

# Integration, Innovation, and Empowerment: Exploring Teaching Reform Paths for Engineering Thermodynamics in the “Dual Carbon” Era

Yang Zhang, Shengnan Zhu, Yaping Zheng, Hongge Tao, Binglin Chen, Guizhuan Xu

Henan Agricultural University, Zhengzhou 450002, Henan, China

**Abstract:** *Against the backdrop of the global energy transition and technological revolution intertwined in the “Dual Carbon” era, the traditional Engineering Thermodynamics course faces multiple challenges such as outdated content, monotonous teaching models, and a disconnect between theory and engineering practice. Based on teaching reform practices from several leading universities, this paper systematically analyzes the core demands of the new era for talent cultivation in this field. It constructs a systematic path for teaching reform from four dimensions: “modernization of content and value guidance,” “intelligent and adaptive teaching modes,” “project-based and challenge-driven teaching methods,” and “collaborative and fully-integrated practical systems.” Research indicates that by deeply integrating cutting-edge technologies like artificial intelligence, building virtual-physical combined practice platforms, and implementing teaching models oriented toward authentic, complex engineering problems, students’ intrinsic motivation can be effectively stimulated. This cultivates their innovative thinking and practical ability to solve frontier energy science and engineering challenges, providing high-quality talent reserves to support the national energy strategic transition. The paper further explores the synergistic effects of these multidimensional reforms and their replicability, offering a comprehensive framework and actionable insights for the transformation of engineering foundational courses in the new era.*

**Keywords:** Engineering Thermodynamics, Teaching Reform, Adaptive Learning, Industry-Education Integration, Dual Carbon Strategy, Challenge-Based Learning.

## 1. Introduction: Remolding the Course Mission in an Era of Change

Engineering Thermodynamics, as a core foundational discipline in fields such as energy, power, aviation, and chemical engineering, provides the indispensable theoretical bedrock for understanding energy conversion, utilization, and optimization. Its principles govern the performance limits of engines, the efficiency of power plants, the design of refrigeration systems, and increasingly, the innovation of sustainable energy technologies. However, this venerable course, with its long history and rigorous classical framework, now finds itself at a critical crossroads amidst a profound global transformation. The convergence of two powerful trends—the urgent imperative for a sustainable energy future and the disruptive rise of digital intelligence—demands a fundamental re-evaluation of its educational mission and pedagogical approach.

The first driving force is the global consensus on addressing climate change, embodied in national “Dual Carbon” (Carbon Peak and Carbon Neutrality) goals. This strategic pivot is accelerating a seismic shift in energy systems toward green, low-carbon, distributed, and intelligent models. This is not merely an incremental change but a paradigm shift. Frontier areas like advanced thermal energy storage (e.g., phase change materials, high-temperature packed beds), multi-energy complementary systems, next-generation power cycles (e.g., supercritical CO<sub>2</sub> cycles), and waste heat recovery technologies are rapidly evolving. These are no longer niche topics but central to the future energy landscape. Traditional curricula, often focused on ideal cycles and steady-state analysis of fossil-fuel-based systems, risk becoming disconnected from these real-world technological currents, leaving graduates unprepared for the challenges ahead.

Simultaneously, the Fourth Industrial Revolution, spearheaded by breakthroughs in artificial intelligence, data science, and cyber-physical systems, is reshaping the nature of engineering work and problem-solving. Generative AI, in particular, has democratized access to information and basic code generation, fundamentally altering how knowledge is acquired, synthesized, and applied. The future engineer is no longer valued primarily for the ability to manually solve textbook problems but for the higher-order cognitive skills of critical thinking, complex system modeling, innovative design, and ethical decision-making. The ability to frame ill-defined problems, collaborate with intelligent tools, and iterate creative solutions is paramount.

Within this dual context, the inertia of traditional Engineering Thermodynamics teaching presents significant risks. A curriculum overly focused on “knowledge transmission” of century-old principles, delivered through passive lectures and standardized problem sets, fails to inspire or adequately equip students. The perceived “dryness” and abstract difficulty of concepts like entropy and exergy can lead to disengagement if not connected to compelling contemporary applications. Therefore, the course’s mission must be radically remolded from a “knowledge-centric” model to a “competency-and-innovation-centric” paradigm. Its new core mission should be threefold: First, to solidify the foundational understanding of irreversible thermodynamic laws and principles that remain timeless. Second, to develop the applied competency to leverage these principles, in concert with modern tools, to analyze, design, and optimize sustainable energy systems for the “Dual Carbon” future [1]. Third, and crucially, to cultivate the innovative mindset and systemic thinking needed to navigate technological uncertainty and contribute to breakthroughs. This tripartite mission necessitates a systemic, holistic reform encompassing

content, pedagogy, technology, and industry collaboration—a transformation this paper seeks to chart.

## 2. Core Reform Pathways: Multi-dimensional Integration and Innovation-Driven Approaches

The challenges outlined above are complex and interconnected, requiring a coherent, multi-pronged strategic response. Isolated adjustments to syllabus or the introduction of a few software tools are insufficient. Drawing upon pioneering practices from leading Chinese engineering universities, we synthesize and propose four deeply interwoven core reform pathways. These pathways are designed to act synergistically, creating a positive feedback loop that enhances student motivation, deepens learning, and builds career-relevant competencies.

### 2.1 Modernization of Content and Value Guidance: Building a Dynamic “Thermal Science+” Course Ecology

Updating teaching content is fundamental to maintaining a course’s vitality. Reform must first break the spatiotemporal limitations of textbook content, organically integrating disciplinary frontiers and national strategic needs into the knowledge system. This tripartite mission necessitates a systemic, holistic reform encompassing content, pedagogy, technology, and industry collaboration—a transformation this paper seeks to chart.

**Table 1:** Framework for Modernizing Content and Integrating Value Guidance

Dimension	Initiative	Objective
Content Update	Integrate frontier cases (e.g., Carnot Battery) with classical theory.	Connect fundamentals to cutting-edge applications.
Interdisciplinary Fusion	Build a “Thermal Science+” curriculum (e.g., AI, materials science).	Cultivate systemic, cross-disciplinary thinking.
Values Integration	Embed national projects & sustainability ethics into technical analysis.	Foster mission-driven innovation.

1) Embedding Frontier Technology Modules: When teaching classical thermodynamic cycles (e.g., the Rankine cycle), simultaneously introduce cutting-edge technology cases such as Organic Rankine Cycles (ORC) and Carnot Batteries used for waste heat recovery and renewable energy storage. For instance, Shanghai Jiao Tong University has incorporated a project on “Performance Analysis of Carnot Battery Power Generation Coupled with Flow Battery Storage” to guide students in exploring this frontier topic of thermal-electrical coupling [2].

2) Strengthening Interdisciplinary Perspectives: Actively integrate knowledge from adjacent fields such as artificial intelligence and materials science. China University of Petroleum (East China) has added courses like “Energy and Artificial Intelligence” and “Carbon Neutrality Technology” to its curriculum, constructing a “Thermal Science+” interdisciplinary course ecology [1].

3) Infusing Curriculum Ideology and Engineering Ethics: Combine knowledge transmission with value guidance. By

introducing “special case studies” originating from major national engineering needs, such as “oilfield water jacket heating furnaces,” or discussing the quantitative contribution of thermal system efficiency improvement to CO<sub>2</sub> emission reduction, students can naturally develop a sense of mission and responsibility to serve national strategies while contemplating engineering solutions.

### 2.2 Intelligent and Adaptive Teaching Modes: Constructing a New “HI+AI” Dual-Track Integrated Teaching Paradigm for Engineering Thermodynamics

Engineering Thermodynamics features abstract content and strong theoretical rigor. Artificial intelligence technology provides new tools to address teaching bottlenecks like “difficult concept comprehension” and “hard-to-imagine processes.” The key to reform lies in constructing a “HI (Human Intelligence) + AI (Artificial Intelligence)” dual-track integrated paradigm tailored to the subject’s characteristics [2] [3]. Its core division of labor and collaborative mechanism are shown in the table below:

**Table 2:** Core Division of Labor in the “HI+AI” Dual-Track Integrated Teaching Mode for Engineering Thermodynamics

Track	Core Function	Key Task
AI Track	Scaffolding & Simulation	Visualize concepts; Provide simulation sandbox; Offer adaptive tutoring.
HI (Teacher) Track	Mentoring & Challenge Design	Design open-ended projects; Facilitate critical dialogue; Guide research.
Synergy	“AI Supports – HI Guides”	AI handles computation; HI focuses on higher-order thinking and innovation.

The success of this model hinges on clearly defining and deeply integrating the responsibilities of HI and AI. AI acts as an “Intelligent Learning Companion,” efficiently training engineering intuition through generative animations that visualize processes like entropy increase or through interactive simulation sandboxes that allow students to freely adjust cycle parameters and instantly observe performance changes. This liberates teachers from repetitive Q&A and basic demonstrations. Teachers are elevated to “Critical Thinking Coaches” and “Challenge Designers,” focusing on designing open-ended projects such as “designing a renewable energy-coupled system for a data center.” They organize students to critically examine AI optimization results, questioning their physical essence and engineering-economic constraints, guiding students to complete the leap from “solving problems” to “defining and solving complex problems.” Together, they form a teaching enhancement cycle of “HI designs challenge → AI supports exploration → HI guides (sublimation),” jointly committed to cultivating students’ core competencies for the future.

### 2.3 Project-based and Challenge-driven Teaching Methods: From “Problem-Solving” to “Solving Complex Problems”

To transition students from being proficient problem-solvers to becoming effective problem-framers and solvers, the pedagogical core must shift toward experiential, inquiry-based learning. Project-Based Learning (PBL) and Challenge-Based Learning (CBL) are the principal vehicles for this shift [4].

**Table 3:** Framework for Project-based and Challenge-driven Teaching Reform

Aspect	Method	Focus
<b>Challenge Authenticity</b>	Adopt PBL/CBL with real-world problems.	Shift from problem-solving to problem-framing.
<b>Progression Design</b>	Sequence projects from foundational to open-ended.	Build competency progressively.
<b>Learning Culture</b>	Encourage iteration in a safe environment.	Cultivate innovative mindset and resilience.

1) **Introducing Real-World Challenges:** Transform actual technical challenges faced by enterprises into course projects or graduation design topics. For example, an undergraduate team from Dalian University of Technology directly tackled the thermodynamic challenges in high-performance manufacturing of aero-engine turbine disks. While overcoming the technical hurdles of “multi-medium high-speed jet partition controllable rapid cooling technology,” they deeply learned and applied knowledge from multiple courses like heat transfer and fluid mechanics, even discovering new applications of the Leidenfrost effect. China University of Petroleum (East China) implements a graduation design reform of “enterprises pose problems, teachers and students solve them, using real problems for authentic work.” [1]

2) **Constructing a Progressive Challenge Chain:** Design a series of projects ranging from basic to comprehensive. Professor Shi Lin from Tsinghua University has long emphasized training students’ ability to extract thermodynamic models from engineering problems through “major assignments.” Xi’an Jiaotong University emphasizes integrating research cases into teaching, guiding students to complete knowledge transfer and re-creation [5].

3) **Encouraging Exploration and Tolerating Failure:** In this process, teachers should create a safe environment for exploration, allowing students to experiment and learn from mistakes. The “deviation” in students’ thinking directions might itself be the seed of innovative thinking. The key is to guide students in establishing a complete engineering thinking loop: “posing questions - establishing models - analyzing solutions - verifying and optimizing.”

#### 2.4 Collaborative and Fully-integrated Practical System: Building a “Course-Practice-Education” Integrated Community

Theoretical and even simulated understanding must be grounded in tangible, hands-on experience. Building a seamless bridge between academia and industry practice is the final, critical pillar of reform.

**Table 4:** Framework for Collaborative and Fully-integrated Practical System Reform

Aspect	Platform & Structure	Goal
<b>Virtual-Physical Blend</b>	Use high-fidelity simulators for complex/high-risk systems.	Expand access and depth of practice.
<b>Capability Ladder</b>	Implement “Foundational → Specialized → Comprehensive → Innovative” stages.	Ensure coherent and progressive skill development.
<b>Ecosystem Collaboration</b>	Deepen ties with industry; promote inter-university & global links.	Align training with industry needs and broaden perspectives.

1) **Combining Virtual Simulation and Physical Experiments:**

Utilize virtual simulation technology to overcome the limitations of high-risk, high-cost experiments. The “Oilfield Combined Station Multi-energy Complementary Virtual Simulation Platform” independently developed by China University of Petroleum (East China) allows students to safely and cost-effectively practice the design and dispatch of complex energy systems in a virtual environment [1].

2) **Building a “Four-stage Progressive” Practice Chain:** Create a progressive ladder of “basic experiments → specialized experiments → comprehensive training → innovation projects.” At the highest level of innovation projects, directly connect with industrial needs. For example, the “Whole-process Engineering Problem Target-oriented Traction” model implemented by the Power Engineering and Engineering Thermophysics discipline at China University of Petroleum (East China) allows students to enter a research path centered on real projects from the start of their studies, ultimately producing convertible patents or technical solutions [6].

3) **Deepening Industry-Education Integration and Inter-university Collaboration:** Establish joint laboratories and future technology colleges with leading enterprises, and hire industry experts as mentors. Simultaneously, expand inter-university resource sharing and international cooperation, broadening students’ horizons through cross-university thesis defenses and international courses.

### 3. Teaching Reform Practice Cases and Effect Analysis

The aforementioned reform pathways have achieved preliminary results in the practices of several universities. Taking the “Engineering Thermodynamics” HI+AI course at Shanghai Jiao Tong University as an example, mid-term student feedback showed that 100% of students acknowledged the flexibility of the course learning and believed it helped them access research frontiers and obtain research guidance. The course achievement level slightly exceeded the expected target. More significant effects are reflected in student development: the course helped about one-third of the class secure research supervisors, and some students were selected for the “Bole Plan” talent cultivation program.

The “Three-Chain Integration” cultivation system at China University of Petroleum (East China) has resulted in a postgraduate advancement rate exceeding 50% for graduates, a 96% satisfaction rate from employers regarding graduates’ engineering practical abilities, and 76 national-level discipline competition awards in the past three years. The undergraduate team from Dalian University of Technology, while tackling aero-engine challenges, has published 10 papers in top journals such as the International Journal of Heat and Mass Transfer [7]. These data indicate that teaching reform oriented toward the demands of the times can effectively stimulate student potential and significantly enhance their innovation and practical abilities.

### 4. Reflection and Future Prospects

Despite notable achievements, challenges remain. First, the

misuse of AI tools may lead to mental laziness. For instance, Shanghai Jiao Tong University found logically incoherent AI-generated text in course projects. This necessitates placing greater emphasis on process assessment and originality checks in the evaluation system. Second, new demands are placed on teachers' capabilities, requiring them to possess a forward-looking academic vision, superb classroom guidance skills, emotional communication abilities, and a certain level of AI literacy.

In the future, the reform of Engineering Thermodynamics teaching should deepen in the following directions:

1) Deep Integration of AI: Develop more specialized and reliable discipline-specific AI tools, and further research the irreplaceable role of teachers in training innovative thinking.

2) Dynamic Curriculum System: Establish a mechanism for dynamic updating of course content synchronized with the development of energy science and technology, enabling rapid response to technological breakthroughs such as hydrogen energy and new energy storage.

3) Reform of Evaluation Systems: Construct multi-dimensional evaluation systems that go beyond standardized testing, placing greater emphasis on the assessment of project outcomes, innovation processes, teamwork, and complex problem-solving abilities.

4) Support for Teacher Development: Establish regular training and support systems for teachers to help them successfully complete their role transformation and adapt to the teaching requirements of the new era.

## 5. Conclusion

The teaching reform of the Engineering Thermodynamics course is an inevitable choice in response to the epochal themes of the "Dual Carbon" strategy and the technological revolution. The core logic of reform is shifting from "teaching-centered" to "learning-centered, ability-oriented, and education-rooted." By systematically integrating cutting-edge technology, intelligent tools, authentic engineering challenges, and collaborative education platforms into the entire course process, the vitality of the course can be reshaped. This integration not only allows the ancient theory of thermodynamics to shine with new brilliance in the new era but also cultivates future engineers and scientists possessing a sense of national purpose, a solid foundation, the courage to innovate, and practical wisdom. This lays a solid talent foundation for supporting the sustainable development of China's energy sector and achieving technological self-reliance.

## Acknowledgments

The present work was funded by Research and Practice of Higher Education Teaching Reform of Henan, China (2024SJGLX0269), Research and Practice Project on Undergraduate Education Teaching Reform (2025XJGLX191).

## References

- [1] Yang Zhengda, Lin Riyi, et al. Fostering the Sentiment of Serving the Nation through Energy and Cultivating Top-notch Innovative Talents [N]. China Education News, 2025-04-02(12).
- [2] Shanghai Jiao Tong University News Network. HI Mentor + AI Teacher: The Classroom Transformation of "Engineering Thermodynamics" for Adaptive Learning [EB/OL]. (2025-09-17).
- [3] Shanghai Jiao Tong University Teaching Development Center. Shanghai Jiao Tong University's "HI+AI Course" Selected for the National Smart Education Public Service Platform "Artificial Intelligence Test Field" [EB/OL]. (2025-03-30).
- [4] Science Education Journal. Exploration of the "Engineering Thermodynamics" Teaching Model Based on the "Challenge-Based Learning" Concept [J]. 2024(31).
- [5] Xi'an Jiaotong University News Network. Xi'an Jiaotong University Holds Teaching Seminar Luncheon on "Cultivating Students' Innovation Ability and Practice - Taking Engineering Thermodynamics as an Example" [EB/OL]. (2025-05-14).
- [6] Yan Junrong. Making Engineering Innovation Achievements "Visible, Usable, and Transformable" [N]. China Chemical Industry News, 2025-08-06.
- [7] China Youth Network. Dalian University of Technology Undergraduate Team "Challenges" Aero-engine Thermal Problems [EB/OL]. (2025-06-17).