 800 - 1000 m so far, and single tape with the length of about 100 - 300 m is economically practical for industry applications. For this HTS magnet, each coil needs to use 5.9 km ReBCO tapes and 200 - 500 m single tape was used to wind the coil. Therefore, each coil has about 300 superconductor-superconductor joints and low resistance joint technique become a critical issue for this industry-scale HTS magnet. In this case, an extra low resistance joint technique was developed by using bridge soldering method to obtain one joint resistance with an order of 10 nΩ [33]. This joint technique has also been applied on other HTS magnets to reduce their total joint resistance.

3) Impregnation of ReBCO pancake coils with extra-large diameter. Superconducting coils need to be impregnated to enhance their mechanical strength, and especially the extra-large diameter leads to higher demand on the coil's strength. Usually the epoxy resin is used for the impregnation of traditional coils. The interfacial deboning between epoxy resin and ReBCO tapes and even damage of ReBCO tapes always happen from time to time. To solve this problem, paraffin matrix composite material is used for the impregnation of ReBCO coils in this magnet. A series of cooling tests have been performed on this impregnation method, and the results show that no interfacial deboning and damage occurs on the ReBCO tapes.

4) Effective cooling system for ReBCO pancake coil with extra-large diameter. There are many cooling modes, such as direct cooling of refrigerator, heat transfer of auxiliary heat pipe, immersion cooling of cryogenic medium etc. The direct cooling method of the chiller is the mainstream direction of the development of the superconducting magnet cooling technology. However, there is no precedent for one large scale

### TABLE 4. Economic performance of the 1 MW HTS DC induction heater and its traditional counterpart.

| Parameter                          | Traditional AC induction heater | Superconducting induction heater |
|------------------------------------|--------------------------------|----------------------------------|
| Heating solenoid                   | 30/60 Hz AC                    | DC                               |
| Rated power                        | 1.25 MW*2                      | 1.12 MW                          |
| Efficiency                         | 45%                            | 80%                              |
| Cost of heater (US $)              | 0.53 M                         | 2.27 M                           |
| Heat temperature                   | 450 °C                         | 450 °C                           |
| Heating quality (temperature       | ±15 °C                         | ±2 °C                            |
| (temperature difference along radial direction) | | |
| Productivity                       | 3400 ton/month                 | 3400 ton/month                   |
| Electricity consumption per ton    | 400 kWh                        | 210 kWh                          |
| Electricity cost per ton (0.1 US $/kWh) | 40 US $                      | 21 US $                          |
| Total electricity cost per year    | 1.63 M                         | 0.857 M                          |
| Reduction on electricity cost (US $)| –                             | 0.65 M/year                      |

### TABLE 5. Design specifications of the HTS magnet for 1 MW DC induction heater.

| Main parts                          | Parameters                          | Quantity |
|-------------------------------------|-------------------------------------|----------|
| Heating method                      | Width/Thickness of ReBCO tape       | 4.80/4.43 mm |
|                                     | Inner diameter                      | 1900 mm  |
|                                     | Heating method                      |          |
|                                     | Number of turns in series           | 3208     |
|                                     | Inner/outer diameter                | 1942/2200 mm |
|                                     | Height                              | 622 mm   |
|                                     | Maximum operation current           | 130 A    |
|                                     | Total length of tape                | 18024 m  |
| HTS magnet                          |                                     |          |
| Cooling system                      | Rated temperature                   | 25 K     |
|                                     | Refrigeration capacity              | 200 W    |
|                                     | Refrigerator                        | AL225    |
|                                     | Refrigerator quantity               | 2        |
| Cryogenic vessel                    | Cryogenic vessel Inner diameter     | 1776 mm  |
|                                     | Outer diameter                      | 2420 mm  |
|                                     | Height                              | 1220 mm  |
conduction-cooled HTS magnet with an inner diameter of 1900 mm. In this project, aluminium nitride particle is filled into the impregnation material to significantly improve the thermal stability of the HTS coils so that the generated heat in the coil can be dissipated quickly.

**B. CHARGING AND DISCHARGING OPERATION OF THE HTS MAGNET**

The HTS magnet is ramped by a DC power supply, and its circuit for the charging operation is shown in Fig.5. \( L_{eq} \) is the inductance value of HTS magnet; \( R_p \) is the equivalent circuit wire resistor; \( R_s \) is a shunt resistor used to detect the instantaneous current in the coil; the Schottky Barrier Diode D1 works as fly-wheel diode; the diode D2 operates as a coil charging reactive voltage buffer; \( R_{joint} \) is the total joint resistance of the HTS magnet; \( R_d \) is a parallel dump resistor that was used to dissipate the stored energy in the magnet during a fail ramping operation. The ramp rate of HTS coils has two limitations: voltage of power supply and ramping loss in coils. The ramp operation of HTS coils generates magnetization loss on the superconducting layers, which is called ramping loss [34], [35]. The ramping loss can lead to heat accumulation as well as temperature rise on the HTS coils, which is main reason of most ramp failures. To avoid the quench risk induced by ramping loss, the ramping process of HTS coils has to be monitored carefully, and a balance point has to be obtained between ramping rate and ramping time. DC power supplies for superconducting magnet always has a feature of high current and low voltage because of the zero-resistance feature of superconductor. This HTS magnet with iron core has a high demand on the voltage of power supply due to its large inductance (190 H). The highest power of the power supply for this HTS magnet is 6 kW (±10 V, ±600 A).

We monitor the voltage of the magnet and adjust the ramping rate accordingly during the ramping operation. As shown in Fig.6, the charge process has two phases: Phase 1, from 0 to 100 A; Phase 2: from 100 to 130 A. The magnet voltage increases fast during the ramping process, and a significant temperature rise is detected at the same time. Therefore, the ramp operation is stopped when the magnet is ramped to 100 A. Then, the magnet voltage drops fast to the ground, and new ramp is started when the magnet voltage drops to 100 mV. Due to the voltage limitation of power supply, the ramping rate is 0.06 A/s during the first ramp operation from 0 to 100 A. The ramping rate can increase to 0.1 A/s during the second ramp operation from 100 to 130 A since the inductance of the magnet drops with the increase of operating current.

Since the HTS magnet is coupled with iron core, the inductance of the magnet depends on the current. Fig.7(a) shows the dependence of the magnetic field at the centre of air gap on the operating current. The results from simulation and experiments match well, and the discrepancy at 60 A is 3.3% (0.01 T). While the operating current is lower than approximate 60 A, the central magnetic field of air gap increases linearly 0.0048 T/A with operation current. When the operation current is higher than 60 A, the iron core starts to be saturated, and the magnet’s inductance starts to drop. The knee-point ranges from 130 to 150 A, which should be the economic point of this magnet. Fig.7(b) shows the distribution of the magnetic field on the iron core with a operating current of 130 A. At this point, most zones of the iron are saturated and the magnetic field at the centre of air gap is 0.47 T.

**IV. ELECTRICAL DRIVING SYSTEM**

**A. ELECTROMAGNETIC TORQUE AND HEATING POWER OF ALUMINIUM BILLETS**

One aluminium billet with the size of Ø446 mm×L1500 mm is driven to rotate by motors in transverse magnetic fields of 0.3 T. The dependence of electromagnetic torque and heating power of the billets on the rotation speed are shown in Fig.8. The results show that the induction heating power increases continually with the rotation speed increasing, and the heating power at a rotation rate of 350 rpm is 309 kW. However, the variation of electromagnetic torque shows a very different trend. It increases rapidly with the increase of rotation speed in a low-speed range of 0 - 29 rpm, and then drops sharply to a relatively small value. After that, there is no considerable increase to occur on the electromagnetic torque with the rotation speed increasing from 100 to 350 rpm. In this case, a peak electromagnetic torque of 18441 N·m occurs in the low-speed of 29 rpm. While the electromagnetic torque at a rotation rate of 350 rpm is only 6331 N·m, which is only one third of the peak value. However, for most of motors, both the torque and power increase with the rated rotation speed.
This unique load characteristic leads to great challenges for the economic selection of motors in this DC induction heater [31]. If the motor was selected according to the power and torque at rated rotation speed (high speed), the billets will suffer from the lack of torque during start-up stage (low speed). If the motor was selected based on the peak torque (low speed), a large power capability (about two third of rated power) will be wasted at rated rotation speed (high speed), which will increase the cost of this heater considerably.

**B. SOLUTION FOR THE DRIVING SYSTEM**

As shown in Fig.9, a driving system consisting of a main motor and an auxiliary motor is developed to rotate the metal billet in order to obtain both advantages on reliability and lower cost. The key idea of this driving system is to use an auxiliary motor to provide an extra torque for the billet during low speed rotation so that the main motor can start-up successfully. The specification details of the motors and gearboxes are shown in Table 6. The main motor is selected according to the power and torque of billet at rated rotation speed. A gearbox with ratio 3.15:1 is engaged with main motor to increase the output torque as well as decrease the output rotation speed. The auxiliary motor provides extra torque at low rotation speed using an auxiliary gearbox with a high ratio (10:1), whose connection with billets is controlled by a clutch.

Fig.10 shows the control flowchart of an independent heating period. Firstly, main motor and auxiliary motor start synchronously. The auxiliary motor is engaged to aluminium billet through the clutch until the main motor is capable of driving the aluminium billet independently. After the rotation speed of aluminum billet reaches 130 rpm, the clutch is disengaged and auxiliary motor stops working, and the main motor independently drives aluminum billets to rotate in rated rotation speed. Subsequently, the temperature of aluminium billet reach the target temperature 450 °C within approximate 4 - 11 minutes of the heating period on rated rational speed. After that, main motor decelerates and drives the aluminium billet independently until its rational speed reach 130 rpm while the clutch of auxiliary motor is still disengaged. During the rotation speed of aluminium billet decreases from 130 to 0 rpm, the auxiliary motor is engaged to rotate the billets again and provide an extra torque, which may avoid a sudden change of large load on motor when the rotation speed of billets drops to the peak torque point (29 rpm for the case in Fig.8). This sudden huge torque load may lead to a certain mechanical damage on the main axle and wire windings of the motor, which should be avoided. Finally, main motor and auxiliary motor decelerated to 0 rpm synchronously, and a typical full heating cycle is finished. Fig.11 shows the measurement on output torque and power of the main motor and auxiliary motor during a heating cycle for aluminium billet Ø446 mm × L1335 mm, $B = 0.3$ T.

**C. INFLUENCE OF BILLET SIZE ON THE PEAK ELECTROMAGNETIC TORQUE**

The above studies show that the peak torque occurring at low rotation speed is a great challenge for the driving system
of HTS DC induction heater. Especially, this peak torque feature is significantly affected by billet size. As shown in Fig. 12, the electromagnetic torque of aluminium billets with different diameters from 100 to 450 mm was analyzed by both simulation and measurement simultaneously. When the transverse magnetic field is 0.5 T and all the billets have a same length of 1500 mm, the dependence of electromagnetic torque on the rotation speed were calculated to obtain the peak torque and its corresponding rotation speed \( n_{\text{peak}} \) for aluminium billets with different diameters. With the billet diameter increasing, \( n_{\text{peak}} \) drops rapidly, and the ratio of peak torque \( T_{\text{peak}} \) to stable torque \( T_{\text{stable}} \) at much higher rotation speed increases sharply (\( T_{\text{peak}} / T_{\text{stable}} \) is used to represent the peak torque effect of billet rotated in transverse magnetic fields). Therefore, the sudden change of peak torque is much more challenging for driving aluminium billets with larger diameter.

Both simulation model based on Matlab/Simulink and on-line testing system were constructed to analyze the electromagnetic torque behavior by adjusting diameter of aluminium billets (Ø200 mm, Ø300 mm and Ø446 mm). The results from simulation match well with that from experiments [31]. Obviously, the peak electromagnetic torque effect is not significant when the diameter of aluminium billet is less than 300 mm. When the diameter exceeds Ø300 mm, the \( T_{\text{peak}} / T_{\text{stable}} \) increases sharply, and it will be a great challenge for the design of driving system in DC induction heater.
V. HEATING QUALITY

A. EVALUATION AND ADJUST ON HEATING QUALITY

The HTS DC induction heater is used to preheat aluminium billets before extrusion processing. Therefore, the temperature uniformity, which has a significant influence on the product quality of extrusion processing, is the most important parameter to evaluate the heating quality of this induction heater. The temperature difference on the billets have two dimensions, one is along the radial direction from the core to the surface of the billet, and the other is along the axial direction from one end to another end of the billet.

Temperature distribution along radial direction: Due to skin effect, most of induced eddy current occurs on the surface of aluminium billets, which leads to temperature difference along radial direction. As well known, the heating depth depends on the frequency of induced current. Lower frequency leads to deeper heating depth and better temperature uniformity along the radial direction. The frequency of traditional AC induction heater is 50/60 Hz, while that of the HTS DC induction heater with the rated rotation of 240 - 750 rpm is 4 - 12 Hz. Therefore, compared with AC induction heater, this HTS DC induction heater has a much better radial temperature uniformity. In addition, for DC induction heater, lower rated rotation may also result in deeper heating depth and better temperature uniformity along the radial direction so that the production efficiency and heating quality need to be balanced appropriately.

Temperature distribution along axial direction: During the extrusion process, friction and deformation will generate heat on aluminium billet, which will result in a considerable temperature nonuniformity along axial direction of aluminium billet. As shown in Fig.13(a), if the aluminium billet has uniform axial temperature of 450°C before extrusion, the temperature at the beginning of billet will be lower than...
that at the end. Therefore, an opposite axial gradient of temperature is required before extrusion to compensate the temperature gradient generated in the extrusion process so that a uniform temperature distribution along axial direction is achieved after extrusion processing, as shown in Fig. 13(b and c). It is a simple and effective method to adjust the magnetic field intensity along axial direction of aluminium billet.

To achieve the above object generating one desirable axial temperature gradient before or after extrusion processing, an adjustable air gap structure is proposed [36]. As shown in Fig. 14(a), one side iron blocks of the air gap can be moved, and the other side is fixed. The distance profile of air gap can be adjusted by moving the position of 10 iron blocks so that the magnetic field intensity along the axial direction of billets can be adjusted in a flexible way to achieve optimal axial temperature distribution. The movable range of the adjustable iron core is designed to be 0 - 15 cm. In practical applications, a desired axial temperature gradient on billet can be achieved after many simulation and tests.

B. CASE STUDY ON AXIAL TEMPERATURE DISTRIBUTION

In our previous research, it was found that the size and rotational speed of aluminium billet directly affects the temperature distribution along axial direction. That is called the end effect of temperature distribution [26], [37]. Here, two case studies are performed to validate the above temperature adjusting method.

The first case is to achieve a uniform axial temperature distribution by adjusting the air gap profile. One aluminium billet with the size of Ø446 mm×L1335 mm was preheated from ambient temperature 25 to 450°C, and the axial temperature distribution is monitored by six type N thermocouples with Yokogawa GP10 monitors. As shown in Fig. 15, when the billet is heated in uniform axial magnetic field at the rotation rate of 400 rpm, the temperature of two ends is 65°C higher than that of middle part due to the aforementioned end effect. By moving the iron blocks in the middle part of air gap, the magnetic field in the zone can be increased to promote the temperature rise of the middle part. Finally, the axial temperature difference is significantly reduced from 65 to less than ±5°C.

The second case is to achieve an axial temperature gradient by adjusting the air gap profile. One aluminium billet with the size of Ø216 mm×L1335 mm was preheated according to the same condition of above experiments. As shown in Fig. 16, when the billet was heated in uniform axial magnetic field at the rotation rate of 400 rpm, the temperature of two ends was about 70°C less than that of middle part due to the aforementioned end effect. After adjusting the air gap profile, the axial temperature distribution was optimized and an approximate 20°C/m axial temperature gradient is achieved.

In brief, the adjustable air gap structure of this HTS DC induction heater is validated to be effective for obtaining an expected temperature distribution along the axial direction.

FIGURE 15. Case study to achieve uniform axial temperature distribution, aluminium billet Ø446 mm × L1335 mm. (a) Position of core block before and after adjusting air gap profile; (b) Measurement on the axial temperature distribution before and after adjusting air gap profile.

VI. CHALLENGES OF HTS DC INDUCTION HEATER

The HTS DC induction heater is the most promising commercial applications of high temperature superconductor. It has great advantages on energy conservation and better heating quality in comparison with conventional AC induction heater using copper windings. However, the main drawback of HTS DC induction heater is high cost, which is about three times higher than that of its AC counterpart presently.

The cost of HTS DC induction heater has three main parts: HTS magnet (45%), driving system (36%), and cooling system of HTS coils (27%). The cost of driving system (motors and gears) is difficult to be reduced in the near future since the prices of motors and gears has been stable for a long time. The cost of cooling system relies on the vacuum Dewar and cryocoolers, which also shows no great potential on price reduction. Thankfully, the cost of HTS magnet has been reducing over the past five years: Firstly, the price of HTS tapes has shown a considerable decrease in the last decade, and most of scientists and producers have expected that the price of 2G HTS tapes will continue to decline by more than 70% in the following years. Secondly, the HTS coils can be operated at lower temperature (for example 20 K) to increase the current capacity of the HTS significantly, which will reduce the usage of HTS tapes and the cost of
magnets to achieve the same magnetic intensity. Therefore, it is promising for the cost of HTS magnet to drop more than 50%, which may lead to more than 23% reduction on the total cost of HTS DC induction heater in the following five years. Thirdly, with the increase of electricity price, the HTS DC induction heater will have greater commercial potential and larger market shares.

The development and test of this 1 MW HTS DC induction heater has validated the practicability and reliability of commercial industry-scale HTS DC induction heater concept. However, the development of HTS DC induction heaters still suffers from four technical challenges. Firstly, the HTS coils with extra-large diameter are indispensable to meet the processing requirement of aluminium billet with larger size. The winding of HTS coils will need the more rigorous winding technique and more excellent performance of low temperature curable resin. These techniques need to improve continually. Secondly, the industry-scale HTS magnet coupled with iron core will store huge magnetic energy during current loading and unloading stages. HTS coils inevitably suffer from the challenges of quench detection and protection, which has not been solved well so far and needs more R&D in the future. Recently, a novel No-insulation (NI) HTS coil has been validated to enhance the thermal stability of HTS coils [38]–[40]. It will be promising to apply NI winding technique on HTS DC induction heater to solve the problem of quench protection. Thirdly, with the diameter of billets increasing, the peak electromagnetic torque of billets at low rotation speed increases significantly, which results in the complexity and high cost of the driving system. This problem becomes more serious for billets with larger diameter. Two solutions have been proposed: fly-wheel energy storage solution and auxiliary motor with gearbox solution. In this project, the latter was chosen due to its low cost and high practicability. However, its life and reliability still need further validation during continuous operations.

VII. CONCLUSION
A 1 MW HTS DC induction heater has been developed to preheat aluminium billets for extrusion, which is the first commercial megawatt HTS DC induction heater so far. Simultaneous operation and test have been performed on this machine for more than 6 months, which validates the practicability and reliability of megawatt HTS DC induction heater concept. Test results showed that the HTS DC induction heater has much higher energy efficiency (80 - 90%) than its AC counterpart (40 - 50%). Cost of the 1 MW HTS DC induction heater is about 4 times that of its AC counterpart, while the extra cost can be paid back by the electricity savings within 3 years in most countries. Therefore, the megawatt HTS DC induction heater has a great commercial potential, and is one of the most promising commercial application of 2G HTS. Four main technique progress has been achieved during this project. Firstly, 2G HTS coils with extra-large diameter is successfully wound for this heater. Secondly, the problem of peak electromagnetic torque at low rotation speed is solved, and a low-cost and practical driving system has been developed to rotate aluminium billets. Thirdly, a mechanical driving system is developed to transmit large torque and drive the billet. Fourthly, an adjustable air gap design is developed to obtain adjustable axial temperature gradient on aluminium billets, which is achieved by changing the distribution of magnetic field in the air gap. The techniques and experience obtained in this project is valuable for development of the next generation HTS DC induction heater and other HTS applications.

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