Case Study of Electrochemical Technology Development and Analysis of Engineering Thinking

Dandan Han[1], **Dan Wu**[2], **Jianshe Wang**[2*]
[1] College of Science, Henan Agriculture University, Zhengzhou 450002, Henan, China
[2] School of Chemical Engineering, Zhengzhou University, Zhengzhou 450001, Henan, China

Abstract: Electrochemistry, an interdisciplinary discipline closely integrated with engineering applications, embeds abundant engineering thinking elements in its successfully developed technological cases. Given the “scientization of engineering” phenomenon and low transformation rate of scientific research achievements in Chinese universities, this paper selects recent typical electrochemical technology development cases in energy, materials and environmental protection fields. It then conducts case analysis from an engineering perspective and summarizes the core engineering thinking for project development, including scenario thinking, terminal thinking and short-board thinking. It is anticipated that such an understanding will contribute to the enhancement of the current state of technological advancement and the transformation of research achievements in the field of engineering.

***Keywords*:** Electrochemical technology; Cases study; Scenario thinking; Terminal thinking; Short-board thinking

1. Introduction

In recent years, extensive debates have emerged concerning the phenomenon of “scientization of engineering” in Chinese universities [1]. This phenomenon stems not only from the Chinese government’s university funding and evaluation mechanisms but also from industrial cognitive differences regarding the theory-practice relationship in engineering and engineering education. The traditional engineering ontology holds “engineering is the application of science”, focusing on in-depth knowledge exploration. In contrast, the new engineering ontology posits “engineering is artifact creation”, emphasizing engineering practice as the driver for theory-practice integration. Specifically, in university engineering education, this means taking practice as the core, adopting a “learning-by-doing” approach, breaking disciplinary barriers, and solving practical problems. This "scientization" tendency is frequently manifested in research practices, where the pursuit of high-impact-factor publications is given priority, while relegating core engineering metrics such as “feasibility,” “stability,” “scalability,” and “economic viability” to a secondary status. As a direct consequence, a prominent gap remains between breakthroughs achieved in laboratory settings and the practical implementation of technologies in industrial contexts.

Corresponding to the scientization of engineering disciplines, the transformation rate of scientific research achievements in Chinese universities has long been low. One reason is the lack of practical verification of these achievements, with a deeper cause being the deficiency in engineering thinking-a core embodiment of the new engineering ontology. In scientific research, engineering thinking manifests as targeting actual demand scenarios, addressing “bottleneck” key issues, and ultimately evaluating achievements via practical applications. As an interdisciplinary discipline closely integrated with engineering applications, electrochemistry has seen intense global research in energy, materials, and environment in recent years, with abundant emerging achievements providing valuable materials for engineering thinking analysis. Based on the author’s experience in applied electrochemistry, this study analyzes recent typical electrochemical cases from an engineering development perspective, proposes the engineering thinking to be emphasized in engineering research, and aims to share insights with university engineering researchers while practicing the new engineering education concept in scientific research.

This paper not only summarizes specific thinking modes through in-depth analysis of typical cases but also intends to construct a practical thinking framework. This framework is designed to bridge the existing gap between academic research and industrial application, thereby providing theoretical support and practical guidance for the reform of engineering education and facilitating the enhancement of technological innovation efficacy in engineering fields.

2. Introduction to Typical Cases

2.1 Seawater Electrolysis for Hydrogen Production

Sun et al. has conducted research on the oxidation of cathode materials caused by cathode reverse current during electrolytic water splitting for hydrogen production driven by fluctuating renewable energy, achieving for the first time the stable operation of seawater electrolysis hydrogen production equipment with anti-fluctuation capability for 10000 hours [2]. It is reported that previous studies mostly focused on the anode, using desalinated seawater and stable current to evaluate electrode performance. However, under fluctuating power supply conditions, the cathode suffers damage and failure due to the impact of reverse current. This practical issue has hindered the industrialization of green electricity-based hydrogen production but has been overlooked by the industry. Upon identifying this issue, Sun et al. simulated the operating conditions of real scenarios, conducted tests using long-duration, high current, and simulated seawater. This work successfully verified the long-term reliability of the electrolytic device, thereby leading the technological iteration of sustainable hydrogen production at the industrial level. Despite this breakthrough in stability, scaling the laboratory-scale electrolyzer to industrial capacity presents further engineering challenges. These include the optimization of reactor design for mass and heat transfer, the reduction of overall system energy consumption, and the development of intelligent coupling control strategies with intermittent renewable power sources like wind and solar. Addressing these scale-up issues exemplifies that engineering thinking is a continuous process from laboratory proof-of-concept to scale-production.

2.2 Electrooxidation of 5-Hydroxymethylfurfural

5-Hydroxymethylfurfural (HMF) is a crucial biomass-derived platform compound. Its oxidation yields 2,5-furandicarboxylic acid (FDCA), which can be further utilized to synthesize bio-based polyethylene 2,5-furandicarboxylate (PEF). As a replacement for polyethylene terephthalate (PET), PEF enables the large-scale production of bio-based degradable plastics. Compared with the chemical oxidation method for FDCA synthesis, the electrochemical oxidation of HMF proceeds under ambient temperature and pressure, without requiring precious metal catalysts or chemical oxidants. Thus, it is recognized as a promising green process.

Most studies on HMF electrooxidation focus on electrocatalysts. Literature reports indicate that the yield of FDCA from HMF electrooxidation can reach 99.4% [3]. Similarly, the electrooxidation of furfural to furoic acid has also been reported to achieve nearly 100% selectivity and 97-99% current efficiency [4]. From the perspective of literature reports alone, the industrialization of FDCA production via HMF electrosynthesis appears imminent. It is worth noting that HMF electrooxidation requires a strong alkaline medium, and previous studies were mostly conducted at relatively low concentrations. For industrial application, it is essential to use high-concentration substrates as raw materials, which also entails relatively long reaction times. In our experiments on high-concentration HMF electrooxidation, we found that the synergy of three factors strongly alkaline environment, high substrate concentration, and long reaction time induces severe side reactions of HMF. However, research reports addressing this critical issue remain scarce.

To solve this problem, our team developed an electrochemical reactor and applied for a patent. Using a NiOOH catalyst, constant current electrolysis was performed on 0.5 M HMF for 11 hours, achieving an HMF conversion rate of 81.4%, an FDCA yield of 68.8%, an FDCA selectivity of 84.5%, and a current efficiency of 83.8% [5]. The reactor was also used to verify the electrooxidation of furfural, yielding favorable reaction performance.

Beyond the aforementioned challenges associated with reaction conditions, the market prospect of electro-synthesized FDCA as a monomer for PEF remains uncertain. This uncertainty arises from the inevitable formation of monocarboxylic acid intermediates during the electrochemical synthesis process, which not only complicates the subsequent purification steps but also elevates overall production costs. This issue, in turn, highlights a critical “short-board” in the product separation segment of the FDCA industrialization chain. However, leveraging “scenario thinking” to explore alternative application directions could open up new development pathways. For instance, benefiting from its inherent green attributes, electro-synthesized FDCA may possess unique application value and economic feasibility in the production of fine chemicals (e.g., pharmaceutical intermediates) or special functional polymers-even if its application potential in bulk plastic manufacturing is constrained.

2.3 Development of Electro-Fenton Technology

With the increasingly strict environmental supervision and upgraded wastewater discharge standards, advanced oxidation technologies for refractory wastewater treatment have emerged as a high-priority development area anticipated by the environmental protection industry in recent years, among which the advancement of electro-Fenton technology has attracted wide attention. Electro-Fenton technology typically utilizes oxygen or air as feedstocks to electrocatalytically generate H_2O_2, and H_2O_2 reacts with Fe^{2+} to generate Fenton’s reagent for wastewater treatment. The development of this technology involves multiple factors including electrocatalysts, gas diffusion layers, reactor structures and operating processes. When first starting with electrocatalysts, we found that the current efficiency of H_2O_2 generation on gas diffusion electrodes (GDE) was higher than that] on rotating ring-disk electrodes (RRDE) [6]. Even the current efficiency of unactivated carbon nanotubes (CNTs) on GDEs was more than twice that of activated CNTs on RRDEs [7], which reflects the importance of electrode performance. Thus, our team shifted to downstream development, assembled an electro-Fenton reactor and investigated its stability. The results showed that electrode performance was prone to degradation, which may be associated with reduced electrode hydrophobicity or surface scaling. In the subsequent work, in-depth research on electrode stability will be carried out. This identified "short-board" electrode scaling and stability directs future engineering development. Priority efforts should be directed toward three core directions: first, designing anti-fouling or self-cleaning electrode coating materials to inhibit scaling formation at the source; second, optimizing reactor hydrodynamics (e.g., introducing turbulence to enhance mass transfer) to mitigate the accumulation of scaling substances on electrode surfaces; and third, developing intelligent online cleaning and regeneration protocols to realize real-time remediation of scaling-related performance degradation. Although these tasks do not involve in-depth exploration of fundamental catalytic mechanisms, they are paramount for the successful industrial deployment of electro-Fenton technology and, more importantly, epitomize the problem-oriented essence of engineering thinking in addressing practical application bottlenecks.

3. Analysis of Engineering Thinking

Through the analysis of the three aforementioned electrochemical technology development cases, the following insights are derived from the perspective of thinking. It is proposed that successful project development is guided by an integrated engineering thinking framework, comprising scenario thinking, terminal thinking, and short-board thinking, all underpinned by an overarching system thinking perspective.

3.1 Scenario Thinking

Scenario thinking mandates grounding research and development in the concrete realities of the intended application, ensuring that laboratory investigations are conducted within the operational boundaries and under the constraints of the real-world environment. For engineering technology development, it is essential to target clear application scenarios and take the real conditions of the scenarios as the basis for evaluating scientific research achievements. Sun et al. focused on the scenario of seawater electrolysis for hydrogen production, which is featured by energy fluctuation and seawater corrosion[2]. Different from the conventional research approach that adopts stable current for desalinated seawater electrolysis, the team closely aligned with the actual scenario requirements and conducted verification using high current, long duration and simulated seawater. The obtained results conformed to practical needs, thus gaining rapid market recognition.

There is a memorable example in the field of CO_2 electroreduction development and application. In 2015, the author noticed the CO_2 electrosynthesis formate project jointly developed by Canada's Mantra Energy Corporation and the University of British Columbia (UBC). The project had achieved a daily CO_2 treatment capacity of 100 kg, which was far ahead of global counterparts. The project positioned the application scenario of formate as fuel cells, and subsequently developed a fuel cell with a mixed feed mode. The results reported in 2019 showed that this fuel cell achieved an apparent power density of 4000 W m^{-2} under a current density of 10000 A m^{-2}[8]. Furthermore, the researchers tested the fuel cell on a 250 W electric scooter at a speed of 10 km h-1 for 15 minutes and completed an economic performance evaluation. Notably, this project defined a clear application scenario for CO_2 reduction products and ultimately completed practical evaluation, setting a commendable example for related research.

3.2 Terminal Thinking

Terminal thinking instills a rigorous validation discipline centered on ultimate performance metrics, which demands that the success of a technology should not be evaluated merely by intermediate laboratory indicators, but rather by its final output quality, long-term operational stability, and economic cost-effectiveness under real-world application scenario conditions. Performance evaluation is integral to scientific research. Once the application scenario is determined, final results must be evaluated under the real scenario conditions, which is the prerequisite for improving achievement transformation rates. Taking the electrooxidation of HMF to FDCA as an example, industrial production has clear requirements: high-concentration raw materials and long reaction times. Conducting only lab-scale tests without these conditions may yield encouraging results, but fails practical application verification. Recognizing the challenges of industrial conditions, our team developed reactors, achieved phased results, and provided valuable exploration for the industrialization of FDCA production via HMF electrosynthesis. Notably, FDCA is used as a monomer to synthesize polymer PEF, which demands high purity. According to literature research, the electrosynthesis process of FDCA will inevitably leave monocarboxylic acid intermediate products, and the difficulty in separating these intermediates increases the production costs. Based on this, the author consider the market prospect of FDCA from HMF electrosynthesis for PEF unclear. In contrast, electrooxidation of furfural to furoic acid, with easy product separation, is a promising green process.

3.3 Short-Board Thinking

Short-board thinking focuses optimization efforts on the weakest link in the technological chain, recognizing that a system’s overall performance and viability are ultimately constrained by its most deficient component or process. For the achievement transformation of engineering development projects, a series of practical verifications must be conducted throughout the entire process, during which problems are exposed and shortcomings are identified. This differs significantly from the prevalent “scientization-oriented” research paradigm in universities. Such a paradigm tends to focus on reporting positive results, devotes excessive efforts to phased issues, and rarely conducts systematic inspections from an overall perspective, which may ultimately hinder the resolution of critical shortcomings. Taking electro-Fenton technology as an example, investing excessive efforts in catalyst research while neglecting electrode durability, a critical issue, indicates a failure to identify the key shortcoming. In fact, commonly used carbon materials can already meet the basic operational requirements of electro-Fenton systems. From the perspective of engineering development, there is no need for excessive in-depth research on carbon-based catalysts. In practical application scenarios, wastewater generally contains calcium and magnesium ions. The increase in cathode pH of the electro-Fenton system will cause scaling, and the performance degradation of electrodes due to scaling is indeed a key problem to be solved urgently.

In addition to requiring shortcoming-oriented thinking for identifying development priorities, such thinking is also essential for selecting process routes. For example, the electrochemical process has significant advantages in environmental protection and safety compared to the chemical process. Therefore, the industrialization process of GO preparation via the electrochemical method has advanced rapidly in recent years. It has been reported that the cost of GO prepared by the electrochemical method is only 1/7 of that by the Hummers method [9]. This route uses only sulfuric acid as the electrolyte, which reduces both the types of hazardous chemicals and wastewater treatment costs compared with the Hummers method. The selection of this route reflects shortcoming-oriented thinking. When a process has inherent defects, it is necessary to courageously explore new paths. During the application of the electrochemical process, the adsorption of water from the environment and electrolyte causes the deintercalation of intercalated graphite raw materials, leading to non-uniform oxidation of the graphene product. After identifying and addressing this shortcoming, Ren et al. invented a micro-liquid film electrolysis method to precisely control the diffusion of water, thereby realizing the industrialized continuous preparation of uniform single-layer GO.

3.4 System Thinking

The aforementioned thinking modes do not operate in isolation but are interconnected within a systemic framework. Engineering projects are complex systems. Scenario thinking defines the system's boundaries, objectives, and external interactions. Terminal thinking ensures the validity and practicality of the system’s output. Short-board thinking focuses on identifying and strengthening the weakest link within the system’s internal structure. The development of electro-Fenton technology serves as a prime example: it was through terminal thinking-conducting long-term stability tests under real scenario conditions-that the critical short-board of electrode scaling was exposed. Conversely, solving this short-board problem must loop back to scenario thinking, seeking solutions that are effective under the specific conditions of actual wastewater composition. This iterative process of defining the scenario, testing the terminal output, and identifying and addressing the short-comings embodies a holistic system thinking approach, which is essential for navigating the complexities of engineering development.

4. Conclusion

Chinese universities have long faced the issues of “the scientization of engineering” and low transformation rate of scientific research achievements, which reflects the lack of engineering thinking in engineering research. An analysis of typical cases of electrochemical technology development in recent years shows that successful project development requires engineering thinking-namely scenario thinking, terminal thinking, and short-board thinking-with the goal of creating high-quality products recognized by the market. Specifically, the application scenario should be clarified during project development, short-board issues identified and addressed in real scenarios, and finally, the achievements verified using real scenario conditions. Building on this analysis, this study further synthesizes these three thinking modes into a cohesive, integrated framework, with system thinking serving as the overarching guiding principle. This framework provides a practical mental model for engineering researchers to bridge the gap between academic discovery and industrial innovation. The implications extend to engineering education, suggesting a greater emphasis on case-based learning and project-based training that cultivates these thinking habits. Furthermore, it calls for a more diversified academic evaluation system that values technological maturity and industrialization potential alongside scientific publication. Future work could involve applying and refining this engineering thinking framework across a wider range of engineering disciplines to validate and enhance its universality and effectiveness.

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