

## AL10 - Industrial Application of Double-Port Energy Saving Technology and HORRS System for Aluminum Electrolysis Cells

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### Abstract

This article introduces the basic principle of "Double-port Energy Saving" for aluminum electrolysis cells, as well as the double-port Heat of Output-Side Recovery Regulating System (HORRS) and its industrial application on 400 kA and 500 kA electrolysis cells. By comparing the changes in electrolysis cell voltage, superheat, ledge profile, and current efficiency before and after the operation of the HORRS system, the contribution of HORRS to "input port energy conservation" was analyzed. By regulating the energy flow of the electrolysis cell and effectively accumulating heat, a large amount of recovered heat energy was obtained, and the operational effect and economic benefits of HORRS were evaluated. The results of industrial experiments indicate that the HORRS system has achieved the energy saving targets of both the input and output simultaneously. Due to its significant ability to regulate the thermal characteristics of electrolysis cells, the HORRS system will undoubtedly become an important technology for achieving flexible production in the primary aluminum industry and energy storage and peak regulation of the power grid in the future. It is of great significance for the primary aluminum industry to consume renewable energy electricity and reduce CO<sub>2</sub> emissions.

**Keywords:** Aluminum electrolysis cell, Double-port energy saving, Thermal characteristics, Industrial application.

### 1. Introduction

In 2022, China achieved a significant milestone in primary aluminum production, reaching a record high of 40.21 million tonnes, representing a year-on-year increase of 4.4 percent. As a result, China has consolidated its position as the world's leading producer of primary aluminum. Since the inception of the Hall-Héroult process, molten salt electrolysis has remained the sole method for large-scale industrial production of primary aluminum. Over the course of 137 years, the field of aluminum electrolysis has made substantial advancements. However, the production of primary aluminum continues to rely heavily on substantial electricity consumption, with an average DC power consumption as high as 13 kWh/kg Al [1]. This results in approximately half of the energy utilized in aluminum production being lost as waste heat, constituting a significant energy wastage. Consequently, energy efficiency improvements in primary aluminum production have consistently been the primary focus of scientific research in this domain.

Figure 1 illustrates the heat dissipation distribution within the aluminum electrolysis cell. Heat loss in the aluminum reduction cell primarily occurs through three major pathways: heat dissipation from the upper regions, heat dissipation from the shell sides, and the remaining heat loss from the bottom and cathode collector bars. The heat in the upper portion of the electrolysis cell is discharged via the flue gas, accounting for over 50 % of the total heat loss. Although

capturing the heat carried away by the flue gas is relatively straightforward, the flue gas temperature is low (120-130 °C), resulting in a low temperature (less than 60 °C) for the medium obtained after heat transfer collection and consequently a low utilization rate. The heat dissipation from the bottom and cathode collector bars is too dispersed to be effectively recovered. On the other hand, convective heat dissipation from the side shells accounts for approximately 35 % of the total heat dissipation and occurs at higher temperatures (240-350 °C), making it the most valuable component for recovery compared to other areas of heat dissipation.

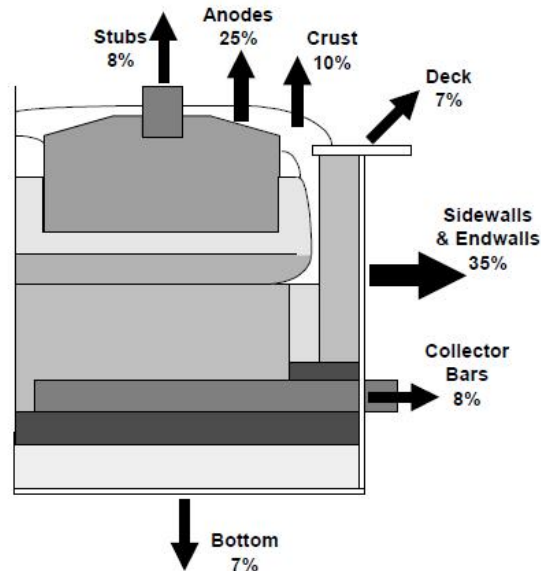


Figure 1. Typical distribution of heat dissipation in aluminum electrolysis cell [2].

The fundamental objective of aluminum electrolysis technology is to minimize energy consumption. The energy consumption required for aluminium production can be calculated using the following formula:

$$W = \frac{298V_{cell}}{\eta} \quad (1)$$

where:

- $W$  Energy consumption, kWh/kg Al
- $V_{cell}$  Average cell voltage, V
- $\eta$  Current efficiency, %

The primary focus of energy-saving efforts in aluminum electrolysis technology revolves around reducing voltage and improving current efficiency, which falls under the category of "input side energy saving." The core objective of input side energy saving technology is to maintain optimal thermal stability through dynamic optimization of thermal characteristics during operation. However, the progress in the field of input side energy saving is hindered by certain technical challenges:

- 1) Real time measurements of thermal parameters are impractical due to the corrosive nature of the electrolyte. This makes it difficult to accurately assess the thermal characteristics of the cell in a timely manner.
- 2) Identifying an adjustment method to achieve the desired thermal characteristics in industrial cells remains elusive. This is primarily due to the theoretical interdependence between the line current control method and the optimal operational objective of electromagnetic stability [3].

One approach to energy saving in aluminum electrolysis involves the accumulation, recovery, and utilization of externally dissipated energy from the cell, known as "energy saving at output." Several notable developments have emerged in this area. In 2010, BHP Billiton Ltd introduced a patented internally cooled side heat recovery device [4]. This device incorporates multiple heat exchange pipes along the inner surface of the electrolysis cell's shell, enabling the guidance of fluid through the shell. The fluid, which can be either air or a liquid medium, is circulated throughout the entire electrolysis cell by a pump. This design facilitates heat exchange and recovery. In 2011, Professor Mark Taylor's team at the University of Auckland designed a shell heat exchanger for side heat transfer in aluminum electrolysis cells. The shell heat exchanger effectively adjusts the heat balance of the entire electrolysis cell by controlling heat loss from the shell. This capability allows for the fine-tuning of the power balance in the electrolysis cell, enabling stable long-term operation and expanding the power modulation window. In 2016, TRIMET Aluminum Plant implemented the EnPot technology, developed by the University of Auckland, in an industrial test involving twelve 120 kA electrolysis cells [5]. The test results demonstrated that the system could effectively regulate the heat dissipation of the electrolysis cells, ensuring their stable operation even with input current fluctuations of  $\pm 25\%$ . However, it was noted that the system had low output medium temperature, which resulted in underutilization of recovered heat.

In the last two decades, extensive global research efforts have been devoted to the field of "energy saving at output." However, the practical implementation of waste heat utilization in industrial settings has faced significant challenges. These challenges arise from several factors, including limitations imposed by the influence mechanism on the thermal characteristics of the electrolysis cell, safety concerns, and difficulties associated with heat recovery and utilization in the electrolysis process [6-8].

Our research group has undertaken extensive and persistent investigations in the realm of energy conservation pertaining to the "output" of aluminum electrolysis cells. We have made significant breakthroughs in several technical challenges, including the optimization and control of thermal characteristics in aluminum electrolysis cells, efficient heat dissipation and accumulation within the cell structures, and the industrial application of heat recovery in aluminum electrolysis. As a result of our endeavors, we have successfully developed a key technology known as "double-port energy saving" and a comprehensive industrial system called HORRS specifically designed for industrial-scale cells. We have achieved groundbreaking success by implementing these technologies on a large 400 kA cell. Moreover, we have successfully integrated the recovered heat from the cell with an urban heating station and a regenerative system for a 300 MW thermal power unit.

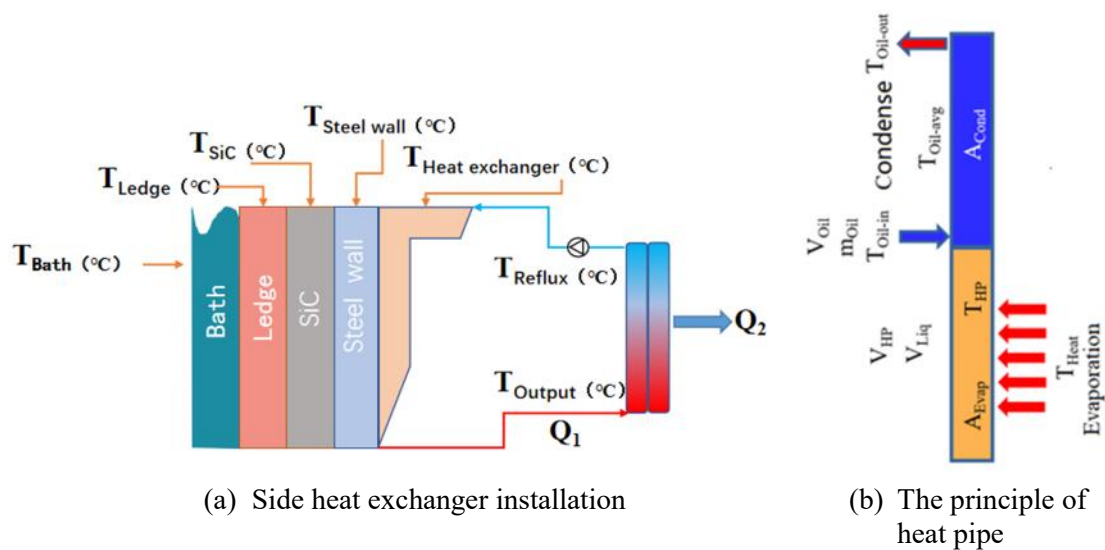
This paper presents an in-depth investigation of the double-port energy saving industrial system HORRS and its practical implementation in a 400 kA electrolysis cell. The primary focus is to analyze the significant contributions of HORRS to "input side energy saving." To assess the system impact, a comparative analysis is conducted, evaluating changes in voltage, superheat, ledge shape, and current efficiency before and after the implementation of the HORRS.

## **2. Double-Port Energy Saving Industrial System and HORRS**

Solheim et al. [9] conducted an extensive study and established that waste heat recovery at the side of the aluminum electrolysis cell was a promising approach. They found that heat pipe technology could effectively optimize and enhance the side wall of the electrolysis cell, resulting in substantial energy savings in aluminum electrolysis. Building upon this research, our research group [10] has developed an energy-saving industrial system called the Heat of Output side Recovery Regulating System (HORRS) for aluminum electrolysis cells. The HORRS system

utilizes heat pipes, addressing technical challenges related to efficient heat dissipation and accumulation in aluminum electrolysis cells, as well as the industrial application of heat recovery. The HORRS system incorporates a specially designed thermal accumulation device, which functions as a heat exchanger utilizing high-quality oil as the thermal medium. Through years of research and development, we have successfully conducted trial production of the latest heat pipe heat accumulator. Figure 2 illustrates the installation diagram of the side heat control and heat exchanger in the cell. The thermal agglomeration device, based on the principles of heat pipes, is highly suitable for regulating and accumulating heat at the side of the cell. Several key advantages include:

1. Efficient heat transfer enabling rapid adjustment of the heat flow at the side of the cell.
2. Excellent temperature uniformity throughout the cell.
3. High heat load capacity of the medium, maximizing the utilization of recovered heat sources.
4. Compact, safe and reliable operation at potshell temperature of up to 450 °C.



**Figure 2. Side heat control and heat exchanger installation of a cell.**

The HORRS system comprises several key components, including the multiple thermal circulation system (HCS system), heat output workstation, heat transmission pipe network, water refill tower, client heat conversion station (power plant terminal station and heat supply station), and an intelligent control system (Figure 3). The HCS system serves as the central component of the HORRS system. It effectively controls and monitors the thickness of the electrolysis cell ledge using a cell thermal control model. Additionally, it measures and captures the heat generated by the electrolysis cell. As the heat collection increases, the ledge thickness increases accordingly, and conversely, as the heat collection rate decreases, the ledge thickness decreases. The recovered heat obtained from the HORRS system has versatile applications, including low-temperature thermal power generation, urban heating systems, integration with power plants for reheating purposes, and industrial refrigeration, among others.

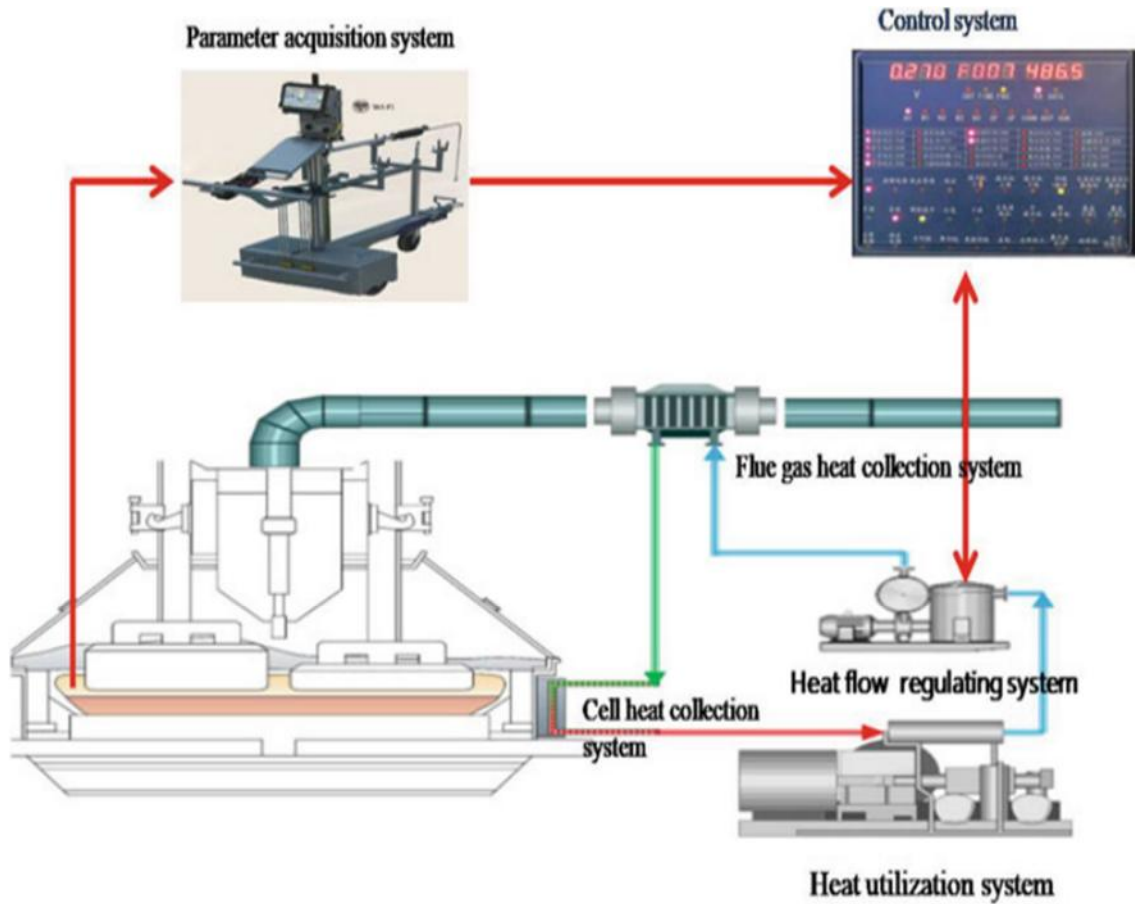


Figure 3. Energy saving at output industrial system (HORRS system).

### 3. Industrial Application of Double-Port Energy Saving Industrial System and HORRS

To enhance the efficiency of heat recovery, an industrial demonstration project was implemented utilizing the HORRS system on the 400 kA potline at Zhongfu Aluminum Plant. The project team conducted a rigorous six-month experiment and testing phase, specifically focusing on conducting thermal characteristic control tests on four cells. Notably, the team achieved successful control of the superheat of the test cells within the desired range of 8-12 °C. The contribution of the HORRS system to "input side energy saving" was comprehensively analyzed by comparing key parameters, including voltage, superheat, ledge shape, and current efficiency, before and after the operation of the HORRS system.

The project team carefully selected four test cells along with two comparison cells (labeled as Cell 5 and Cell 6) for the study. Among the test cells, two were ordinary pot life production cells (designated as Cell 1 and Cell 2), while the remaining two were old production cells (labeled as Cell 3 and Cell 4). Considering the distinct pot life characteristics of these cells, a low voltage technology solution was employed for the electrolysis cells with a service life of 2000 days. Additionally, a technology solution aimed at improving current efficiency was implemented for the two cells with a service life exceeding 3000 days. All pots had similar performance before the test. The current efficiency and voltage of the test cells before testing is basically consistent with that of the comparison cells. By adjusting the technical parameters and collaborating with the HORRS system, the project team carried out corresponding thermal regulation experiments tailored to each specific cell.

### 3.1 Voltage Balance Data and Analysis

The basic model for online thermal stability control involves adjusting the energy input through the working voltage of the cell. A 100 mV increase (or decrease) in the cell voltage corresponds to approximately a 5 % increase (or decrease) in the heat dissipation of the electrolysis cell. By modifying the anode-cathode distance and adjusting the set working voltage of the electrolysis cell, the energy balance of the cell can be immediately adjusted. Metal height often serves as a crucial parameter for energy balance adjustment. It is frequently utilized as a mean to regulate energy balance. The HORRS system plays a vital role in effectively controlling the side heat dissipation of the electrolysis cell, facilitating the adjustment of energy balance. This, in turn, ensures the relative stability of the cell voltage and the metal height, while also preventing the occurrence of magnetohydrodynamic (MHD) instability of the cell [10].

Based on the pot life and production operation characteristics of the cells, stable voltage and current efficiency tests were performed on electrolysis cells 3 and 4. In addition, a voltage reduction test was conducted on electrolysis cells 1 and 2. The obtained voltage balance test data for the four test cells and two comparison cells are summarized in Table 1.

**Table 1. The voltage balance for each test cell.**

Cell number	Cell voltage V	Cell internal voltage drop V	Anode voltage drop V	Cathode voltage drop V	Inter-electrode voltage drop V	Busbar voltage drop V
1	3.858	3.655	0.278	0.345	3.032	0.203
2	3.867	3.671	0.278	0.352	3.041	0.196
3	3.937	3.735	0.278	0.466	2.991	0.202
4	3.931	3.695	0.278	0.462	2.955	0.236
5	4.001	3.795	0.278	0.494	3.023	0.206
6	3.966	3.755	0.278	0.378	3.099	0.211

The test results presented in Table 1 indicate that the total voltage measured for the four test cells falls within the range of 3.858-3.937 V, with an average voltage of 3.898 V. For the comparison cells, the recorded voltages are 4.001 V and 3.966 V, respectively, resulting in an average voltage of 3.984 V. Consequently, the average voltage of the test cells is 86 mV lower than that of the comparison cells. The results of the industrial operation tests further demonstrate the effectiveness of the HORRS system. For the aged electrolysis cells (with a service life of approximately 2000 days), the achieved cell voltages were 3.897 V and 3.900 V, with corresponding DC power consumptions of 12.538 kWh/kg Al and 12.581 kWh/kg Al in the 400 kA aluminum electrolysis cells. In the case of the over-aged electrolysis cells (with a service life of approximately 3000 days), the recorded cell voltages were 3.940 V and 3.947 V, accompanied by DC power consumptions of 12.798 kWh/kg Al and 12.828 kWh/kg Al.

The industrial test results demonstrate the significant energy-saving potential of the HORRS system on the 400 kA aluminum electrolysis cell. Specifically, the system has been found to save 0.417 kWh/kg Al of electricity in the ordinary pot life test cells and 0.438 kWh/kg Al in the old test cells.

### 3.2 Superheat Test and Analysis

Superheat in the context of aluminum electrolysis refers to the temperature difference between the electrolyte temperature and the freezing point (liquidus) temperature of the electrolyte. The superheat has a significant impact on the formation of side crusts and ledge, as well as the solubility of alumina in the electrolyte. The superheat is influenced by the thermal equilibrium in the cell. Reducing the superheat results in an increased thickness of the side ledge, subsequently reducing the surface area of the aluminum liquid surface. This, in turn, increases the current efficiency of the cell [11]. In this study, the optimized differential thermal analysis is used to measure the superheat [12, 13].

The electrolyte temperature, liquidus temperature, and superheat of four sets test cells and two sets comparison cells are shown in Table 2.

**Table 2. Electrolyte and liquidus temperature, and superheat (averages).**

Cell number	Electrolyte temperature °C	Liquidus temperature °C	Superheat °C
1	940.9	932.3	8.6
2	951.4	942.1	9.3
3	940.6	930.8	9.8
4	947.9	937.1	10.8
5	950.4	935.9	14.5
6	945.4	937.5	7.9

The measurement results presented in Table 2 demonstrate noteworthy observations. Firstly, the test cells equipped with the HORRS system exhibit higher electrolyte temperatures compared to the comparison cells. Additionally, the electrolyte temperature remains stable throughout the duration of the test period. The liquidus temperature ranges from 930.8 °C to 942.1 °C, with varying values observed among the tested cells. Regarding superheat control, the four test cells installed with the HORRS system consistently maintain stable superheat ranging from 8.6 °C to 10.8 °C. In comparison, the two comparison cells exhibit superheat control within the range of 7.9 °C to 14.5 °C, indicating a broader superheat control interval compared to the test cells with the HORRS system.

### 3.3 Ledge Thickness Test and Analysis

The ledge of the aluminum electrolysis cell refers to the solidified electrolyte layer that forms between the molten electrolyte and the side wall of the cell. It gradually develops into varying thicknesses, thus creating a cavity in the cell. This cavity serves as the site for electrochemical and physicochemical reactions during the aluminum electrolysis process. The shape and stability of the cavity play a crucial role in ensuring the safe, stable, and efficient operation of the cell. Maintaining a regular and stable cavity shape is of utmost importance in achieving optimal performance and operational reliability in aluminum electrolysis.

The thickness of the ledge in industrial cells is primarily influenced by the cell shell structure and the working surface area of the cell, ultimately determined by the heat balance of the cell. The heat input to the cell depends on factors such as cell current and voltage. On the other hand, the heat loss from the electrolysis cell depends on the electrolyte temperature, metal height, thickness of the anode cover, and lining structure of the cell. A decrease of heat input to the cell decreases,

electrolyte temperature and superheat decrease. As a result, ledge thickness increases. Conversely, when the heat input to the cell increases, the electrolyte temperature and superheat rise, resulting in the dissolution of the ledge and a reduction of its thickness.

The project team conducted meticulous measurements to determine the thickness of the ledge in four sets of test cells and two sets of comparison cells. The obtained measurement results are summarized in Tables 3. Table 4 presents the average ledge thickness derived from the collected measurements.

**Table 3. Average thickness of ledge and deviation of electrolysis cells 1- 6 in cm.**

Detection location		1	2	3	4	5	6	7	8	9	10	11	12
Cell 1	Average (A side)	14.4											
	Deviation	1.7	-0.3	0.7	-1.3	-3.3	-0.3	0.7	-0.3	1.7	0.7	-0.3	1.7
	Average (Bside)	14.1											
	Deviation	0.7	0.7	1.7	0.7	-3.3	-2.3	1.7	-3.3	0.7	-0.3	-1.3	1.7
Cell 2	Average (A side)	13.9											
	Deviation	2	1	2	-3	1	-3	0	-4	0	-1	2	2
	Average (Bside)	14.2											
	Deviation	2	2	1	1	-3	-1	-3	-1	0	1	1	2
Cell 3	Average (A side)	13.9											
	Deviation	2.2	2.2	-2.8	0.2	-0.8	-1.8	-0.8	-1.8	0.2	0.2	2.2	2.2
	Average (Bside)	13.7											
	Deviation	2.2	2.2	-0.8	1.2	-2.8	-2.8	-2.8	-2.8	-1.8	2.2	1.2	3.2
Cell 4	Average (A side)	14.9											
	Deviation	3	1	-2	0	-2	-3	-1	-2	-1	1	2	3
	Average (Bside)	15.0											
	Deviation	2	2	1	-2	-1	-3	-2	0	0	1	0	2
Cell 5	Average (A side)	13.3											
	Deviation	3.5	2.5	0.5	2.5	-5.5	-0.5	-2.5	-1.5	1.5	1.5	3.5	3.5
	Average (Bside)	11.8											
	Deviation	2.5	2.5	1.5	-2.5	-4.5	-3.5	-2.5	-4.5	-3.5	1.5	2.5	2.5
Cell 6	Average (A side)	13.1											
	Deviation	3.4	3.4	0.4	-6.6	2.4	-0.6	0.4	-6.6	1.4	2.4	2.4	3.4
	Average (Bside)	12.1											
	Deviation	4.4	1.4	-1.6	-6.6	-1.6	-0.6	-4.6	0.4	-3.6	1.4	1.4	3.4

**Table 4. Average thickness of ledge of each cell in cm.**

Number	1	2	3	4	5	6
A side	14.4	13.9	13.9	14.9	13.3	13.1
B side	14.1	14.2	13.7	15.0	11.8	12.1
Full cell	14.3	14.0	13.8	15.0	12.5	12.6

The results of the ledge thickness tests reveal notable observations. The maximum ledge deviations for the four test cells equipped with the HORRS system are measured at 3.3 cm, 4 cm, 3.2 cm, and 3 cm, respectively. In contrast, the maximum ledge values for the two comparison cells are recorded at 5.5 cm and 6.6 cm, respectively. These findings indicate that the test cells with the HORRS system exhibit superior ledge uniformity compared to the comparison cells.

The average ledge thickness test results presented in Table 4 and Figure 4 provide insightful findings. It is evident that the installation of the HORRS system on both sides of the cavity of the four test cells contributes to well-formed ledge. The average thickness of the ledge on both sides

of the cells is comparable, although the ledge on the B side of the comparison cell is approximately 1 cm thinner than that on the A side. Furthermore, the average ledge thickness of the test cells equipped with the HORRS system is approximately 2 cm greater than that of the comparison cells. These differences highlight the significant impact of the heat recovery collector installed on the side walls of the test cells in adjusting ledge thickness and enhancing ledge regularity.

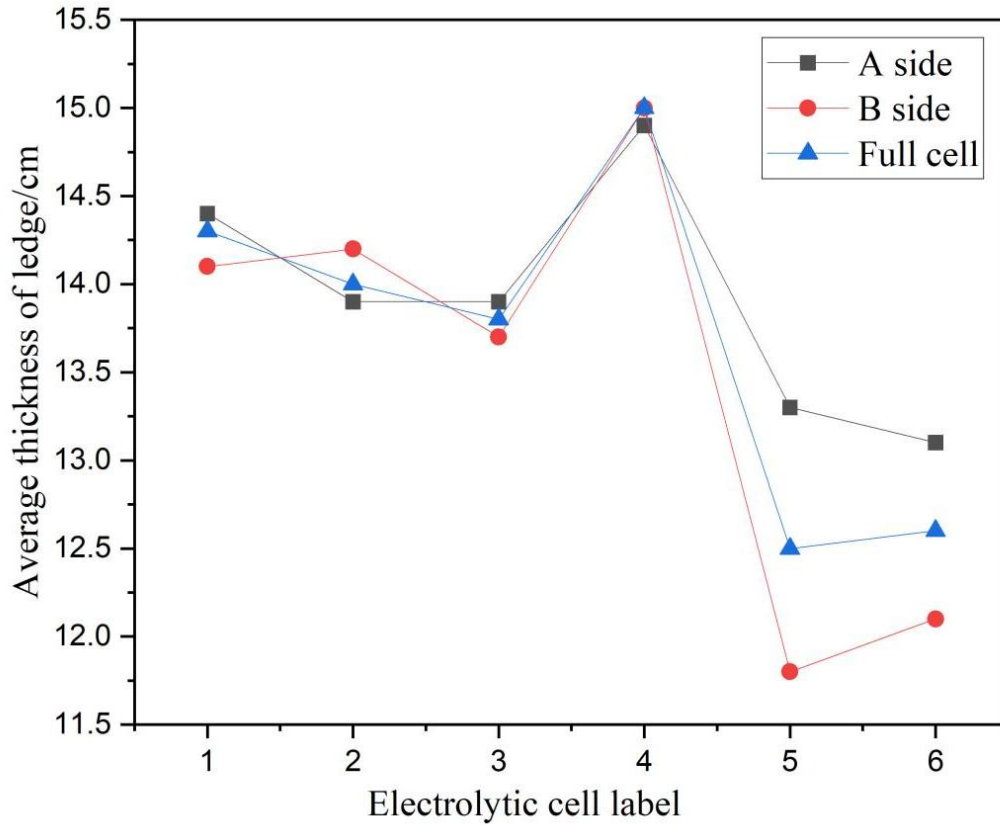


Figure 4. Average thickness of ledge of each cell.

### 3.4 Current Efficiency Test and Analysis

Current efficiency is a vital parameter in aluminum electrolysis. Current efficiency is defined as the ratio of actual production to the theoretically achievable production, proportional to electric current. Current efficiency of four test cells and two comparison cells is shown in Figure 5.

The test results indicate that the current efficiency values for the test cells range from 90.4 % to 93.4 %. The average current efficiency across the test cells is calculated as 92.67 %. In comparison, the average current efficiency for the comparison cells is found to be 90.81 %. The test cells demonstrate a 1.86 % higher average current efficiency compared to the comparison cells, showcasing superior performance and improved current efficiency of the test cells.

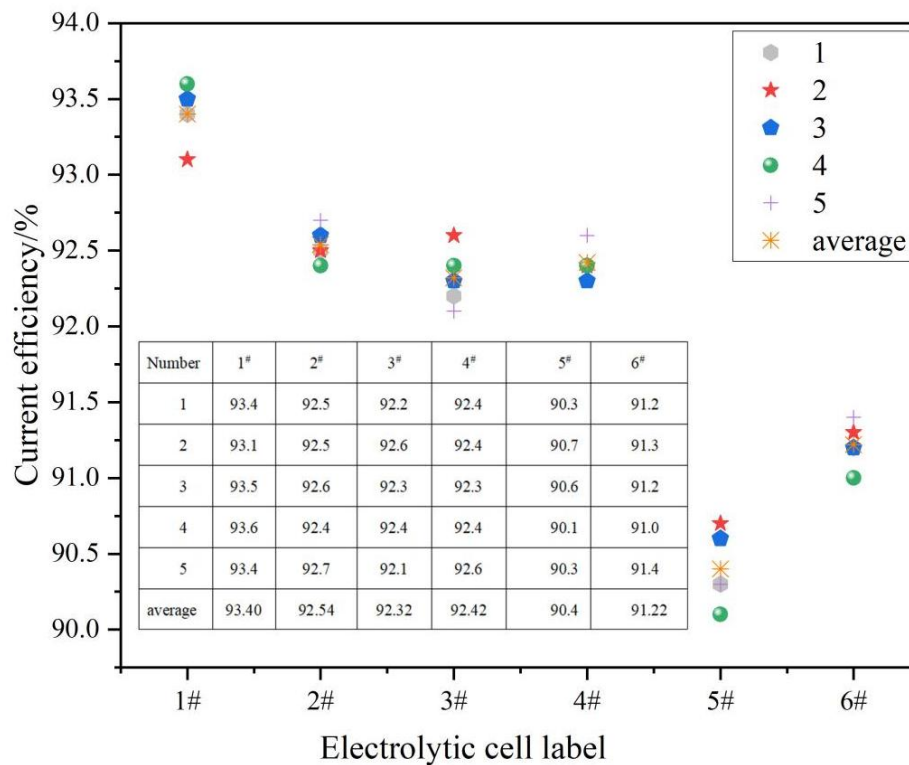


Figure 5. Current efficiency of test cell and comparison cell.

#### 4. Operation Effect of Double-Port Energy Saving Industrial System (HORRS)

Through meticulous measurement and analysis of the voltage, superheat, ledge shape, and current efficiency of four sets of 400 kA test cells installed with the HORRS system, as well as two sets of comparison cells, significant findings have been obtained. By optimizing the input thermal characteristics, it has been observed that the cell voltage decreases to below 3.9 V, showing a reduction of 80-100 mV compared to the original voltage. Consequently, the superheat decreases by 4-5 °C, leading to a notable increase in current efficiency by 0.7 %. This improvement in current efficiency translates to substantial electricity savings, surpassing 0.379 kWh/kg Al. The heat recovery collector installed on the side wall of the test cells demonstrates a clear influence on adjusting the thickness of the ledge and enhancing its regularity.

By implementing the heat energy accumulation and recovery system at the output side, the recovered heat energy is effectively utilized for urban heating during winter, resulting in a significant energy saving of 308 kWh/t of Al for power generation. Furthermore, when connected to the thermal generator set in summer, the power generation can be further increased by 97.5 kWh/t of Al.

With the integration of the double-port energy-saving industrial system (HORRS), the overall energy saving achieved is estimated to be 0.785 kWh/kg Al, encompassing both heat and electricity. This comprehensive energy-saving approach yields a remarkable 6.03 % reduction in energy consumption for the electrolysis cell.

#### 5. Conclusions

The "double-port energy saving" industrial system (HORRS), which is based on the regulation of side heat dissipation in aluminum electrolysis cells, has been successfully implemented in a

400 kA aluminum electrolysis cell. This innovative system combines optimal adjustment of thermal characteristics with heat accumulation recovery and utilization, leading to significant advancements in industrial applications. The HORRS technology effectively reduced the cell voltage in the test cells by optimizing superheat, thereby improving current efficiency, and achieving energy savings on the input side. Next, we plan a large-scale test to demonstrate it. Furthermore, the HORRS system ensures thermal stability even in the face of fluctuating input energy in the electrolysis cell, providing crucial technical support for the flexible production of primary aluminum.

The waste heat recovered from the electrolysis cell through the implementation of the HORRS system is effectively channeled into the heat recovery system and urban heating system of the thermal generator set, marking the successful integration and utilization of thermal energy resources across different industrial systems. This breakthrough achievement establishes a comprehensive "double-port energy saving" technology for aluminum electrolysis and enables the efficient utilization of low-temperature thermal energy resources.

Furthermore, the application of the HORRS system has been extended to a 500 kA electrolysis cell at the Gansu Dongxing Aluminum Industry Co.,Ltd. The system is currently undergoing preparations and is expected to commence operations in September 2023.

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