
Research on the Construction Paths of Digital Textbooks Empowered by Intelligent Technologies: A Case Study of Thermodynamics and Fluid Mechanics

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Abstract: To accelerate the digital transformation of higher education and the rapid advancement of intelligent technologies, the development of digital textbooks has emerged as a crucial pathway for enhancing the quality and effectiveness of engineering education. Taking the core mechanical engineering course Thermodynamics and Fluid Mechanics as a case study, the limitations of traditional paper-based textbooks are systematically analyzed in the present study. To address these challenges, a comprehensive construction framework is correspondingly proposed, which includes knowledge system reconstruction, multimodal visualization, integration of virtual simulations, personalized learning support based on learning analytics, embedding of engineering cases, and data-driven continuous optimization. The proposed approach will improve visualization, interactivity, and instructional effectiveness in mechanical engineering education, and offer a replicable reference for the digital transformation of textbooks in related engineering disciplines.

Keywords: Digital textbooks; Mechanical engineering education; Artificial Intelligent; Education digitalization

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1. Introduction

With the rapid development of artificial intelligence (AI), big data, virtual simulation, and smart education technologies, higher engineering education is undergoing a significant digital transformation. Digital textbooks, as a critical carrier of educational digitalization, are evolving from traditional static knowledge repositories into intelligent learning systems integrating multimodal resources, interactive functions, and data-driven feedback ^[1-4]. For engineering foundation courses, textbooks not only serve as tools for knowledge transmission but also play a crucial role in cultivating students' analytical abilities, engineering thinking, and problem-solving competence ^[5-6]. Therefore, exploring the construction path of digital textbooks empowered by intelligent technologies has become an important issue in the reform of engineering

education.

Thermodynamics and Fluid Mechanics course is a compulsory core course for mechanical engineering majors, which lays the theoretical foundation for subsequent courses such as energy systems, fluid machinery, and thermal equipment design. The course involves complex theoretical systems, abstract physical concepts, strong coupling of thermal-fluid processes, and significant engineering application relevance. Its content covers thermodynamic laws, fluid statics and dynamics, and fundamental heat transfer mechanisms, all of which require students to understand multi-physical field interactions and mathematical modeling. However, traditional paper-based textbooks remain limited by linear textual descriptions, static formulas, and two-dimensional diagrams, which are insufficient for presenting dynamic thermal-fluid phenomena such as flow evolution, temperature field distribution, and energy conversion mechanisms. In addition, under the background of advanced manufacturing and energy transition, mechanical engineering education is shifting toward interdisciplinary integration and engineering innovation, which puts forward higher requirements for the timeliness, interactivity, and engineering relevance of teaching materials.

Intelligent technologies provide a new paradigm for the construction of digital textbooks. At the practical level, the development of digital textbooks is confronted with issues such as the mere superposition of digital technology and traditional textbooks, insufficient knowledge integration in content organization, and inadequate media literacy among users. Therefore, it is necessary to innovate the application of digital textbooks by improving technical standards, optimizing content organization, and enhancing the digital media literacy of both teachers and students, so as to promote the effectiveness of digital textbook-based teaching^[7]. Lin^[8] proposed a threefold driving logic for the construction of digital textbooks in local universities, and concluded that the construction path was supported by digital textbook content development, platform building, technical standards, and security assurance. Zhang et al.^[9] proposed a “Content Generation-Scene Simulation-Intelligent Evaluation” model for digital textbook construction of “Engineering Project Management”, in which Artificial Intelligence Generated Content (AIGC) technology dynamically reconstructed and cross-modally presents textbook content, created highly realistic virtual project scenarios to enhance immersive learning, and integrated intelligent evaluation with personalized guidance. Wang et al.^[10] systematically proposed a feasible path for the construction of a digital textbook for “Medicinal Chemistry” under the background of the New Engineering Education initiative in the AI era, covering aspects such as overall design, research content, research methods, and innovative practices. Gong et al.^[11] systematically investigated the development processes of multimodal resources as the reconstruction path of digital textbook design for “Graphics and Fundamentals of Machinery”, including parametric 3D models, micro-videos, and virtual simulations, and designs interactive tools such as an intelligent error-correction system, a Q&A chatbot, an electronic notebook, and a learning progress tracker. The main objective of the present study is to investigate the construction path of a digital textbook empowered by intelligent technologies for Thermodynamics and Fluid Mechanics course, thus enhancing visualization, interactivity, and learning effectiveness in mechanical engineering education.

2. Existing problems in the paper textbook construction

2.1. Insufficient support for complicated thermal-fluid cognition

Current paper textbooks for Thermodynamics and Fluid Mechanics mainly adopt static forms of presentation, including text, equations, and two-dimensional schematic diagrams. Such forms are inadequate for illustrating dynamic physical phenomena such as boundary layer development, flow pattern transition, and heat transfer processes. Mechanical engineering students often find it difficult to establish an intuitive understanding of flow fields, temperature distributions, and energy conversion mechanisms, as they must rely heavily on abstract mathematical expressions. This static knowledge representation weakens the connection between physical processes, mathematical models, and engineering applications, thereby limiting the depth of conceptual understanding.

2.2. Weak integration between theoretical content and practical applications

As a compulsory course for mechanical engineering majors, Thermodynamics and Fluid Mechanics should closely align with engineering practices such as thermal system design, fluid machinery analysis, and heat exchanger optimization. However, existing paper textbooks contain relatively limited engineering cases and lack systematic integration with real mechanical engineering scenarios. Students are often unable to effectively apply theoretical knowledge to practical problems, resulting in insufficient knowledge transfer ability and weak engineering awareness.

2.3. Low degree of integration between experiments and teaching materials

Experimental teaching is an essential component of Thermodynamics and Fluid Mechanics, including flow visualization experiments, heat transfer experiments, and comprehensive thermal system tests. Nevertheless, traditional paper textbooks are often separated from experimental modules, and experimental content is not deeply embedded within the knowledge system. Due to constraints in laboratory equipment, time, and cost, some key experiments involving complex flow and heat transfer phenomena cannot be fully conducted, which restricts students' experiential understanding of fundamental thermal–fluid mechanisms. The lack of virtual simulation resources integrated into textbooks further limits the implementation of blended experimental teaching.

2.4. Insufficient learning interactivity and lack of personalized support

Traditional paper textbooks follow a one-way knowledge transmission model with limited interactive learning design. The course involves complex derivations, differential equations, and multi-level knowledge difficulty, leading to significant differences in students' learning needs. However, existing teaching materials cannot provide adaptive learning paths or intelligent guidance, making it difficult to support individualized learning for mechanical engineering students with diverse academic backgrounds.

2.5. Slow content updating and limited reflection of disciplinary frontiers

With the rapid development of mechanical and energy engineering technologies, the application scope of Thermodynamics and Fluid Mechanics is continuously expanding to advanced thermal management, energy systems, and sustainable engineering fields. However, traditional textbooks have long updated cycles and limited flexibility, making it difficult to incorporate the latest engineering technologies, industrial cases, and interdisciplinary knowledge in a timely manner. This lag reduces the forward-looking nature and practical relevance of the course.

2.6. Disconnection between teaching evaluation and textbook system

At present, course evaluation mainly depends on homework and final examinations, lacking dynamic assessment based on learning process data. The textbook, as the core teaching resource, is not effectively linked with learning analytics, formative assessment, and outcome-based evaluation. Consequently, it is difficult to continuously optimize textbook content and structure through data feedback, which constrains the sustainable improvement of teaching quality.

3. Construction path of the digital textbook for thermodynamics and fluid mechanics

Considering that Thermodynamics and Fluid Mechanics course is a compulsory foundational course for mechanical engineering characterized by abstract theories, complex physical mechanisms, and strong engineering relevance, the construction of a digital textbook should be centered on the course knowledge system and supported by intelligent technologies. A systematic construction path should be established from the perspectives of knowledge structure reconstruction, multimodal resource development, virtual-real experimental integration, intelligent learning support, and data-driven optimization.

3.1. Reconstruction of the knowledge system

The course integrates thermodynamics, heat transfer, and fluid mechanics, and traditional textbooks usually follow a linear disciplinary logic, which cannot fully reflect the intrinsic coupling among these domains. Under the empowerment of intelligent technologies, the knowledge structure should be reorganized in a modular and hierarchical manner, focusing on the cultivation of engineering competencies. Specifically, a three-level framework of “fundamental theories-physical mechanisms-engineering applications” can be established, which links thermodynamic laws, conservation equations, and transport phenomena with typical mechanical engineering problems such as energy system analysis, pipeline flow calculation, and heat exchanger design.

In addition, the existing knowledge graph developed for this course on the Chaoxing learning platform can be integrated into the digital textbook. Key concepts such as Reynolds number, Nusselt number correlations, boundary layer theory, and heat conduction equations can be mapped into this knowledge graph, enabling visualization of logical relationships among knowledge points. By embedding this platform-based knowledge graph, students can navigate the interconnected concepts dynamically, fostering a systematic understanding of thermal-fluid processes and enhancing their analytical and integrative learning abilities.

3.2. Development of multimodal visualization resources for abstract theory representation

To facilitate comprehension of abstract physical processes, the digital textbook should incorporate multimodal visualization resources, including three-dimensional animations, dynamic simulations, interactive plots, and visually enhanced computational modules. For instance, transitions between flow regimes under varying Reynolds numbers can be illustrated through animated flow field visualizations, while temperature distributions in conduction and convection processes can be dynamically represented using contour maps.

These multimodal representations establish a direct correspondence between mathematical formulations and physical phenomena, substantially reducing the cognitive load associated with complex differential equations and dimensionless analyses. For mechanical engineering students, this approach improves spatial reasoning, deepens conceptual understanding, and strengthens the ability to interpret thermal-fluid mechanisms within practical engineering contexts.

3.3. Deep integration of virtual simulation experiments with textbook content

Given the experimental significance of Thermodynamics and Fluid Mechanics, the digital textbook should embed virtual simulation experiments within each knowledge module to form an integrated “theory-simulation-analysis” learning system. In the thermodynamics section, virtual experiments can illustrate processes such as isothermal and adiabatic compression and expansion, ideal and real gas cycles, and energy balance analyses of simple thermal systems. In the heat transfer section, simulation modules can be used to analyze temperature distributions under different boundary conditions, including conduction through composite walls, forced and natural convection, and transient heat conduction scenarios. In the fluid mechanics section, virtual experiments on pipe flow resistance allow students to adjust parameters such as flow rate, diameter, and surface roughness to observe variations in pressure drop.

Integrating virtual experiments with textbook content effectively mitigates the constraints of physical laboratory resources, enhances experiential learning, and strengthens students’ conceptual understanding of complex thermal-fluid interactions. Furthermore, this approach supports blended teaching modes that combine virtual and physical experiments, aligning well with the needs of mechanical engineering education and fostering deeper engagement with theoretical and applied aspects of the course.

3.4. AI-based personalized learning support mechanism

Given the steep difficulty gradient and strong mathematical nature of Thermodynamics and Fluid Mechanics, mechanical engineering students often exhibit substantial variation in learning progress and comprehension levels. By embedding artificial intelligence and learning analytics into the digital textbook, students’ learning behaviors, such as time spent on

reading, problem-solving accuracy, and engagement with specific knowledge points, can be continuously collected and analyzed to generate individualized learning profiles.

Based on these profiles, the system can deliver personalized resource recommendations, adaptive exercises, and targeted feedback for challenging topics, including energy balance analysis, flow modeling, and heat transfer computations. Moreover, intelligent tutoring systems and knowledge-association prompts can assist students in establishing logical connections across different modules, thereby enhancing learning efficiency, promoting self-directed study, and fostering a deeper understanding of complex thermal–fluid concepts.

3.5. Integration of engineering cases and mechanical engineering frontiers

To enhance the engineering orientation of the compulsory course, the digital textbook should incorporate representative mechanical engineering cases, including thermal system efficiency analysis, heat exchanger optimization, thermal management in mechanical equipment, and fluid machinery performance evaluation. Embedding these cases within theoretical chapters can bridge the gap between abstract knowledge and real engineering practice.

Moreover, frontier topics such as advanced thermal management technologies, energy-saving systems, and sustainable mechanical engineering applications can be included as extended modules. This design not only broadens students' academic horizons but also strengthens the relevance of the course to modern mechanical engineering development.

To strengthen the engineering orientation of this compulsory course, the digital textbook should integrate representative mechanical engineering case studies. For example, students could analyze the thermal efficiency of a Rankine cycle in a steam power plant, optimize the design of a shell-and-tube heat exchanger for maximum heat transfer with minimal pressure drop, evaluate the cooling performance of an air-cooled turbine blade in a gas turbine, or assess pump and fan performance in a complex piping system under varying flow conditions. Embedding these cases within theoretical modules helps bridge the gap between abstract concepts and practical engineering applications, enabling students to directly apply foundational knowledge to realistic scenarios.

Furthermore, frontier topics can be incorporated as extended modules to expose students to cutting-edge developments. Examples include advanced thermal management in electric vehicle battery packs, design and simulation of compact heat exchangers for waste heat recovery, implementation of energy-saving HVAC systems in industrial plants, and sustainable fluid machinery applications. Integrating such cases and frontier topics not only broadens students' academic horizons but also enhances the course's relevance to modern mechanical engineering challenges, fostering innovation awareness and strengthening practical problem-solving skills.

3.6. Data-driven dynamic updating and evaluation optimization path

A key advantage of an intelligent digital textbook is its capacity for data-driven feedback and continuous optimization. Using smart teaching platforms, data on students' engagement with core concepts can be systematically collected and analyzed. Metrics such as time spent on complex derivations, success rates in problem-solving exercises, interaction with virtual labs, and frequency of accessing specific knowledge points allow instructors to identify challenging topics and knowledge gaps within the textbook.

Based on the analytical results, instructors can iteratively enhance the digital textbook by enriching visualizations for difficult chapters, adding engineering case studies, or reorganizing knowledge sequences to improve conceptual progression. Additionally, formative assessments, virtual experiment performance, and interactive learning logs can be integrated into a comprehensive evaluation system, creating a closed loop of “textbook-learning-assessment-improvement.” The mentioned data-driven mechanism ensures the sustainable enhancement of the digital textbook and teaching quality for the Thermodynamics and Fluid Mechanics course.

4. Conclusion

As a compulsory foundational course for mechanical engineering majors, Thermodynamics and Fluid Mechanics plays a prominent role in cultivating students' theoretical foundation and engineering competence. Under the background of educational digitalization and intelligent technology development, constructing a digital textbook empowered by intelligent technologies is an inevitable trend for curriculum reform. By systematically analyzing the existing problems in traditional paper textbooks, the present study proposes a construction path focusing on knowledge system reconstruction, multimodal visualization, virtual simulation integration, AI-based personalized learning, engineering case embedding, and data-driven optimization. The construction path in this study may provide a comprehensive framework for the digital transformation of other similar textbooks.

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Disclosure statement

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