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Curriculum Construction of Fuel Cell Technology Based on PBL under the Background of Emerging Engineering Education

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Abstract: To promote the construction of high-quality "Golden Course" for fuel cell courses and solve the educational pain points including insufficient advancedness and systematicity in curriculum teaching, so as to meet the training demands of interdisciplinary engineering talents in the field of new comprehensive energy, this paper sorts out and analyzes the core problems existing in current fuel cell teaching in colleges and universities. At present, fuel cell courses are faced with prominent fragmentation of knowledge systems. Most teaching adopts modular and scattered lecture modes with disjoint multidisciplinary knowledge points and disconnection of knowledge before and after the curriculum. As a result, students cannot build a complete and systematic knowledge framework covering basic principles, core components, stack integration, and engineering applications, and their ability to integrate and transfer knowledge is weak. Meanwhile, traditional teaching only focuses on fuel cells as a single power generation device and a single energy conversion dimension, ignoring the industrial application characteristics of multi-energy coupling conversion among hydrogen energy, electric energy, and thermal energy as well as the coordinated operation of wind-solar-hydrogen-energy storage systems. Teaching fails to cultivate students' systematic thinking of multi-energy coupling, leading to the common lack of overall engineering vision and system optimization thinking among students, and making it difficult for them to tackle complex engineering problems of comprehensive energy systems. The above problems disconnect curriculum teaching from actual industrial demands and restrict the improvement of education quality and connotation construction of golden courses. By clarifying the existing defects of fragmented teaching and lack of systematic vision, this paper provides a problem basis and reform reference for reconstructing systematic, coupled, and cutting-edge curriculum knowledge systems, optimizing advanced teaching modes, and building high-quality fuel cell golden courses for cultivating interdisciplinary new energy talents.

Keywords: Fuel Cell Technology; Golden Course construction; Interdisciplinary talent training

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1. Curriculum background

Guided by the national "Dual Carbon" strategic goals (carbon peaking and carbon neutrality), China's energy structure is undergoing profound low-carbon transformation. Building a new power system dominated by renewable energy has become a major national strategic demand. However, renewable energy such as hydrogen energy is inherently random, bringing severe challenges to power grid operation [1]. How to efficiently absorb large-capacity fluctuating power is a core bottleneck to be solved urgently in the development of clean energy in China [2,3]. In this technical landscape, Reversible Solid Oxide Fuel Cell (RSOFC) is an advanced bidirectional energy conversion device operating at 600–900°C, which can switch efficiently between SOFC power generation mode and SOEC hydrogen electrolysis mode [4]. As core equipment realizing multi-energy coupling conversion of electricity-heat-chemical energy, this technology can deeply integrate green hydrogen production, waste heat utilization, coordinated carbon dioxide resource recovery, and industrial electric fuel manufacturing by constructing an integrated comprehensive energy system of wind-solar-RSOFC-hydrogen storage-SNG synthesis-gas pipeline network [5]. It provides a technical paradigm for breaking the barriers among power grids, heat networks, and gas networks and realizing low-carbon transformation of the whole industrial chain [6]. Faced with such grand national strategic demands, the industry is witnessing explosive growth in demand for interdisciplinary engineering R&D talents with multi-dimensional cross-cutting vision [7].

Nevertheless, the traditional teaching mode of Fuel Cell Technology fails to keep pace with cutting-edge scientific research and national industrial development. Teaching contents are mostly limited to micro-electrochemical mechanisms of single cells, lacking macro vision of free switching between power generation and electrolysis modes as well as full-process system integration [8]. Teaching methods lack integration of advanced engineering simulation software and multidisciplinary approaches, leaving students helpless when tackling complex engineering problems such as multi-objective optimization and variable operation strategies under dynamic conditions. Therefore, it is urgent to respond to the call of the Ministry of Education for the construction of emerging engineering education, and feed cutting-edge scientific research achievements of integrated RSOFC process simulation and multi-energy system optimization back into teaching [9]. By building a PBL project-based "Golden Course" with advanced and innovative attributes, we can cultivate urgently needed interdisciplinary innovative talents for long-term energy storage and new energy industrialization of new power systems.

2. Core problems in traditional teaching

Although the contents of this course keep up with the times, the traditional teaching mode has three major pain points restricting talent cultivation quality.

2.1. Fragmented knowledge system and absence of systematic multi-energy coupling vision

Traditional teaching lays excessive emphasis on explaining micro-materials and electrochemical mechanisms of single fuel cells, separating single cells from macro energy processes. Students lack an overall macro vision of full-process system integration and multi-energy complementation (electricity-heat-chemical energy). Current teaching is always confined to the single energy conversion dimension of fuel cells, with teaching perspectives focusing on performance optimization of single equipment rather than coordinated operation of comprehensive energy systems. Systematic teaching thinking of multi-energy coupling, multi-equipment linkage, and multi-scenario adaptation has not been established. Under the background of constructing new power systems and comprehensive energy systems, fuel cells have broken through the positioning of a single power generation device and become the core hub for multi-energy coupling conversion among hydrogen, electricity, heat, and energy storage. Their core engineering applications include hydrogen-electric cogeneration, combined heat and power generation, and coordinated operation of wind-solar-hydrogen-energy storage systems, whose core lies in coupled matching, coordinated regulation, and efficient utilization of multiple energy forms.

2.2. Single teaching means and insufficient application of advanced engineering simulation tools

Core formulas of the course, such as the Nernst equation, Butler-Volmer equation, and Arrhenius equation, are mostly limited to theoretical derivation and simplified manual calculation after class. Students lack training on industrial process simulation software such as Aspen Plus and co-simulation tools including Python/MATLAB, making them unable to conduct calculations of reaction kinetics, charge and mass transfer impedance under real complex working conditions.

2.3. Disconnection between teaching and frontier scientific research

Teaching is disconnected from cutting-edge research, lacking training on dynamic operation and multi-objective engineering decision-making. Most teaching cases adopt steady-state flow field analysis under ideal conditions, without introducing cutting-edge academic debates such as the actual mechanism of CO_2 in steam feedstock. There is a lack of practical training on start-stop, load variation, and multi-objective optimization (system round-trip efficiency, hydrogen production cost over full life cycle, service life, carbon emission) under fluctuating output of renewable energy such as wind and solar power.

3. Optimization and improvement

The optimized PBL curriculum teaching takes "Advanced Modeling and Integrated Optimization of Wind-Solar-Hydrogen Storage Systems Based on RSOFC" as the overall project clue, and the course lasts for 16 weeks. The PBL project design of this course abandons fragmented experimental assembly in traditional teaching and is completely reconstructed following the logical framework of "research methods and system modeling" in standard academic papers.

3.1. Learning of modeling methods (weeks 1–3)

In the first stage of micro-thermodynamic and electrochemical integrated mechanism modeling, students first build a multi-component physical property environment containing H_2, O_2, H_2O, CO, CO_2, and N_2 on the simulation platform. The core cell unit is constructed by calling RGibbs reactors based on the principle of minimum Gibbs free energy and cathode oxygen separators. Combined with the Nernst equation and area-specific resistance (ASR) impedance model framework, mathematical characterization of basic electromotive force and current density is realized.

3.2. Learning of simulation and expansion methods (weeks 4–7)

The second stage focuses on dual-mode full-process simulation and embedding of dynamic kinetics. Students further extend the topology in the process simulation software to build an SOFC power generation module and a complete SOEC electrolysis module containing pre-reaction (REA1), mixing, electrolysis (REDUCE), equilibrium (REA2), and water vapor circulation. Since general process simulation software has no built-in polarization kinetic equations for solid oxide cells, students must write custom FORTRAN calculator blocks through system extension interfaces to embed hyperbolic sine-approximated Butler-Volmer equation, Arrhenius-based electrolyte conductivity function, and porous electrode concentration polarization formula based on effective diffusion coefficients, so as to realize iterative dynamic solution of activation, ohmic, and diffusion voltage losses.

3.3. Data correction and verification (weeks 8–11)

The third stage focuses on structural impedance correction and benchmark verification with multiple groups of experimental data. Students conduct comparative analysis on internal impedance distribution differences between electrolyte-supported and fuel electrode-supported cells. A typical industrial pain point is that conventional models tend to overestimate diffusion losses of fuel electrode-supported cells under high current. Students integrate Knudsen diffusion and binary diffusion theories and propose a mathematical correction method for mass transfer models via correction of effective fuel electrode thickness. Afterward, students collect multiple groups of polarization curves and outlet gas component experimental data from the literature to conduct full-condition calibration and correction.

3.4. Cultivation of dialectical thinking (weeks 11–14)

The fourth stage carries out quantitative analysis of micro-reaction mechanisms and parametric research on the seesaw effect in an all-round way. Based on the verified model above, students adopt the control variable method to quantitatively analyze the influence laws of temperature (600–900°C), pressure and inlet gas ratio on system dual-mode voltage and current density, and verify the rationality of regarding the cell interior as a reactor close to chemical equilibrium. During this process, students deeply perceive the seesaw effect of operating parameters on power generation and electrolysis performance through simulation graphs.

3.5. Multi-objective optimization (weeks 14–16)

The fifth stage involves system boundary expansion and full-lifecycle multi-objective optimization. The project boundary is fully expanded from micro single cells to macro systems, constructing a full-process multi-energy coupling system integrating wind-solar power absorption, bidirectional RSOFC conversion, high-pressure hydrogen storage, SNG methanation, and gas pipeline transportation. Students independently design thermal management schemes containing multi-stage compressors and heat exchanger networks. Breaking the limitation of single software, students build a co-simulation control framework of Aspen Plus and MATLAB/Python, integrating techno-economic evaluation models covering investment, operation, and service life losses.

4. Conclusion

In summary, the curriculum construction closely follows the connotation of emerging engineering education, and successfully transforms cutting-edge scientific research achievements of RSOFC into an innovative carrier of advanced PBL project-based teaching. Through five standardized modules including discrimination of micro-reaction mechanisms, dual-mode full-process simulation, structural impedance correction, and system-level multi-objective joint optimization, the chronic drawbacks of fragmented knowledge and disconnection between theory and practice in traditional teaching are eliminated. Students realize the thinking leap from micro-electrochemical mechanisms to macro multi-energy coupling engineering decision-making under standardized scientific research training. This teaching mode featuring scientific research feeding teaching, tools empowering design, and multi-dimensional cross-innovation greatly improves the advancedness, innovativeness, and challenge degree of the course, providing a typical paradigm for the integration of teaching and research on high-temperature electrolysis and fuel cell systems. In the future, the teaching team will focus on the industrial application of renewable energy coupled green hydrogen systems, further expand system boundaries based on existing simulation achievements, strengthen advanced teaching on dynamic variable-condition operation optimization and multi-software co-simulation, and promote the in-depth integration of high-temperature water electrolysis technology and comprehensive energy systems.

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Disclosure statement

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