



The Effectiveness of Practical Applications on Teaching Thermal Engineering

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Abstract: The integration of engineering thermodynamics education with emerging engineering applications plays a vital role in cultivating high-quality modern engineering professionals who can meet the demands of today's rapidly evolving technological landscape. However, traditional teaching methods continue to face significant challenges, particularly in bridging the gap between theoretical knowledge and practical applications. This study systematically reviewed the existing framework of thermodynamics education, identifying key problems within the teaching process, and subsequently designed an innovative reform plan that integrates advanced manufacturing cases and technology platforms. Through practical implementation at Beihang University, the study demonstrates that incorporating cutting-edge engineering technology into teaching significantly enhances students' interest in learning and their practical problem-solving abilities. The primary innovation of this study lies in the integration of interdisciplinary teaching resources into the thermodynamics classroom, proposing a scalable educational reform model. This model serves as a valuable reference for advancing international engineering education and addressing its pressing challenges.

Keywords: engineering thermodynamics; engineering application; teaching method; evaluative feedback; Beihang University

1. Introduction

In recent years, there has been a growing demand for energy due to exponential population growth and industrialization. Within this context, the importance of engineering thermodynamics cannot be overstated. This discipline focuses on the conversion and utilization of energy, elucidating the principles of energy conservation and thermal efficiency through the study of energy flow, transformation laws, and the interrelation between heat and work. Moreover, thermodynamics has wide-ranging applications in industries and daily life. The emergence of numerous innovative system designs (such as high-efficiency and low-consumption co-generation systems) [1-3] and advanced manufacturing methods (such as high-energy beams for extreme fabrication) [4-8] has facilitated societal progress.

The main purpose of this course is to enable students to master a comprehensive knowledge of thermodynamics and cultivate students' professional practice ability. However, there are obvious shortcomings in the traditional thermodynamics teaching methods. For example, there is a disconnect between theoretical teaching and practical engineering application, resulting in low learning interest of students [9]; Teachers use inefficient teaching methods [10]; Insufficient teaching resources hinder effective teaching [11]. Therefore, it is imperative to find innovative teaching methods that incorporate the latest engineering advances into thermodynamics teaching. In recent years, scholars and educators have proposed various effective teaching methods. For example, offline strategies such as practice-oriented, project-based and scenario-based teaching [12-14] significantly improves students' learning motivation. In addition, online platforms and simulation software [15-16] have also been integrated into thermodynamics classrooms, with positive results in both teaching and assessment. These innovative teaching initiatives continuously optimize the effectiveness of thermodynamics teaching.

Most of the current research focuses on the discussion of a single teaching method, and less attention is paid to how to systematically combine engineering cases, advanced technology and course teaching to form a teaching model that attaches equal importance to theory and practice. In addition, the existing literature has not fully solved the problems of slow updating of teaching resources and insufficient cultivation of students' practical ability. Therefore, the core issue of the research is: how to effectively integrate cutting-edge engineering technology into thermodynamics teaching through innovative methods, so as to cultivate students' interdisciplinary application ability and innovative thinking.

This paper of this study is to fill the research gap, and to design and implement a set of teaching reform of engineering thermodynamics course by introducing advanced engineering cases and manufacturing techniques. begins with a discussion

of the basic concepts, the latest applications, and the challenges faced in the engineering context of thermodynamics teaching. The concrete measures of thermodynamics teaching and evaluation are summarized, and the basic principles of course teaching are put forward. Finally, the reform measures and achievements of engineering thermodynamics course and teaching literature in Beihang University are systematically introduced. Not only discusses the key problems existing in traditional teaching, but also puts forward concrete solutions, which provides a new idea for engineering education.

2. Research problems and methods

2.1 Research problem

This study aims to answer the following specific questions through a literature review:

- (1) What are the main challenges and research gaps in the teaching of engineering thermodynamics?
- (2) Are the current teaching reform programs and methods effective in promoting students' practical ability and learning interest?
- (3) How can advanced engineering techniques be used in thermodynamics teaching to achieve an efficient combination of theory and practice?

2.2 Literature search strategies

This review employed the following search strategies to evaluate the most recent scientific evidence. To get relevant specific literature, search engines such as Google Scholar, Web of Science, ScienceDirect, MDPI, and CNKI are used. In the literature search process, the following keywords and their related variants were used to ensure that all relevant literature was covered: "Engineering Thermodynamics Education", "Innovative Teaching Methods", "Active Learning in Thermodynamics", "Simulation Tools for Thermodynamics", "Advanced Manufacturing in Education", "Challenges in Teaching Thermodynamics", "Student Engagement in Thermodynamics", "Emerging Engineering Fields in Education".

2.3 Inclusion and exclusion criteria

To ensure the scientific and relevant nature of the literature review, the following inclusion and exclusion criteria were developed, Inclusion criteria: (1) Research related to the education of engineering thermodynamics (focusing on teaching methods, student learning outcomes, or teaching tools), (2) Empirical studies involving cases of teaching reform (including innovative approaches such as experimental teaching or flipped classrooms), (3) Relevant research using advanced technologies (e.g. simulation tools, manufacturing techniques) or curriculum design, (4) Most of the papers were published within the last 5 years to ensure the timeliness of the study, (5) Published in peer-reviewed journals or international conferences. Exclusion criteria: (1) Research that does not involve teaching engineering thermodynamics (such as purely theoretical research or a non-engineering background), (2) Teaching research involving only primary and secondary schools or non-engineering disciplines. (3) Literature is not in English or Chinese (no translation provided). (4) This is a review discussion only, without empirical or case support.

2.4 Objectivity and consistency

To ensure objectivity and consistency in the literature inclusion/exclusion process, the following steps are taken:

- (1) Multi-investigator independent screening: Literature was screened by two researchers respectively, and the initial inclusion was determined according to the title and abstract.
- (2) Consistency check: Compare the screening results of the two researchers, discuss the literature with differences, and invite third-party researchers to arbitrate if necessary.

3. Literature review

3.1 Theoretical framework

The field of engineering thermodynamics explores the conservation and transformation of energy during its transfer processes. Its foundation lies in two fundamental laws of thermodynamics: the first law and the second law. The main content of thermodynamics is developed around the theoretical groundwork and engineering application [17]. Theoretical groundwork involves studying the fundamental characteristics of the working medium and thermal processes, while engineering application focuses on the design and analysis of various systems. Figure 1 provides a visual representation of these domains. Refer to Figure 2 for a visual representation of the interrelation between thermodynamic knowledge and its practical applications in engineering.

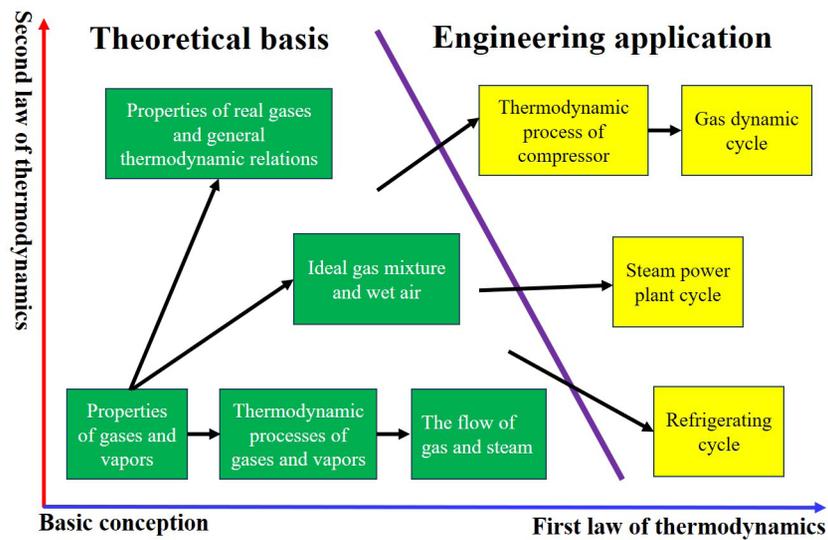


Figure 1. The content of the thermodynamics course

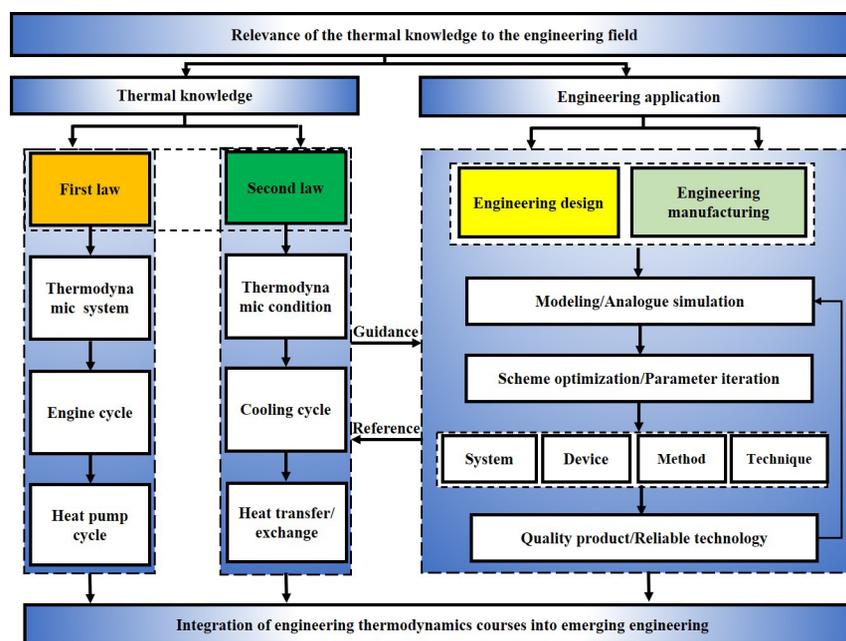


Figure 2. The connection between thermodynamic knowledge and engineering field

3.2 Advanced thermal engineering case

3.2.1 Engineering design

The principle of thermodynamics plays an important guiding role in the engineering design. This section highlights recent advancements in the utilization of thermodynamics in power systems, cooling systems, and thermal devices, and emphasizes the importance of incorporating these novel design concept into thermodynamics teaching.

Typical power systems include steam turbines, gas turbines, etc., which are designed based on thermodynamic cycle concepts like the Carnot, Rankine, and Brayton cycles, and are widely employed in areas such as power generation and energy-driven. Shan et al. [1] proposed TSRC, a thermodynamic model combining thermophotovoltaic (TPV) devices and steam Rankine cycle (SRC), improving fuel conversion efficiency (see Figure 3a). Zhang et al. [2] developed a power generation system based on the gas turbine and Kalina cycle, resulting in better thermal and exergy efficiency (see Figure 3b). Pirkandi et al. [18] introduced SOFC-GT-ST, an integrated system of gas turbines (GT), steam turbines (ST), and solid oxide fuel cell (SOFC), enhancing net power and efficiency (see Figure 3c). Huo et al. [3] presented a new type of combined cooling and power (CCP) system using solar energy and ocean thermal energy, which can achieve an exergy efficiency and

primary energy efficiency ratio of 11.94% and 9.99%, respectively (see Figure 3d).

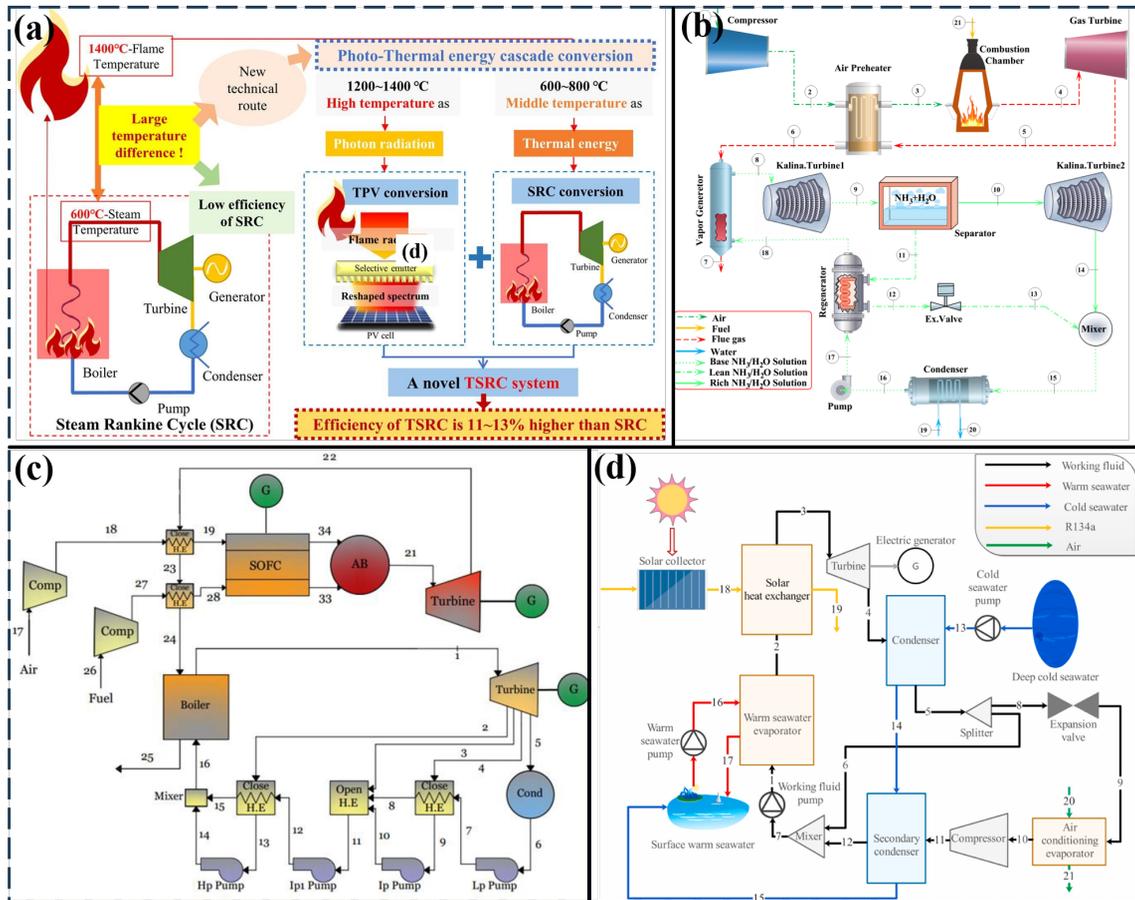


Figure 3. Case studies of advanced dynamical systems: (a) TSRC system; (b) Power generation system; (c) SOFC-GT-ST system; (d) CCP system

Different cooling systems, including cooling towers and refrigeration equipment, are commonly used in industrial cooling and home refrigeration applications. The design of these systems involve concepts such as evaporative cooling cycles and absorption cooling cycles. Mazumder et al. [19] (2023) developed an LNG (liquefied natural gas) manufacturing process that reduced energy consumption and improved efficiency (see Figure 4a). Ayoub et al. [20] designed a natural ventilation cooling tower model and evaluated the effect of extreme weather on cooling efficiency (see Figure 4b). Ruangtrakoon et al. [21] proposed a calculation method for steam ejectors and proved its high accuracy.

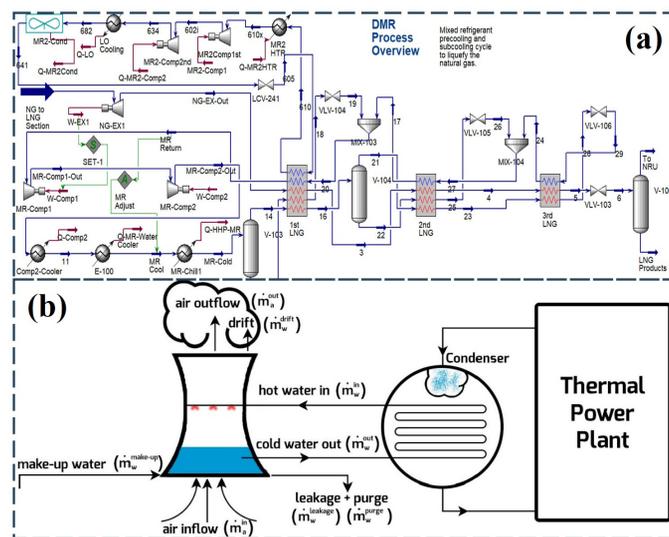


Figure 4. Case studies of advanced cooling system: (a) LNG system; (b) Cooling tower model

Typical thermal equipment include heat exchangers, evaporators, and boilers, which are designed based on thermodynamic principles such as conduction, convection, and radiation. These devices are primarily utilized in large-scale systems such as power plants. Lee et al. [22] designed a heat recovery boiler with water spray (HR-B/WS) with a 95% thermal efficiency under optimal conditions (see Figure 5a). Wang et al. [23] developed a helix finned tube heat exchanger that met cooling requirements for a superfluid helium cryogenic system (see Figure 5b). Deharkar et al. [24] introduced a detachable vertical tube evaporator with high heat transfer coefficient, efficiency, and cost-effectiveness.

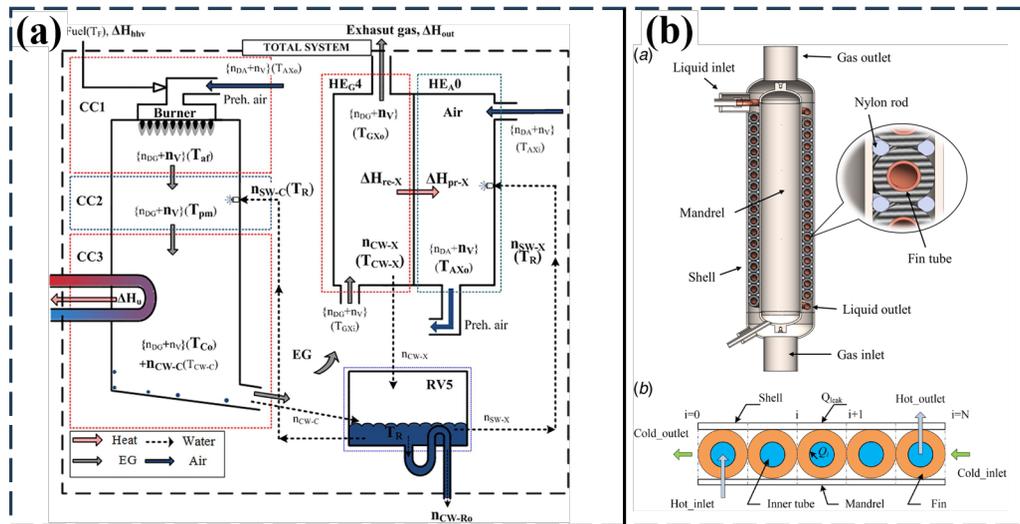


Figure 5. Case studies of advanced thermal apparatus: (a) HR-B/WS; (b) Helix finned tube heat exchanger

3.2.2 Engineering manufacturing

In recent years, the demand for high-end manufacturing has spawned the development of a series of new technologies. Taking the engineering application of emerging heat sources as an example, BLT uses laser additive technology to produce aerospace parts (see Figure 6a), Zenith Tecnica printing satellite parts uses electron beam melting (see Figure 6b), and AML 3D uses wire arc additive technology to produce mechanical parts (see Figure 6c).

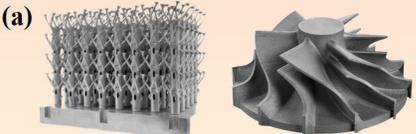
Emerging heat sources	Advantage (vs. traditional)	Product example
<p>Laser</p> 	<ul style="list-style-type: none"> High precision High applicability (Material, atmosphere, etc.) High efficiency 	<p>(a)</p> 
<p>Electron beam</p> 	<ul style="list-style-type: none"> Non-heat affected zone Vacuum processing (less pollution, High processing quality) High speed 	<p>(b)</p> 
<p>Plasma arc</p> 	<ul style="list-style-type: none"> Low-cost High material utilization High processing quality High applicability 	<p>(c)</p> 

Figure 6. Advantages and applications of emerging heat sources: (a) Full chamber support and impeller manufactured by laser; (b) Titanium satellite components manufactured by electron beams; (c) Pump ring and piston manufactured by wire arc

By integrating thermodynamic simulations into the manufacturing process, product performance can be effectively controlled and optimized. For example, in additive manufacturing, researchers have conducted proactive explorations related to emerging heat sources. Bock et al. [25] utilized a finite element model coupled with thermo-mechanical analysis to simulate temperature, residual stresses, and deformation in laser metal deposition additive manufacturing (see Figure 7a)

and Figure 7a2). Cui et al. [26] studied the solidification characteristics of AlCu5MnCdVA alloy and developed a transient heat transfer model to analyze the feasibility of using electron beam free forming (EBF3) for Al-Cu alloys (see Figure 7b1 and Figure 7b2). Li et al. [27] constructed a comprehensive model considering thermodynamic and electromagnetic effects in the arc and workpiece regions of plasma arc welding (see Figure 7c1 and Figure 7c2). This model enabled precise predictions of arc pressure and a better understanding of the keyhole phenomenon.

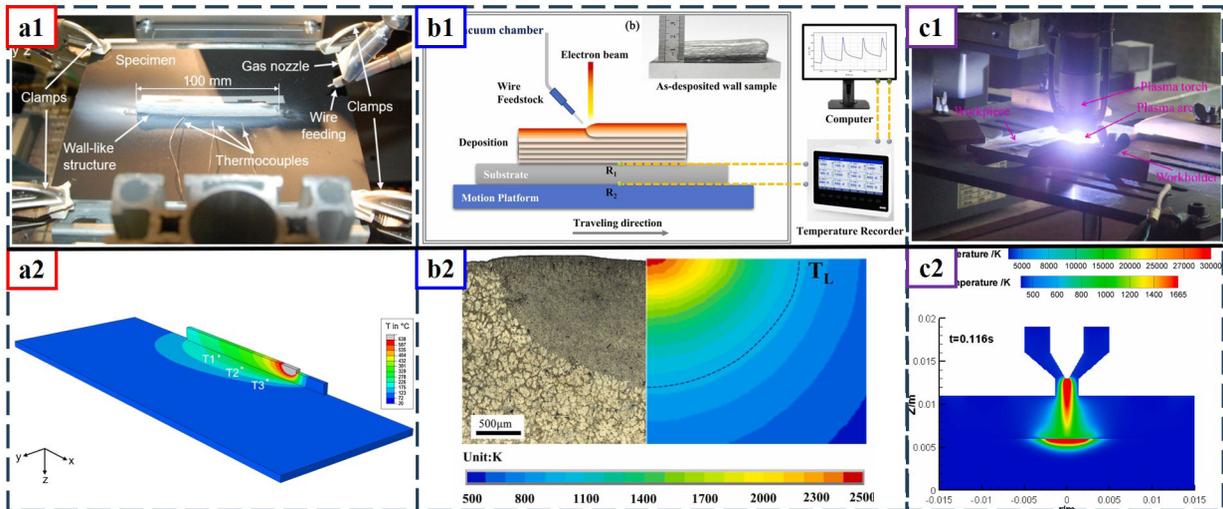


Figure 7. Thermal manufacturing and thermal simulation processes: (a1, a2) Laser; (b1, b2) Electron beam; (c1, c2) Plasma arc

3.3 Teaching challenge

In this section, we will explore the main challenges encountered by the three aspects (student, teacher, and resource) in teaching engineering thermodynamics (see Figure 8).

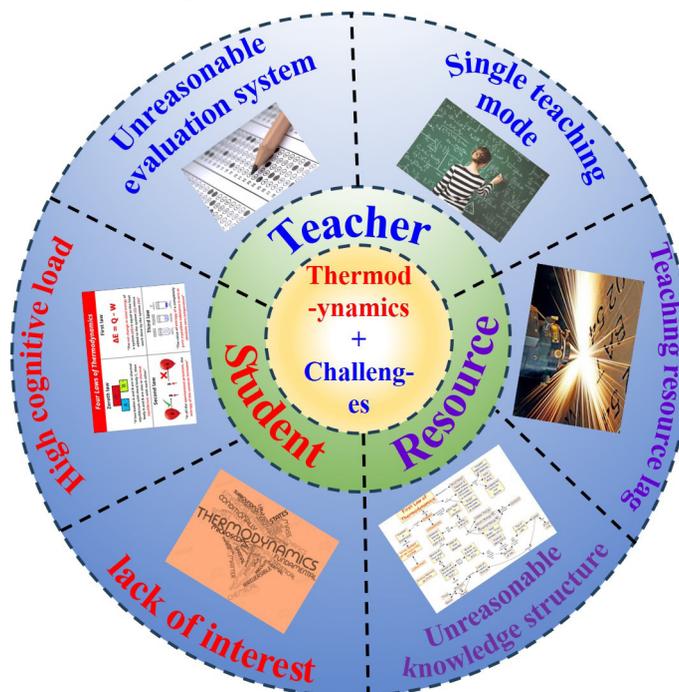


Figure 8. Current situation and challenges of thermodynamics teaching

3.3.1 Student level

Thermodynamics is a complex subject that involves abstract concepts and mathematical operations, where these concepts are deeply interconnected. Meltzer et al. [28] found that students face challenges in understanding fundamental

concepts such as heat, work, and cyclic processes, as well as the first and second laws of thermodynamics. Dukhan [29] highlighted several issues in students' learning of thermodynamics, including cognitive load, difficulty connecting theory with practical applications, and lack of structured pedagogy. Additionally, thermodynamic theory seems disconnected from real-world applications, which also results in low motivation for students to learn.

3.3.2 Teacher level

Costa [11] noted that many thermodynamics educators choose easily understandable resources to avoid the complexity of the teaching process but fail to encourage students to pursue deeper knowledge actively. Arnas [30] pointed out the lack of formal training for thermodynamics instructors, with teaching taking a backseat to research and limited funding. Due to various factors, many educators continue to use traditional teaching approaches, favoring cramming education and a single evaluation method. These approaches neglect the use of cutting-edge resources and advanced teaching concepts, fail to value timely student feedback, and rely solely on written exams to assess student performance. This type of teaching does not take into account the learning preferences of different students, which hinders students' understanding in thermodynamics.

3.3.3 Resource level

With the rapid advancement of science and technology, the knowledge of thermodynamics is constantly updated. Costa [11] suggests that optimizing teaching resources, such as comprehensive reference materials, efficient software tools, and engineering illustrations, can make thermodynamics more friendly, engaging, and interesting. This can motivate students to invest more time and effort into learning the subject deeply. However, most textbooks still focus on basic engineering applications and do not fully incorporate the latest advancements of thermodynamics. This creates a gap between theoretical understanding and practical application. Additionally, the lack of coherence among knowledge structures also makes it difficult for students to make clear connections between different topics, further increasing the difficulty of the learning process.

3.4 Teaching model analyses

3.4.1 Modern teaching methods

In the rapidly evolving field of education, it is crucial to optimize/reformulate teaching models in order to achieve efficient teaching. This section aims to explore contemporary teaching methods, including both offline strategy and cutting-edge technologies/tools.

3.4.1.1 Offline strategy

The offline teaching strategy emphasizes the active participation of students, creating a diverse and immersive learning environment that involves a range of offline activities. This approach helps cultivate students' creativity and cognitive abilities. In this section, we will elaborate on and analyze the offline methods used in thermodynamics education, focusing on three main aspects: research-based/situational teaching, integration and optimization of teaching resources, and innovative teaching modes (see Table 1).

Research-based and situational teaching methods focus on engaging students with real-world problems to apply their theoretical knowledge practically. Various international case studies show positive outcomes, such as an insulated container project that improved students' creativity and performance during COVID-19 [31], and mechanic students from a university improving their professional skills through hands-on experience at a power company. Innovative teaching techniques like using visual analogies [32] have facilitated learning complex concepts, and situational teaching method [33] has been proven to enhance students' learning interest and comprehension abilities more effectively than traditional methods.

Table 1. Summary of offline strategies for teaching thermodynamics

Strategy	Methods	Merits/Features
Research-based / Situational teaching	Practice-oriented Curriculum projectization Concept visualization Scene/Case teaching	High learning initiative Simplification of complex /abstract knowledge Thinking ability enhancement Facilitate understanding
Integration and optimization of teaching resources	Multi-disciplinary integration Knowledge-base construction Knowledge structure optimization Construction of teaching team	Cross complementarity Convenience and efficiency Facilitates knowledge linkages Teaching quality assurance Favors knowledge expansion
Innovative teaching mode/ idea	OBE PI PBL STS PCT FKCP CDIO C-PBL	Vividly and efficient High acceptability Scientific and practical Interactivity and motivation Advanced and instructive

Educational resources have been optimized by integrating principles of Gestalt psychology [34], creating shared knowledge repositories [35] like reusable learning objects (RLO), and developing cohesive knowledge frameworks [36], all contributing to improved learning outcomes. Through a three-stage teacher training mechanism consisting of preparation (independently completing the production of teaching materials and mastering the course system and content), practice (delivering knowledge points and advancing logical relationships), and summary (reviewing course issues and proposing improvement measures), it has been demonstrated to effectively enhance the teaching quality of educators [37].

Advanced teaching concepts have been suggested for thermodynamics teaching, including STS (Science education, technology education, and social education) education [38], Peer Instruction [39] for conceptual comprehension, Problem-based learning [40] for scientific skills training, CDIO (Design-Implement-Operate) for application-focus in engineering [41], Flipped classroom models [35] for increased class engagement, and Context-and Problem-Based Learning [42] for improving students' communication skills and self-assurance.

3.4.1.2 Cutting-edge technologies and tools

Amidst the rapidly advancing field of science and technology, modern education has placed significant importance on employing cutting-edge teaching techniques and tools. Figure 9 presents a timeline showcasing the platforms and simulation software utilized in the teaching of thermodynamics [15,16,43-68].

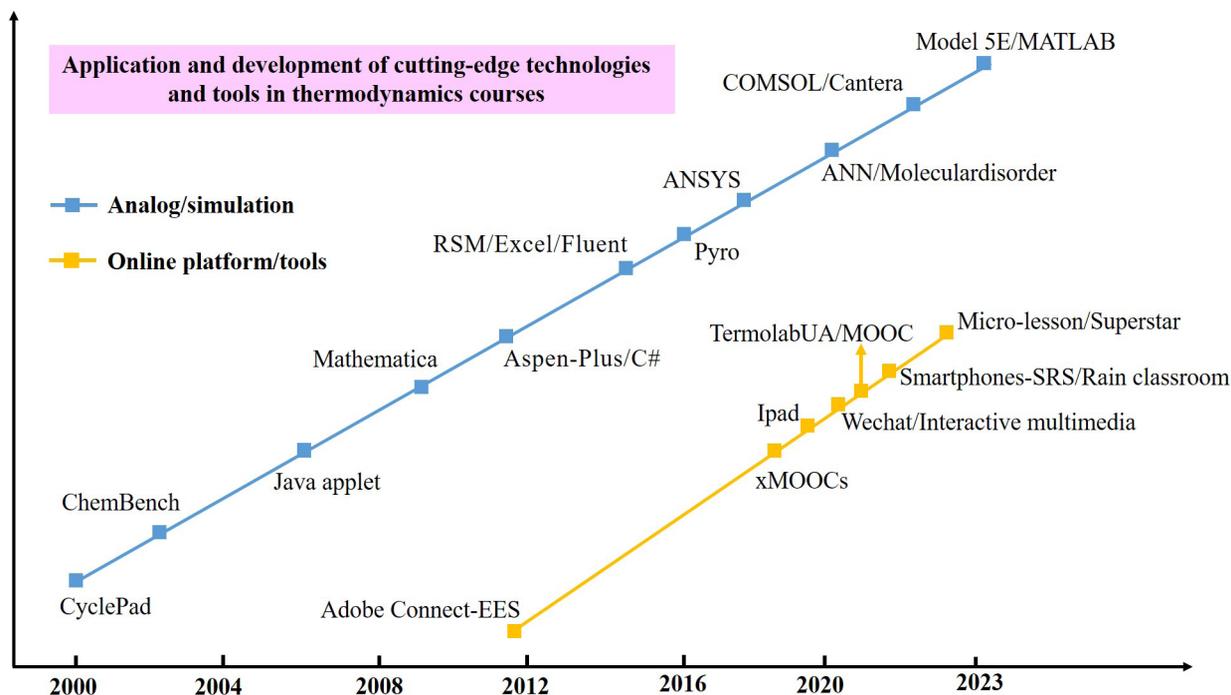


Figure 9. Timeline of platform/tools used for teaching thermodynamics

Online platforms have become essential in contemporary education, providing students with a convenient learning environment enriched with abundant resources. As depicted in Figure 9, the Adobe Connect-EES platform, introduced by Lopez in 2011, allows for efficient on-site teaching to both local and remote learners. Furthermore, the continuous advancement of science and technology has introduced portable devices such as iPads and smartphones, as well as chat platforms like WeChat, which have been utilized to enhance thermodynamics teaching. These tools are highly convenient and efficient in their usage. Moreover, the concept of resource sharing and interconnection has given rise to open online resource platforms including xMOOCs, TermolabUA, and MOOC, which have increasingly become the predominant methods for teaching thermodynamics. These approaches not only enhance students' higher-order thinking skills and enthusiasm for learning, but also receive widespread acclaim. Additionally, specific online teaching platforms like Rain Classroom, Superstar, and Interactive Multimedia have yielded favorable results in practical applications by significantly improving classroom interaction during the teaching process. A summary of the advantages and effectiveness demonstrated by these online platforms in teaching practices can be found in Table 2.

Table 2. Summary of teaching effectiveness of online platform

Online platform/tools	Implementation effect/advantage	Reference
Adobe Connect-EES	High convenience/versatile	Lopez et al., 2011
xMOOCs	Higher order thinking skill(>81.25)	Serevina et al., 2017
Ipad	High learning efficiency	Srinivasan et al., 2018
Wechat	High penetration rate (95%)	Xu et al., 2011
Interactive multimedia	High recognition (93.11%)	Wiyono et al., 2019
TermolabUA	High grades	Acevedo et al., 2020
MOOC	High pass rate (90%)	Li et al., 2020
Smartphones-SRS	High prediction accuracy($R^2=0.91$)	Caserta et al., 2021
Rain classroom	High attendance (97.16%), interaction rate (61.64)	Xue et al., 2021
Micro-lesson	Vividly/efficiently	Zhao et al., 2022
Superstar	High participation (98.7)	Dong et al., 2022

Table 3. Summary of simulation for teaching thermodynamics

Analog/simulation	Teaching content	Characteristic/Effect	Reference
CyclePad	Brayton cycle	Virtual laboratory	Bhattacharyya, 2000
ChemBench	Combustion explosion	Environmental simulation	Kirillov, 2002
Java applet	Equilibrium composition of ideal gases	Numerical simulation	Paolini et al., 2006
Mathematica	State equation /phase equilibrium	Numerical calculation	Luo et al., 2009
Aspen-Plus	Phase equilibrium of mixture	Process simulation	Chen et al., 2011
C#	Gas status/ thermodynamic properties/ thermodynamic cycles	Computer courseware	Liu, 2011
RSM	Membrane separation process	Experimental design	Khayet et al., 2015
Excel	Maxwell-Boltzmann distribution/ Isothermal process of an ideal gas	Model calculus	Grigore et al., 2015
Fluent	Thermal conductivity problem	Numerical solution	Pan, 2015
Pyro	Brayton cycle	Property calculator	Martin et al., 2016
ANSYS	Steady-state evaporation rate	Simulation experiment	Guanq et al., 2017
ANN	Specific enthalpy of steam	Training verification	Narendranath et al., 2020
MolecularDisorder	Enthalpy/entropy/energy transfer	Analogue simulation	Di Blasi et al., 2019
COMSOL	Plane heat source method with constant heat rate	Numerical simulation	Chen et al., 2021
Cantera	Combustion theory	Software library	Feng et al., 2021
Model 5E	Heat/temperature	Teaching & Evaluation	Zarate et al., 2023
MATLAB	Steam and gas power/vapor-compression refrigeration cycles	Numerical simulation	Dominguez et al., 2023

Simulation technology provides students with the opportunity to acquire knowledge and improve their skills in a virtual environment. In order to facilitate visualized instruction and numerical computation of abstract concepts, scholars have utilized prevalent programming languages such as Java, C#, and Python to develop various teaching models and courseware. Simulation software such as Fluent, ANSYS, COMSOL, MATLAB, Aspen-Plus, Excel, and Mathematica has been employed to teach thermodynamics visualization. Additionally, the integration of machine learning techniques like Artificial Neural Networks (ANN) and Response Surface Methodology (RSM) has propelled the optimization of thermodynamic experiments teaching within the classroom. To comprehensively evaluate teaching experiments, innovative schemes such as CyclePad, ChemBench, MolecularDisorder, and Model 5E are utilized. These initiatives have been successful in simplifying and visualizing the core curriculum content (see Table 3) of concepts/states/cycles/applications to students with good results. Table 3 summarizes what these simulations involve in teaching and their effectiveness.

3.4.2 Evaluation and feedback

Assessment and feedback are integral parts of the teaching and learning process and have a significant impact on student

learning and the improvement of teaching quality. This section aims to provide a comprehensive exploration of modern evaluation feedback techniques, including concrete operation and theoretical modeling.

3.4.2.1 Concrete operation

In recent years, educators and researchers have been actively exploring and experimenting with ways to enhance the evaluation system in thermodynamics. Reisel et al. [69] employed frequent testing to mitigate exam anxiety with little impact on learning. Ambiyar [70] applied the PAOR (planned-action-observation-reflection) method to optimize teaching, boosting student engagement and course satisfaction. Chen et al. [71] used classroom observation to identify issues and improve teaching strategies. Xu et al. [72] introduced the whole-process control strategy, which can track learning effects and improve learning efficiency. Orekhova et al. [73] applied the enhanced feedback model to online teaching, improving student performance and communication ability. Table 4 summarizes the evaluation indicators and final results of these different approaches.

Table 4. Summary of actual practices used for teaching evaluation

Concrete operation	Evaluation index	Implementation effect/Merits	Ref.
Frequent-quiz	Test score	The first cycle fails, the second cycle succeeds Improve academic performance	Reisel et al., 2013
Formative Evaluation	Knowledge quality, level of student proficiency, progress, average grade	Learning quality improvement Real-time interaction enhancement	Ambiyar, 2011
Classroom observation	Behavior statistics	Improve students' problem, evidence, Interpretation and communication skills	Chen et al., 2018
Entire process control	Basic knowledge, Professional quality and ability	Take control of student's learning results Cultivate students' innovation ability	Xu et al., 2019
Enhanced feedback	The results of the course final exam	Reduce students' test anxiety Prompt correction /consolidate of concepts	Orekhova et al., 2021

3.4.2.2 Theoretical model

The use of software models in assessing teaching effectiveness can result in unexpected outcomes. Xu et al. developed an AI model for objective grading, while Xu et al. [74] used SPSS for performance analysis, identifying factors crucial for student development. Yang et al. [75] adopted the AHP for precise evaluation of teaching reform effects. Additionally, Cai created a fuzzy comprehensive evaluation model based on entropy weight, emphasizing continual learning over final exams. Table 5 provides an analysis of the evaluation parameters and effects used in these different model approaches.

Table 5. Summary of theoretical model used for teaching evaluation

Theoretical model	Evaluation index	Implementation effect/Merits	Ref.
ANN	Student indicators	Scores are more evenly distributed High-efficiency/authenticity	Xu, 2012
Factor analysis	Professional ability, public curriculum ability, mathematical logic ability, physical and moral quality, historical and cultural literacy	High grades ≠ high comprehensive quality Scientificity/applicability/reasonability	Liu et al., 2013
Analytical Hierarchy	Written test score, Experiment and homework, Classroom Teaching, Online Course Usage	Steady improvement in teaching effectiveness High accuracy /objectivity /practicability	Yang et al., 2015
Entropy weight method	Final grade, attitude achievement	Reflect the students' real learning situation Simple process/easy calculation /results rationalize	Cai, 2018
Model 5E	Drawings and written descriptions of concepts	Realize the effective acquisition of knowledge and conceptual integration	Zhang et al., 2023

3.5 Instructional design principles

3.5.1 Diversified approach

Integrating online and offline resources to leverage the strengths of each approach proves beneficial in advancing teaching quality. For example, Zhang et al. [77] combined BOPPPS teaching concept (Bridge-in, Objective, Pre-assessment, Participatory Learning, Post-assessment, Summary) into both online and offline instruction. This comprehensive approach provides a multi-modal learning experience before, during, and after class, fully utilizing the advantages of digital tools and platforms. Consequently, it enhances students' motivation to learn and improves overall teaching quality.

3.5.2 Systematic thinking

Systems thinking encourages a holistic approach to acquiring knowledge in thermodynamics. It involves deducing unfamiliar ideas from existing knowledge, understanding the interconnections between various variables and causality within complex systems, and applying this knowledge in engineering practices [78]. This cognitive approach enables the seamless integration of learning, knowledge, and application, without strict reliance on rigid theoretical understanding. Figure 10 depicts the schematic representation of the systematic thinking structure in the process of thermodynamics teaching.

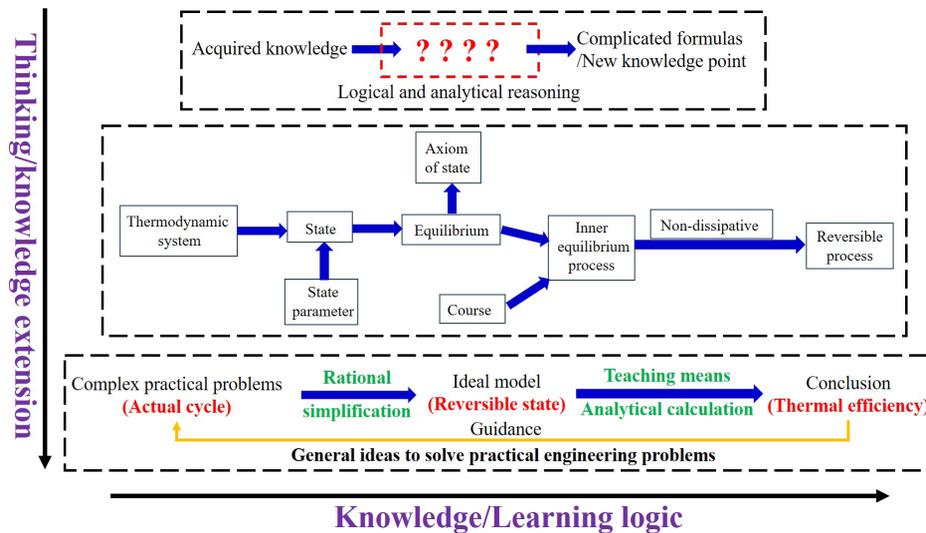


Figure 10. Illustration of systematic thinking in teaching thermodynamics

4. Engineering teaching practice in Beihang University

4.1 Engineering thermal manufacturing background

Beihang University is committed to promoting the development of engineering applications with advanced manufacturing technology, of which laser manufacturing technology has been extensively researched and applied. Laser manufacturing technology, renowned for its exceptional precision and efficiency, has become an important means of high-end manufacturing. Figure 11 illustrates the technology and application directions of lasers in additive, subtractive, and formative manufacturing, and summarizes the thermodynamic processes involved in laser processing. Below, we present the latest scientific research and industrial advancements in laser processing by Beihang University, as well as the successful integration of these research findings into the teaching of engineering thermodynamics.

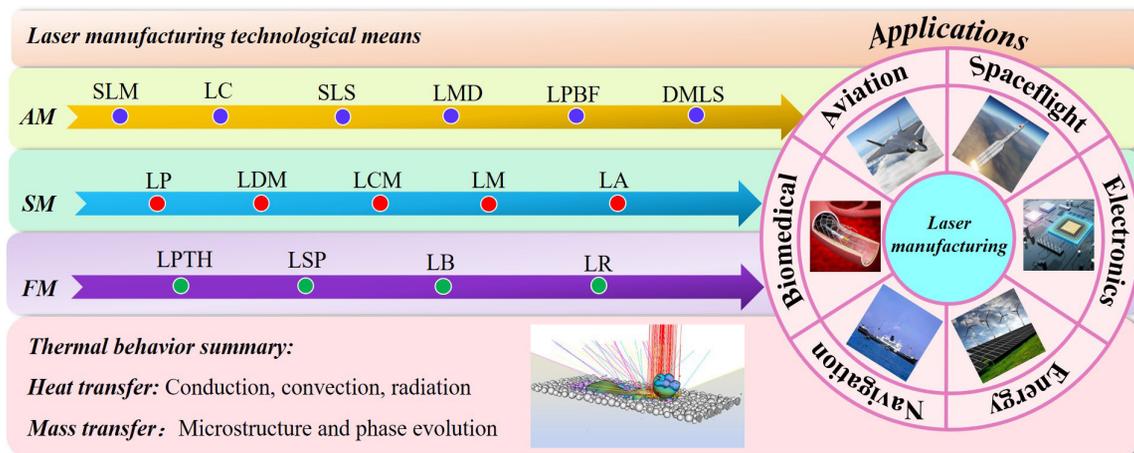


Figure 11. Technology, application and thermal behavior of laser manufacturing

Note: AM: Additive Manufacturing; SM: Subtractive Manufacturing; FM: Formative Manufacturing; SLM: selective laser melting; LC: laser cladding; SLS: Selective Laser Sintering; LMD: Laser Metal Deposition; LPBF: laser powder bed fusion; DMLS: Direct Metal Laser Sintering; LP: Laser polishing; LDM: Laser drilling method; LCM: Laser cutting method; LM: laser milling; LA: laser ablation; LPTH: laser phase transformation hardening; LSP: laser shock peening; LB: Laser bending; LR: laser remelting.

Numerous studies utilized numerical simulations for understanding the thermal behavior of various laser manufacturing processes. Liu et al. [4] used Fluent software to simulate weld morphology and temperature distribution (see Figure 12f), while Li et al. [5] investigated the thermal dynamics of laser polishing (see Figure 12g). They found correlations between thermal behavior, composition, and temperature gradient changes in the polishing layer. Additionally, Guo et al. [6] introduced an analytic model focusing on the thermal impact in Selective Laser Melting (SLM) parts, contributing to accurate predictions of the part's forming state (see Figure 12h). Arthanari et al. [7] assessed thermal behavior during the laser cladding process via finite element simulation and found relationships with the material's microstructure (see Figure 12i). Li et al. [8] conducted laser grinding on silicon sheets and explained the mechanisms under laser action (see Figure 12j). Refer to Table 6 for a summary of these studies, Figures 12(a-e) depict thermal processes involved in these methods, and Figures 12(k ~ o) depict commonly used analytical software in these simulations. Table 7 provides a comprehensive overview of the thermal simulation methodologies and software utilized in course [79].

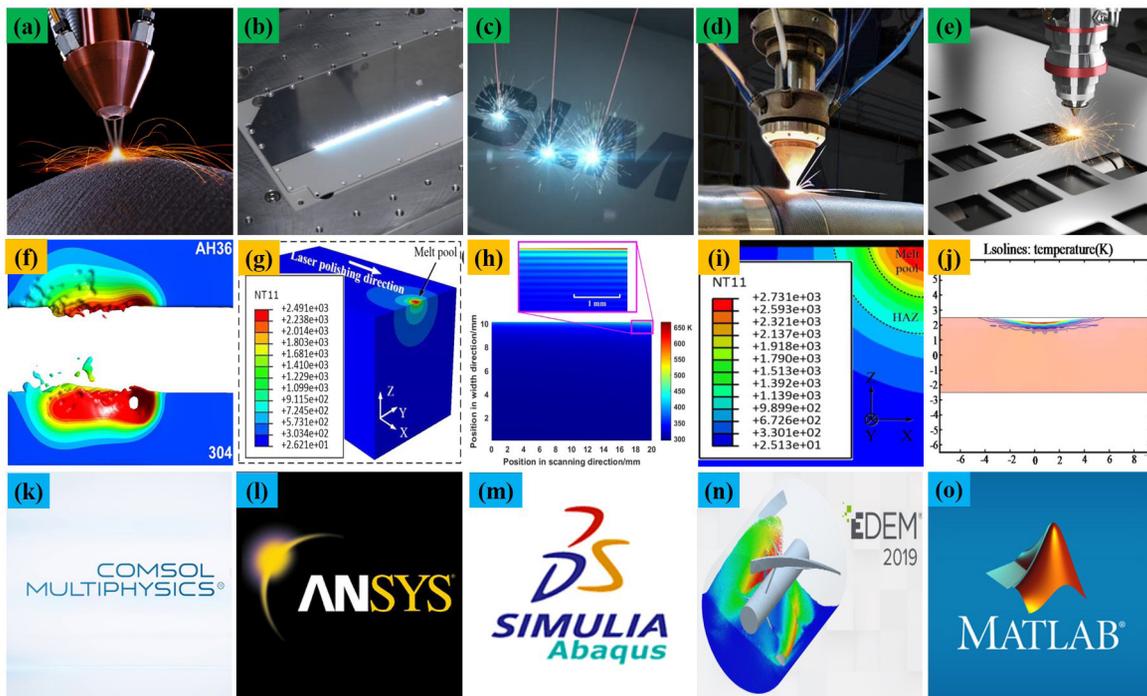


Figure 12. Laser manufacturing in Beihang University: (a ~ e) Illustration; (f ~ j) Thermal simulation process; (k ~ o) Simulation tools.

Table 6. Laser manufacturing research summary of Beihang University

Processing method	Base material	Model	Software/Simulation method	Output from simulation	Effect
Laser welding	AH36/ 304 steel	Part scale heat transfer and fluid flow model	Fluent (CFD)	Temperature field, velocity field	Molten pool/ element distribution
Laser polishing	Inconel 718	Part scale heat transfer model	ABAQUS (FEM)	Temperature field	Tissue/component interpretation
Selective laser melting (SLM)	Ti6Al4V/ SS316L	Part scale heat transfer model	ISM+ FEM	Temperature field	Finished product forecast
Laser cladding	Mg-Gd-Y-Zn-Zr alloy+Al-SiC	Part scale heat transfer model	ABAQUS (FEM)	Temperature field	Reaction/second phase analysis
Laser grinding	Single-crystal silicon	Part scale heat transfer model	ABAQUS (FEM)	Temperature field	Mechanism analysis

Based on advanced laser manufacturing methods, Beihang University has made a series of significant progress in the field of engineering. For example, Figure 13 shows the overall reinforced frame and window frame of the fuselage manufactured by Beihang research team, which has been successfully applied to the C-919 airplane. These real-world engineering applications are also incorporated into Beihang's engineering thermodynamics program, providing students with basic knowledge and stimulating their curiosity while guiding them to practical applications of what they have learned.

Table 7. Common thermal simulation methods and software

Simulation method	Description	Software/tool
FEM	Finite element method	COMSOL Multiphysics
FVM	Finite volume method	FLOW-3D FLUENT ANSYS
FDM	finite difference method	ProCAST
VOSET	A coupled volume-of-fluid and level set	MSC Marc
ALE	Arbitrary Lagrangian Eulerian	MATLAB
VOF	Volume of fluid	EDEM

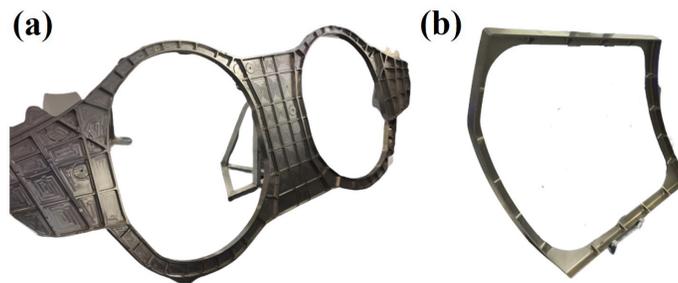


Figure 13. Key aircraft components produced based on laser additive manufacturing technology (a) overall fuselage reinforcement frame; (b) Window frames.

4.2 Optimization of teaching documents

4.2.1 Introduction chapter

The overall structure of the preface, found in the engineering thermodynamics textbook used at Beihang University, is visually depicted in Figure 14. It begins with the basic physical concepts of power, then delves into the origins of energy and introduces the background of the greenhouse effect to help students understand the purpose of the course. Building on this contextual knowledge, connecting essential thermodynamic concepts (such as heat engines and working mediums) with applications in thermal power generation systems, material processing, and material forming. Finally, the first and second laws of thermodynamics are introduced, starting with the concept of perpetual motion machines.

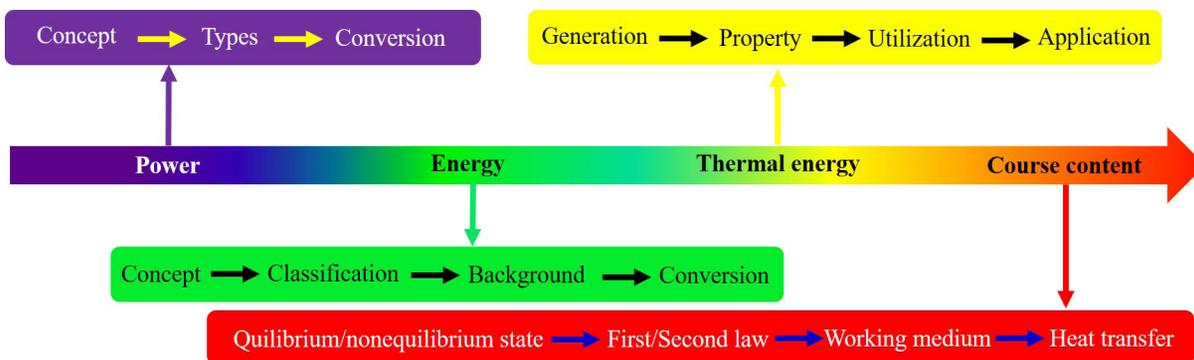


Figure 14. The overall logic of the introduction chapter

4.2.2 Knowledge structure

Figure 15 provides the knowledge structure of the textbook of Beihang University. The textbook begins by focusing on fundamental concepts, followed by an analysis of thermodynamic processes and properties of the working medium based on the two laws of thermodynamics. It then delves into the theory of thermal cycles and associated devices, and concludes with the theory and application of heat transfer. In comparison to Shen Weidao's [80] engineering thermodynamics textbook, the Beihang University textbook consolidates the content related to common working substances (such as ideal gas, actual gas, steam, and moist air) into a single chapter. This facilitates concentrated comparative learning and added the content of heat transfer. In comparison to Engel' [81] textbook "Thermodynamics: An Engineering Approach", this book achieves a streamlined knowledge hierarchy by summarizing detailed concepts into concise sections, maintaining interrelatedness among concepts, and retaining the core chapters of thermodynamics, thereby reducing students' overall cognitive load.

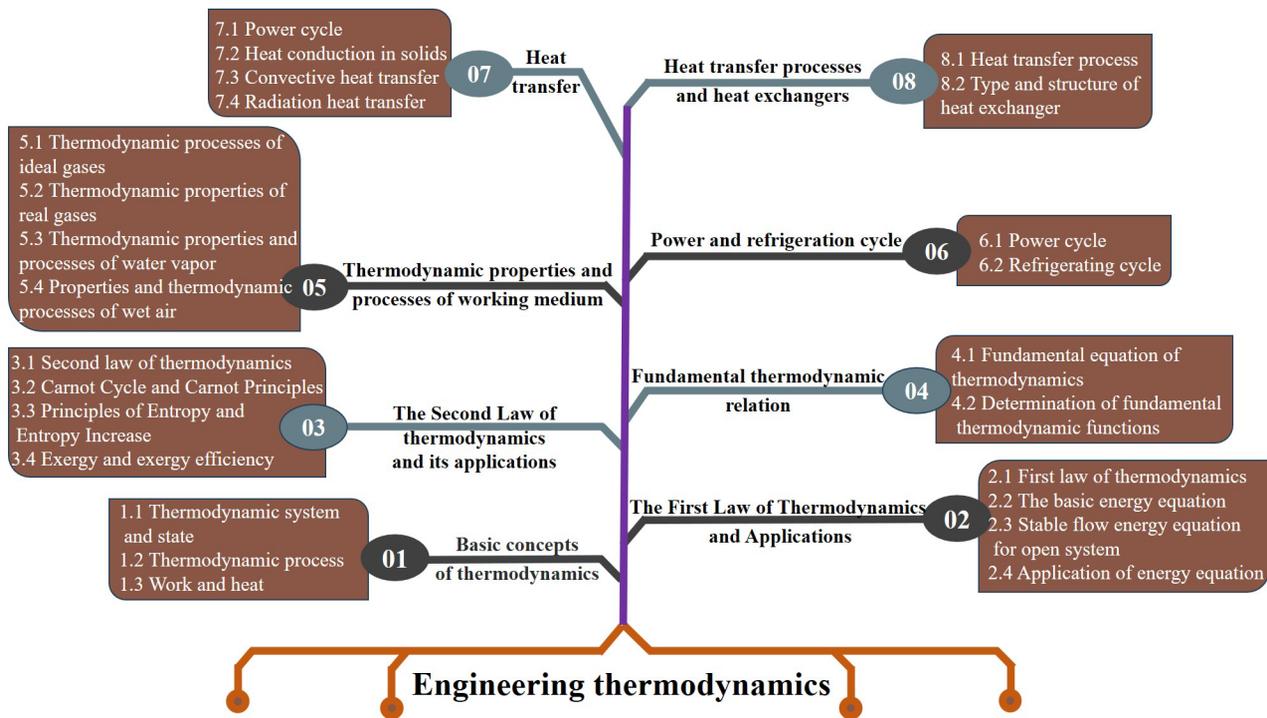


Figure 15. Knowledge structure of engineering thermodynamics textbooks in Beihang University

4.2.3 Engineering orientation

The main objective of Beihang University in teaching engineering thermodynamics is to simplify and visually present complex concepts, guiding students in efficiently grasping fundamental knowledge. For instance, the textbook employs diagrammatic representations to elucidate the first law of thermodynamics (see Figure 16a) and the second law of thermodynamics (see Figure 16b), thereby simplifying perplexing terms such as "system," "boundary," and "reversible process." Additionally, the textbook includes illustrations of specific thermodynamic devices (see Figures 16c and 16d) and thermal processes (see Figure 16f), allowing students to grasp intuitively their actual operational mechanisms and applications.

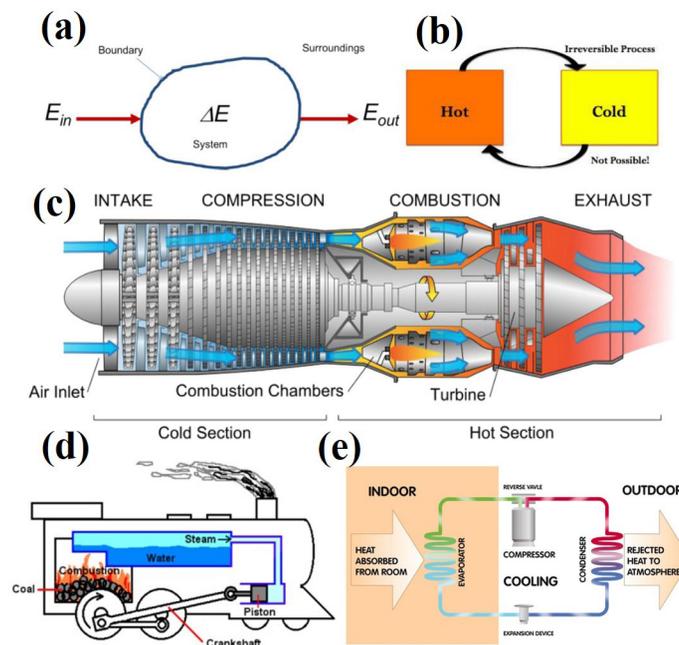


Figure 16. Illustrations from the engineering thermodynamics textbook of Beijing University: (a) The first law of thermodynamics; (b) The second law of thermodynamics; (c) Gas power system; (d) Steam power system; (e) Refrigerating cycle

4.2.4 Knowledge consolidation/expansion

The textbooks authored by Beihang University present a wide range of high-quality inquiries and exercises in each chapter. These content cover various aspects of conceptual understanding, literature research, and engineering design. For example, the first chapter of the textbooks includes ten thought-provoking questions and seven practical exercises, each with its own distinct focus. These patterns of inquiry include: 1. Conceptual interpretation: students are encouraged to explain concepts such as equilibrium state and state parameters in their own words, demonstrating their understanding of the subject matter. 2. Summary and analysis: students are prompted to elucidate the relationship between positive and reverse cycles, as well as the relationship between heat and work, highlighting the interconnectedness of these concepts. 3. Research and summary: students are tasked with comprehending the four fundamental thermal processes and grasping their significance within the realm of research and engineering. These questions not only improve students' ability to summarize, analyze, and draw conclusions but also foster divergent thinking by building their knowledge framework.

4.3 Advanced teaching concept

The following passage explores the innovative teaching and assessment methods implemented by Beihang University throughout the instructional process. The specific details can be found in Figure 17.

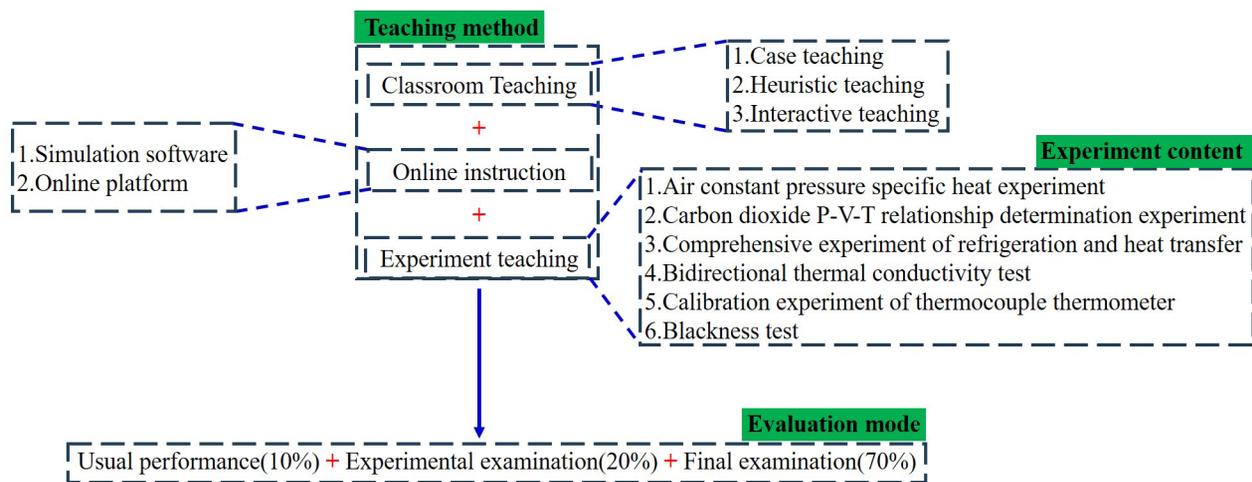


Figure 17. Teaching and evaluation methods of engineering thermodynamics in Beihang University

4.3.1 Multiple teaching methods

Beihang University actively promotes engineering thermodynamics education and has developed a series of effective teaching strategies. Taking the example of heat transfer instruction, it involves three distinct phases: pre-class, in-class, and post-class.

1. Pre-class: Before the class sessions, teachers promote students' understanding of the basic concepts of heat and their practical applications through sharing engineering-themed content. Examples include visualizations of temperature fields (Figure 18a), mitigation of thermal radiation and its applications in aerospace (Figure 18b). Additionally, online learning resources and pre-class Q&A sessions are provided to facilitate effective course previews.

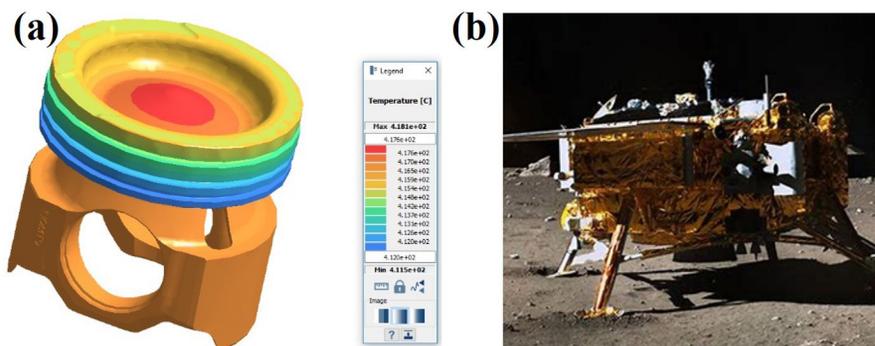


Figure 18. (a) Conceptual diagram of temperature fields; (b) Thermal radiation protection measures

2. In-class: (1) Classroom instruction: In contrast to traditional memorization-based learning, teachers employ methods such as case studies, inspiration, and interaction to facilitate teaching. When studying the chapter on heat transfer, different modes of heat transfer are initially presented visually (Figure 19a), followed by a detailed examination of heat transfer processes in laser-material interaction as an example, deepening students' understanding of thermodynamic concepts such as conduction, convection, and radiation. Finally, group discussions and explorations into everyday heat transfer phenomena are conducted, providing thermodynamic explanations and employing relevant mathematical models for problem-solving.

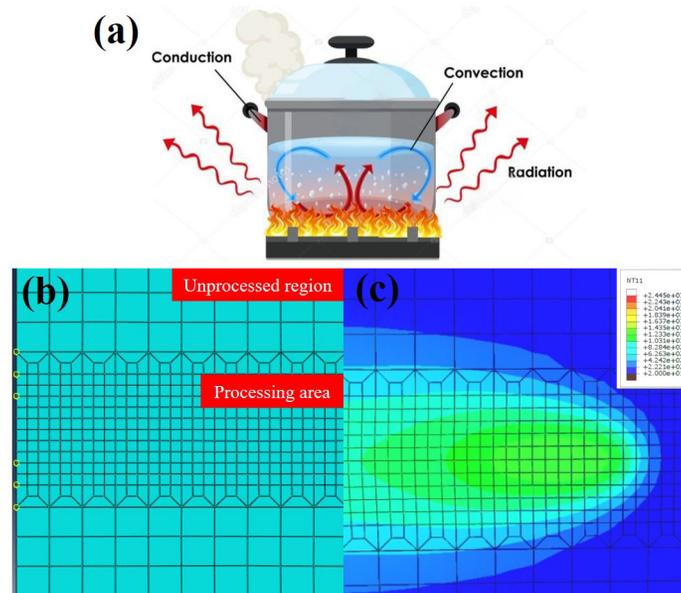


Figure 19. (a) Modes of heat transfer; (b) Laser processing area; (c) Thermodynamic simulation of laser processing

(2) Online instruction: Visualization technologies aid students in grasping complex and abstract concepts, bridging theoretical knowledge with practical applications. Figures 19b and 19c illustrate the use of ABAQUS software to simulate temperature field distributions during laser-material interaction, enhancing students' intuitive understanding of heat transfer phenomena. Additionally, high-quality online platforms like Rain Class are utilized for real-time online assessments, teacher-student interactions, and distance learning.

(3) Experimental instruction: Aligning with course objectives, six core experiments (refer to Figure 17 for details) have been carefully selected to enhance students' hands-on capabilities and cultivate essential skills for future engineering practice. In addition, relying on the advantages of Beihang research platform, manufacturing processes under extreme conditions (nanosecond laser polishing of alloy parts, laser welding of heterogeneous materials, etc.) will be demonstrated to students to help them get closer to and understand cutting-edge engineering research.

3. Post-class: On the basis of exercises after class, students are encouraged to independently analyze engineering cases. This involves simulations of thermal processes under extreme conditions using specialized software. Additionally, students are motivated to actively participate in scientific research projects and competitions, promoting a deeper understanding and practical application of thermodynamic knowledge within the realm of scientific.

4.3.2 Multidimensional evaluation system

Beihang University adopts a comprehensive approach to assess its curriculum, aiming to accurately evaluate students' mastery of knowledge. This evaluation process comprises three main components: usual performance (10%), experimental examination (20%), and final examination (70%). usual performance assessment includes classroom participation, task completion, and cognitive expansion. The experimental examination focus on pre-preparation, completion of the lab, and the quality of the lab report. The final examination sets the difficulty level in a gradient manner based on the learning objectives, and includes thermodynamics questions in an engineering context to comprehensively assess students' understanding and mastery of the core knowledge in thermodynamics course. This multidimensional assessment method enables an integrated evaluation of students' knowledge and abilities, and provides an overall assessment of their performance through an engineering-oriented approach.

4.4 Effectiveness of Teaching Reform

To evaluate the effects of the thermodynamics course reform at Beihang University, a mixed-methods approach was

adopted to gather data from multiple sources. The primary data included feedback from 31 students collected via a structured questionnaire, supplemented by semi-structured interviews with 5 students and 3 instructors. Classroom observations were also conducted to assess student engagement and instructor performance. This multi-source data collection strategy ensured a comprehensive evaluation of the reform outcomes.

The questionnaire was designed to evaluate four areas: knowledge mastery, teaching effectiveness, skill training, and overall satisfaction. As shown in Figure 20a, the majority of students reported a significant improvement in acquiring knowledge and applying it to engineering applications. This feedback suggests that integrating real-world engineering cases and advanced manufacturing technologies into the curriculum has helped students better understand theoretical concepts and apply them in practice. However, the potential for self-report bias and social desirability bias in these results cannot be ignored, as students might have overstated their learning outcomes. To mitigate this issue, qualitative data from interviews revealed additional insights. For example, one student commented, “The inclusion of advanced engineering applications, such as simulations of thermal systems, has made learning more practical and engaging.”

In Figure 20b, students evaluated the overall teaching effectiveness. A high percentage of participants acknowledged that the course content was comprehensive, covering the historical foundations of thermodynamics, current advancements, and emerging applications in engineering fields. This was further supported by the integration of representative case studies, such as innovative thermal systems and cutting-edge technologies, which broadened students’ perspectives. Nonetheless, some students expressed difficulties in keeping up with the course’s rapid pace, especially when tackling advanced simulation-based tasks without adequate preparation.

As depicted in Figure 20c, the thermodynamics course significantly enhanced students’ practical abilities, including information retrieval, communication skills, and generalization capabilities. For instance, students were required to independently analyze engineering problems, conduct simulations, and present their findings in group discussions. Classroom observations confirmed these improvements, with instructors noting increased collaboration and active participation during problem-solving activities. However, some students struggled with advanced computational tools, highlighting the need for additional training in simulation software as part of the curriculum.

Finally, Figure 20d presents the overall student satisfaction with the course. The majority of students rated the course highly, emphasizing its relevance to modern engineering challenges and its innovative teaching methods. They particularly appreciated the balanced approach between theoretical instruction and practical applications. However, a few students suggested that more structured pre-class materials and additional guidance on simulation tools could further enhance their learning experience.

Compared with similar courses at other universities, the thermodynamics course at Beihang stands out in systematically integrating interdisciplinary resources and advanced technologies. While this approach offers significant benefits, it also poses challenges for scalability in institutions with limited technological resources. Therefore, the reform’s broader applicability requires careful adaptation to different educational contexts.

Table 8. Questionnaire on the evaluation of engineering thermodynamics teaching effect

Question types	Number	Question description
Knowledge mastery	1	I am familiar with the thermal phenomenon in mechanical engineering and the basic law of the mutual conversion of thermal energy and mechanical energy
	2	I have mastered the basic laws of engineering thermal cycle and application
	3	I have mastered the principles and basic laws of heat transfer and their analytical methods
	4	I have mastered the ability to comprehensively analyze and solve practical thermal problems in engineering
	5	The course content can reflect the development status, history and frontier of engineering thermal science
Teaching effect evaluation	6	The content of the course can reflect classic and cutting-edge cases, which will help improve the ability of analyzing and solving problems
	7	The content of the course is rich, the main points are clear, and the data forms are diverse
	8	The course assessment standard is scientific and the homework time is reasonable
	9	The teachers are responsible for the course teaching, and their teaching attitude is serious
	10	The instructor can publish the information about the course in a timely and accurate manner
	11	The instructor is able to guide the class question and answer, which helps to increase interest in learning
	12	In the course of teaching, teachers will guide ideological and political teaching, which is helpful to establish a correct career view

Question types	Number	Question description
Ability training	13	I will use the library, bilibili and other channels for independent learning
	14	Through the study of this course, I have improved my communication and oral expression skills, as well as my ability to search and organize materials
General evaluation	15	The study of this course has satisfied my expectation of the overall classroom teaching effect

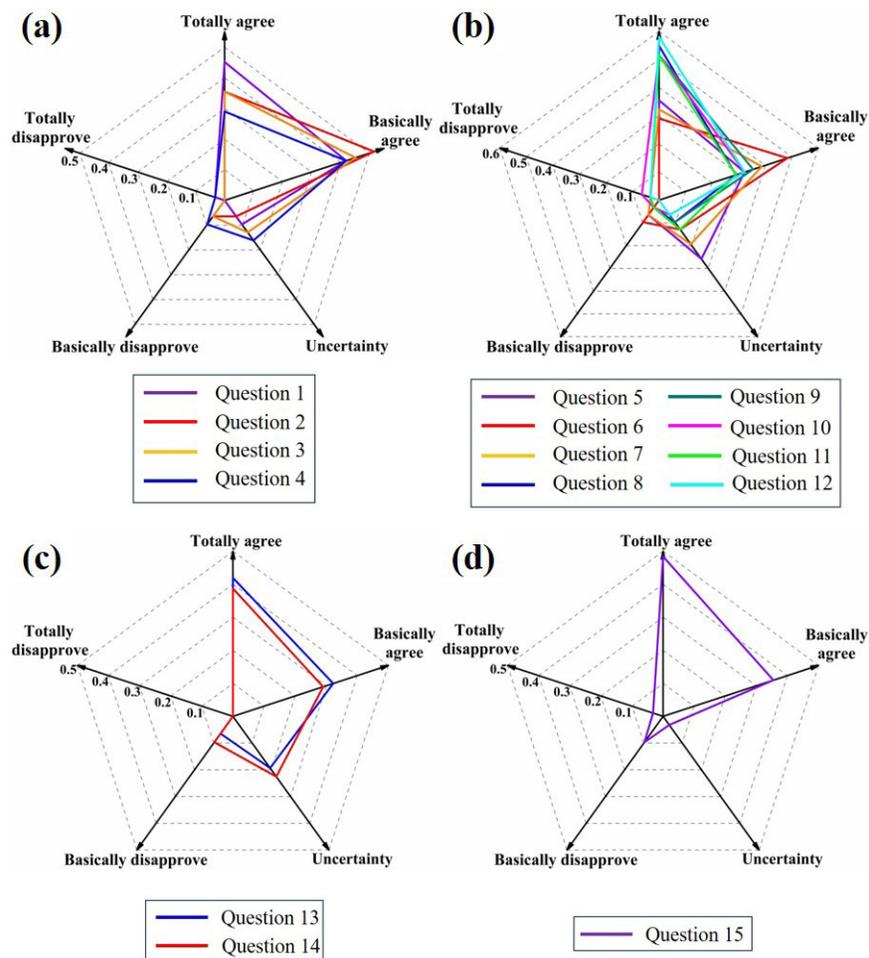


Figure 20. Results of the engineering thermodynamics course survey: (a) Knowledge mastery; (b) Teaching effect evaluation; (c) Ability training; (d) General evaluation.

5. Conclusion

It is important to integrate engineering applications into the teaching of thermodynamics. With the continuous advancement of technology, numerous innovative system devices and high-end manufacturing technologies have emerged. However, incorporating these new knowledge and technologies into textbooks and classrooms presents a significant challenge. This article provides a summary of recent teaching practices, which can be categorized into two approaches: offline strategies and cutting-edge technology application. Offline schemes, such as experiments and projects, stimulate students' enthusiasm and encourage interaction. On the other hand, the utilization of cutting-edge technologies helps students grasp and apply knowledge in a more intuitive and efficient manner. Evaluation and feedback strategies prioritize comprehensiveness and practicality, achieved through concrete operation and theoretical models. The implementation of various cases demonstrates the necessity of systematic thinking and diversified methods in practical thermodynamics teaching design. Furthermore, the educational reform in thermodynamics at Beihang University offers novel approaches, such as integrating high-quality resources and advanced manufacturing technology into thermodynamics teaching materials and curricula, as well as adopting innovative teaching concepts and methods. This integration facilitates the creation of high-quality classrooms, building upon

these teaching practices.

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Statements and Declarations

Competing Interests: The authors state that they have no known competing financial interests or personal relationships that would appear to influence the work reported in this article.

References

- [1] Shan, S.Q., Chen, B.H., Tian, J.L., et al. (2022) Improving the performance of steam power cycle through thermo-photovoltaic device: a novel combined system and thermodynamic analysis. *Energy Conversion and Management*, 269, 116139.
- [2] Zhang, B., Chen, Y.X., Wang, Z.G., et al. (2020) Thermodynamic, environmental, and optimization of a new power generation system driven by a gas turbine cycle. *Energy Reports*, 6, 2531–2548.
- [3] Huo, E., Chen, W., Deng, Z., et al. (2023) Thermodynamic analysis and optimization of a combined cooling and power system using ocean thermal energy and solar energy. *Energy*, 278, 127956.
- [4] Liu, F.Y., Zhou, X.H., Chen, X., et al. (2022) Melt flowing behaviors and microstructure evolution during laser offset welding of dissimilar metals between AH36 and 304 steels. *Optics and Laser Technology*, 151, 108024.
- [5] Li, Y.H., Zhang, Z., Guan, Y.C. (2020) Thermodynamics analysis and rapid solidification of laser polished Inconel 718 by selective laser melting. *Applied Surface Science*, 511, 145423.
- [6] Guo, K., Huang, Z.C., Tu, Y.Q., et al. (2023) Improved inherent strain extraction algorithm based analytical surface modeling for Ti-6Al-4V and SS316L selective laser melting part. *Journal of Manufacturing Processes*, 101, 618–638.
- [7] Arthanari, S., Li, Y.H., Nie, L., et al. (2020) Microstructural evolution and properties analysis of laser surface melted and Al/SiC clad magnesium-rare earth alloys. *Journal of Alloys and Compounds*, 848, 156598.
- [8] Li, X.X., Wang, Y.M., Guan, Y.C. (2021) Laser grinding of single-crystal silicon wafer for surface finishing and electrical properties. *Micromachines*, 12(3), 262.
- [9] Karimi, A. (2008) Challenges in teaching applied thermodynamics. In: *ASME International Mechanical Engineering Congress and Exposition* (ed ASME), Vol. 48708.
- [10] Gamez Leal, R., Jurado Pineda, M. (2019) Strategies to face some difficulties in the teaching-learning process of engineering thermodynamics. In: *ICERI2019 Proceedings* (ed ICERI), 4789–4796.
- [11] Costa, V.A.F. (2018) Some considerations and reflections on engineering thermodynamics teaching and learning. In: *2018 3rd International Conference of the Portuguese Society for Engineering Education (CISPÉE)* (ed CISPÉE), 1–8.
- [12] Wang, C.Y., Hou, C.H. (2012) Teaching differentials in thermodynamics using spatial visualization. *Journal of Chemical Education*, 89(12), 1522–1525.
- [13] Trivett, A. (2014) An attempt to gamify a first course in thermodynamics. In: *2014 ASEE Annual Conference & Exposition* (ed ASEE), Paper ID #8996.
- [14] Wright, K. (2020) Collaborative projects with simulation assignments in mechanical engineering thermodynamics courses. *International Journal of Mechanical Engineering Education*, 48(2), 140–161.
- [15] Acevedo, J.G., Ochoa, G.V., Obregon, L.G. (2020) Development of a new educational package based on e-learning to study engineering thermodynamics process: combustion, energy and entropy analysis. *Heliyon*, 6(6), e04094.
- [16] Dominguez, J.C., Lorenzo, D., Garcia, J., et al. (2023) Matlab applications for teaching applied thermodynamics: thermodynamic cycles. *Computer Applications in Engineering Education*, 31(4), 900–915.
- [17] Cao, R., Deng, X.S. (2015) The whole process of engineering thermodynamics teaching design reform (in Chinese). *Industrial & Science Tribune*, 14(01), 204–206.
- [18] Pirkandi, J., Penhani, H., Maroufi, A. (2020) Thermodynamic analysis of the performance of a hybrid system consisting of steam turbine, gas turbine and solid oxide fuel cell (SOFC-GT-ST). *Energy Conversion and Management*, 213, 112816.
- [19] Mazumder, M., Xu, Q., Nath, F. (2023) Thermodynamic-certified conceptual design of a DMR refrigeration system for the natural gas liquefaction process. *Industrial & Engineering Chemistry Research*, 62(4), 1916–1926.
- [20] Ayoub, A., Gjorgiev, B., Sansavini, G. (2018) Cooling towers performance in a changing climate: techno-economic modeling and design optimization. *Energy*, 160, 1133–1143.
- [21] Ruangtrakoon, N., Aphornratana, S. (2019) Design of steam ejector in a refrigeration application based on thermodynamic performance analysis. *Sustainable Energy Technologies and Assessments*, 31, 369–382.

- [22] Lee, C.E., Kim, D.H. (2020) Heat recovery boilers with water spray. Part I: Thermodynamic analysis validation and boiler practicality. *Thermal Science and Engineering Progress*, 18, 100491.
- [23] Wang, X.J., Niu, X.F., Bai, F., et al. (2023) Design and optimization of a helix finned tube heat exchanger for 2 K superfluid helium vertical test stand. *Journal of Thermal Science and Engineering Applications*, 15(6), 061007.
- [24] Deharkar, R., Mudgal, A., Patel, V. (2022) Investigation on detachable vertical tube evaporator for small scale multi effect distillation system: design, modelling, fabrication and experimental analysis. *Heat and Mass Transfer*, 58(8), 1441–1458.
- [25] Bock, F.E., Herrnring, J., Froend, M., et al. (2021) Experimental and numerical thermo-mechanical analysis of wire-based laser metal deposition of Al-Mg alloys. *Journal of Manufacturing Processes*, 64, 982–995.
- [26] Cui, R., Wang, L., Yao, L.H., et al. (2022) On the solidification behaviors of AlCu5MnCdVA alloy in electron beam freeform fabrication: Microstructural evolution. *Additive Manufacturing*, 51, 102606.
- [27] Li, Y., Su, C., Wang, L., et al. (2022) An easy-to-use multi-physical model to predict weld pool geometry in keyhole plasma arc welding. *Results in Engineering*, 14, 100429.
- [28] Meltzer, D.E. (2006) Investigation of student learning in thermodynamics and implications for instruction in chemistry and engineering. In: *Physics Education Research Conference* (ed AIP), Vol. 833, 38–41.
- [29] Dukhan, N. (2015) On the worldwide engineering students' meager performance in thermodynamics. *QScience Proceedings*, 2015(4), 17.
- [30] Arnas, A.O. (2016) Education-teaching teachers to teach-thermodynamics. In: *12th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics (HEFAT)* (ed HEFAT), 185–190.
- [31] Buentello-Montoya, D.A., Garcia-Amezquita, L.E., Rico-Gutierrez, L.M. (2022) Experiential learning at home in an engineering thermodynamics course. In: *2022 IEEE Global Engineering Education Conference (EDUCON)* (ed IEEE), 1788–1793.
- [32] Zhang, K.F., Zhang, Y.L., Xu, W.W., et al. (2018) Exploration of concept visualization and analogy in engineering thermodynamics teaching (in Chinese). *Petroleum Human Resources*, (03), 71–75.
- [33] Mahmutovic, S., Mesic, V. (2018) The effects of a context-rich approach in teaching thermodynamics. *Bulletin of the Chemists & Technologists of Bosnia & Herzegovina*, (50), 7–12.
- [34] Guo, R., Hua, Y.M., Li, S.H., et al. (2019) Application of Gestalt cognitive psychology in engineering thermodynamics teaching (in Chinese). *Research in Higher Education of Engineering*, (S1), 68–71.
- [35] Pena, B., Zabalza, I., Uson, S., et al. (2017) Flipped pilot classroom experience to improve the teaching-learning process in the subject of technical thermodynamics. In: *Congreso Nacional De Innovacion Educativa Y Docencia En Red (In Red 2017)* (ed IN-RED), 552–561.
- [36] Guo, Y., Ma, L.M. (2020) Research and Practice of Teaching "Knowledge Tree" Basing on the Course Line —In the Case of "Engineering Thermodynamics" (in Chinese). *Education Teaching Forum*, (06), 163–164.
- [37] Hua, Y.M., Duan, L.B., Liu, X.J. (2023) Exploration and practice of training young teachers' high quality teaching ability (in Chinese). *Research in Higher Education of Engineering*, (S1), 226–228.
- [38] Liu, J., Zhu, H.J. (2010) The Mean of STS Education Infiltrating the Thermotics (in Chinese). *Journal of Xinjiang Normal University (Natural Sciences Edition)*, 29(01), 95–98.
- [39] Koretsky, M.D., Brooks, B.J. (2011) Comparison of student responses to easy and difficult thermodynamics conceptual questions during peer instruction. *International Journal of Engineering Education*, 27(4), 897–908.
- [40] Tatar, E., Oktay, M. (2011) The effectiveness of problem-based learning on teaching the first law of thermodynamics. *Research in Science & Technological Education*, 29(3), 315–332.
- [41] Li, M.D., Gu, X.M., Zhu, H., et al. (2017) Teaching Reform and Practice of Engineering Thermodynamics Based on CDIO Mode (in Chinese). *Education Teaching Forum*, (12), 108–109.
- [42] Baran, M., Sozibilir, M. (2018) An application of context- and problem-based learning (C-PBL) into teaching thermodynamics. *Research in Science Education*, 48(4), 663–689.
- [43] Lopez, G.W. (2011) Work in progress: Distance teaching of thermodynamics with adobe connect and dedicated engineering software. In: *2011 ASEE Annual Conference & Exposition* (ed ASEE), Paper ID #2011-1530.
- [44] Serevina, V., Octavi, R.L. (2017) Development of web extended massive open online course (xMOOCs) on thermodynamics subject to increase high order thinking skill of students. In: *Vision 2020: Sustainable Economic Development, Innovation Management, and Global Growth* (ed IBIMA), 2405–2414.
- [45] Srinivasan, A., Bairaktarova, D. (2018) Learning thermodynamics with Ipad: Adaptation and learning opportunities for both instructor and students. *International Journal of Engineering Education*, 34(5), 1615–1625.
- [46] Xu, J.J., Yao, S.G., Feng, G.Z. (2019) Research and practice of engineering thermodynamics teaching based on Wechat public platform (in Chinese). *Research in Higher Education of Engineering*, (S1), 139–141.
- [47] Wiyono, K., Ismet, I., Noprianti, N., et al. (2019) Interactive multimedia using multiple-intelligences-based in the lesson of thermodynamics for high school. In: **3rd Sriwijaya University Learning and Education International Conference (SULE-IC 2018)** (ed SULE-IC), 040005.

- [48] Li, F.C., Jin, J.J. (2020) Research on Engineering Thermodynamics teaching based on MOOCS platform (in Chinese). *Technology Wind*, (06), 81–82.
- [49] Caserta, S., Tomaiuolo, G., Guido, S. (2021) Use of a smartphone-based student response system in large active-learning chemical engineering thermodynamics classrooms. *Education for Chemical Engineers*, 36, 46–52.
- [50] Xue, Y., Huang, C., Yang, J. (2021) Realization of Efficient of Engineering Thermodynamics Based on Rain Classroom (in Chinese). *Journal of Yulin University*, 31(02), 114–118.
- [51] Zhao, L., Liu, Y., Rui, W.H., et al. (2022) Design and production of systematic micro-course based on new form teaching materials — Taking Engineering Thermodynamics course as an example (in Chinese). *China Educational Technology & Equipment*, (21), 63–66.
- [52] Dong, M., Wang, Z., Qi, S.S., et al. (2022) Research on Application of Chaoxing Platform in the “Engineering Thermodynamics” Course (in Chinese). *Modern Information Technology*, 6(07), 176–179.
- [53] Bhattacharyya, S. (2000) Examining staged enhancements for thermodynamic cycles to improve performance using an intelligent instruction software. *International Journal of Engineering Education*, 16(4), 340–350.
- [54] Kirillov, I.A. (2002) Computer-Aided reaction engineering software for virtual educational laboratorium on chemical kinetics and thermodynamics of combustion and explosion. *Journal de Physique IV*, 12(PR7), 307–316.
- [55] Paolini, C., Bobba, K., Surana, P., et al. (2006) A Java based web application for performing chemical equilibrium analysis in thermodynamics courses. In: 36th Annual Frontiers in Education, Conference Program (ed FIE), 1–6.
- [56] Luo, M.J., Zhang, H.Y. (2009) The Application of Mathematica in the Assisting Instruction of Chemical and Engineering Thermodynamics (in Chinese). *Higher Education in Chemical Engineering*, 26(05), 73–77+87.
- [57] Chen, X., Zhao, Q., Qian, C. (2011) Teaching chemical engineering thermodynamics with aspen-plus-phase equilibrium calculations for mixtures. In: *2011 Aasri Conference on Artificial Intelligence and Industry Application (AASRI-AIIA 2011)* (ed AASRI), 200–205.
- [58] Liu, Y. (2011) Development of instructional courseware in thermodynamics education. *Computer Applications in Engineering Education*, 19(1), 115–124.
- [59] Khayet, M., Porras, B., Essalhi, M. (2015) Use of response surface methodology in sciences physics education: practical trainings in thermodynamics laboratory. In: *Edulearn15: 7th International Conference on Education and New Learning Technologies* (ed EDULEARN), 2992–2999.
- [60] Grigore, I., Miron, C., Barna, E.S. (2015) Exploring excel spreadsheets in the teaching and learning of certain concepts of statistical physics and thermodynamics. In: *Proceedings of the 10th International Conference on Virtual Learning* (ed ICVL), 171–176.
- [61] Pan, G. (2015) Application of Fluent software in the heat transfer teaching of undergraduate course (in Chinese). *Science and Technology Innovation Herald*, 12(25), 144–145.
- [62] Martin, C.R., Moore, J.P., Ranalli, J.A. (2016) Teaching the foundations of thermodynamics with Pyro. In: 2016 IEEE Frontiers in Education Conference (FIE) (ed FIE), 1–5.
- [63] Guang, G., Lin, Y., Yang, Q., et al. (2017) Simulation experiment of steady-state evaporation rate of LNG storage tank based on ANSYS (in Chinese). *Experimental Technology and Management*, 34(01), 129–131+142.
- [64] Narendranath, A.D. (2020) Introducing artificial neural networks as a specific enthalpy approximator for a course on introductory thermodynamics. In: 2020 IEEE Frontiers in Education Conference (FIE 2020) (ed FIE), 1–5.
- [65] Di Biasi, M.R., Valencia, G.E., Obregon, L.G. (2020) A new educational thermodynamic software to promote critical thinking in youth engineering students. *Sustainability*, 12(1), 110.
- [66] Chen, T.C., Huang, Z.C., Ding, X.D., et al. (2021) Simulation of plane heat source method with constant heat rate and its application in thermodynamic course (in Chinese). *Physics and Engineering*, 31(S1), 61–65.
- [67] Feng, Y.C., Ma, L.K., Zhu, J.J., et al. (2021) Practice and discussion of open-source software Cantera in the teaching of combustion theory course (in Chinese). *Journal of Higher Education*, 7(28), 98–101+105.
- [68] Zarate-Moedano, R., Suarez-Medellin, J.M., Perez-Hernandez, R.L. (2023) Model 5e and teaching thermodynamics. Design and evaluation of a teaching-learning sequence. *Uniciencia*, 37(1), 1–20.
- [69] Reisel, J.R. (2013) Analysis of the impact of testing frequency on student performance in a basic thermodynamics course. In: 2013 ASEE Annual Conference (ed ASEE), Paper ID #7038.
- [70] Ambiyar. (2015) Application of formative evaluation with instructor directional feedback to improve students learning outcomes on thermodynamics subject. In: *Proceedings of the 3rd UPI International Conference on Technical and Vocational Education and Training* (ed UPI), 1–6.
- [71] Chen, W.L., Ruan, X.B. (2018) Optimization of scientific inquiry teaching strategy under classroom observation — taking the teaching of "Scientific Inquiry: Specific Heat Capacity of Matter" as an example (in Chinese). *Physics Teaching*, 40(06), 31–33.
- [72] Xu, W.W., Li, Q. (2019) Exploration and Practice of Engineering Thermodynamics Assessment Method Based on Whole Process Control (in Chinese). *China Modern Educational Equipment*, (17), 40–42.
- [73] Orekhova, Y.Y., Sysoev, S.M., Alekseev, M.M. (2021) Use of enhanced feedback in an electronic learning course "fun-

- damentals of molecular physics and thermodynamics". *Periodico Tche Quimica*, 18(39), 71–87.
- [74] Xu, Z.J. (2012) On analyzes the daily grades evaluation for Engineering Thermodynamic courses (in Chinese). *Shanxi Architecture*, 38(18), 266–267.
- [75] Yang, X.Y., Jiang, K.Y., Shen, W., et al. (2015) Application of analytic Hierarchy process (AHP) to evaluate the teaching reform effect of Engineering thermodynamics (in Chinese). *University Education*, (12), 111–113.
- [76] Cai, Z.R. (2018) Application of entropy weight based fuzzy comprehensive evaluation method in learning quality evaluation (in Chinese). *Computer Era*, (12), 75–77.
- [77] Zhang, R.Q., Wang, L. (2023) Research on Online and Offline Blended Teaching Mode Based on BOPPPS Model: Taking Engineering Thermodynamics as an Example (in Chinese). *Journal of Shenyang Institute of Engineering (Social Sciences)*, 19(01), 126–131.
- [78] Wang, H., Wei, Z.Y., Song, J., et al. (2023) Application of “Logical Chain” Teaching in the Course of Engineering Thermodynamics (in Chinese). *Chemical Enterprise Management*, (07), 30–33.
- [79] Tan, C., Li, R., Su, J., et al. (2023) Review on field assisted metal additive manufacturing. *International Journal of Machine Tools and Manufacture*, 189, 104032.
- [80] Shen, W.D. (2007) *Engineering Thermodynamics - 4th Edition*. Higher Education Press.
- [81] Çengel, Y.A., Boles, M.A. (2006) *Thermodynamics: An Engineering Approach*. McGraw-Hill.