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AI-Empowered Design of the "Fundamentals of Thermal Engineering" Course for Mechanical Engineering Majors under Insufficient Teaching Hours

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Abstract: Fundamentals of Thermal Engineering is a compulsory foundational course for mechanical engineering majors. Under a schedule of only 32 class hours, the course covers a large body of fine-grained knowledge points spanning engineering thermodynamics and heat transfer. Although both parts offer clear paths of knowledge extension, students frequently find the content difficult to absorb, which weakens teaching effectiveness. This paper investigates how course design can be improved in the context of artificial intelligence. Drawing on an AI-enabled course development practice, a design framework is proposed that maps the capabilities of AI onto four concrete difficulties of the course: dense content, fine-grained knowledge points, clear but under-absorbed extension paths, and low student receptivity. The framework is built on a "basic theory teaching—AI-empowered engineering application" dual-track progressive architecture and rests on four pillars: knowledge-graph-based atomization and dynamic reconstruction of knowledge points, a progressive AI-assisted engineering case library, an intelligent teaching analysis platform for precise learning diagnosis, and a knowledge-ability-value multi-dimensional evaluation system. The paper further argues that the application of AI in course design must adhere to the principles of teacher leadership, value guidance, data security, and appropriate use of technology. The proposed framework offers design ideas and guiding principles for foundational engineering courses with insufficient teaching hours in the AI era.

1. Introduction

The rapid development of artificial intelligence, and generative AI and large language models in particular, is reshaping higher education [1]. AI provides new means to organize knowledge, diagnose learning and personalize instruction, but it also challenges the conventional course design that was built on fixed syllabi and one-way knowledge transmission. For engineering education, foundational professional courses face a structural tension: they are expected to lay a rigorous theoretical basis for subsequent specialized courses, yet they are often compressed into a limited number of class hours.

Fundamentals of Thermal Engineering is a compulsory foundational course for mechanical design,

manufacturing and automation majors and robotics majors at our university. It integrates engineering thermodynamics and heat transfer, two classical disciplines with rich and rigorous theoretical systems. The course carries only 32 class hours and 2 credits, while its syllabus covers the first and second laws of thermodynamics, the properties of common working substances, gas mixtures and humid air, thermodynamic processes, the flow of gases and vapours, steady heat conduction, convective heat transfer and radiative heat transfer. The knowledge points are numerous, fine-grained and strongly interdependent. More importantly, although both the thermodynamics part and the heat transfer part present logically clear paths of knowledge extension, students often perceive the course as abstract and difficult, and their receptivity is unsatisfactory.

A similar tension between dense content and limited hours has been observed in other mechanical engineering courses, where learning-centred and teaching-reform modes have been introduced to improve effectiveness [2-3]. With the further advance of AI technology, course design has a new opportunity to go beyond the trade-off between coverage and depth: AI can externalize part of the knowledge organization, case connection and learning diagnosis that previously had to be compressed into classroom hours. This paper therefore explores how course design can be improved in the AI context, and proposes a design framework and a set of guiding principles for this course, with the aim of offering transferable ideas for tight-credit-hour foundational engineering courses.

2. Dilemmas of the Course under insufficient teaching hours

2.1. Dense content versus limited class hours

The course compresses two complete classical disciplines into 32 class hours. The thermodynamics part alone spans fundamental concepts, the first law, the second law, the properties of ideal gases, water vapour, gas mixtures and humid air, basic thermodynamic processes, and the flow of gases and vapours; the heat transfer part spans conduction, convection and radiation. Each of these topics contains a chain of fine-grained knowledge points that build on one another. Under such a schedule, the classroom has traditionally been dominated by knowledge transmission, leaving little room for the demonstration of thinking processes, engineering connection, or individualized guidance. Prior attempts, such as the online-offline blended teaching reform of this course, have alleviated the problem to some extent but have not fundamentally resolved the tension between coverage and depth [4].

2.2. Fine-grained knowledge points and clear but under-absorbed extension paths

A distinctive feature of this course is that both parts possess logically clear paths of knowledge extension. Taking the chapter "Flow of Gases and Vapours" as an example, the knowledge chain proceeds from the mass conservation equation, the process equation and the energy equation, to the mechanical and geometrical conditions governing velocity variation, then to the speed of sound and the Mach number, the selection of nozzles (convergent versus convergent-divergent), the critical pressure ratio, and finally the calculation of flow rate. The chain is rigorous and well structured, which in principle should help students follow the reasoning. In practice, however, mastering this chain requires the simultaneous handling of several coupled equations and a set of abstract assumptions—steady, adiabatic, one-dimensional and reversible—so that many students can follow each individual step but fail to grasp the whole chain. The knowledge extension is clear to the teacher but not readily absorbed by the student, and this is exactly where the course becomes difficult.

2.3. Disconnection from the mechanical engineering profession

Most published textbooks of this course are oriented toward thermal power engineering, and their typical objects—power machinery, heat exchangers and boiler cycles—are unfamiliar to mechanical engineering students. As a result, students often do not see how the knowledge they have learned can be applied in their own discipline. This disconnection further weakens motivation and receptivity, a problem that has been widely recognized in the teaching reform of mechanical practical courses [3].

3. Guiding Ideology and Overall Framework

3.1. From coverage-driven to structure-driven and AI-assisted design

The core guiding ideology of the proposed course design is to shift from a coverage-driven logic to a structure-driven and AI-assisted logic. In a coverage-driven course, the limited hours are used to transmit as many knowledge points as possible, and the difficulty of absorption is left to the students. In the AI era, this allocation can be inverted: the classroom hours should be devoted to helping students build the knowledge structure and the thinking methods, while AI tools take over the organization of fine-grained knowledge, the connection of engineering cases and the diagnosis of learning, all of which can be performed outside the classroom. The guiding ideology can be summarized as "knowledge graph as the skeleton, engineering cases as the veins, intelligent analysis as the engine, and value guidance as the soul".

This ideology is implemented through a principle of dual synergy: AI-empowered teaching, as advanced in recent smart teaching models [5], is combined with individualized value education [6], so as to cultivate students who can not only use AI but use it appropriately and ethically. The design deliberately avoids two extremes—rejecting AI on the one hand and over-relying on it on the other—and instead positions the teacher as the designer and value guide of the AI-assisted process.

3.2. The dual-track progressive architecture

On the basis of this ideology, the course is reorganized into a "basic theory teaching—AI-empowered engineering application" dual-track progressive architecture, which is further divided into four teaching modules: fundamentals of engineering thermodynamics, thermodynamic processes of working substances, applications of engineering thermodynamics, and heat transfer. The basic-theory track keeps the rigorous deductive logic of the two disciplines; the AI-empowered application track runs in parallel and links each theory block to mechanical engineering scenarios through AI-supported cases and knowledge graphs. The two tracks are progressive in the sense that every round of theoretical learning is immediately followed by an engineering application, so that knowledge, ability and value are advanced together.

3.3. The knowledge-ability-value transformation chain

The framework explicitly aims at a transformation chain from knowledge to ability to value as shown in Figure 1. Knowledge refers to the mastery of fundamental concepts and laws; ability refers to the capacity to abstract and simplify real thermal problems into solvable models; value refers to the awareness of energy saving, green and low-carbon development, and engineering ethics. AI is used to connect these three levels: the knowledge graph organizes knowledge, the case library converts knowledge into ability, and the multi-dimensional evaluation combined with sentiment analysis turns value education into an observable and adjustable process [7].

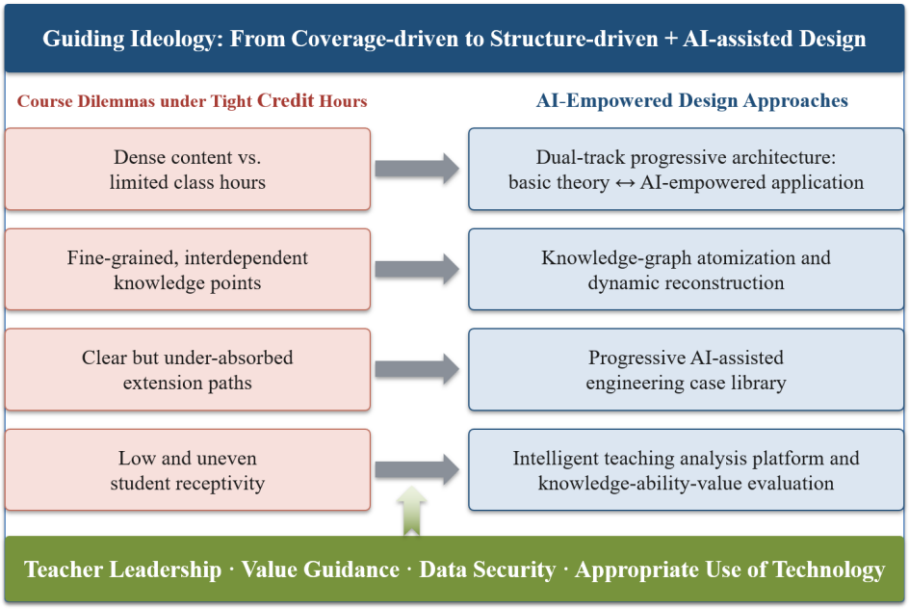


Figure 1. Overall framework of the AI-empowered course design: mapping the four course dilemmas to AI-empowered design approaches.

4. Key Approaches to Course Design

4.1. Knowledge-graph-based atomization and dynamic reconstruction

To resolve the difficulty caused by fine-grained and interdependent knowledge points, the course decomposes the core knowledge of thermodynamics and heat transfer into "atomic" knowledge units and reconstructs them into a knowledge graph. Knowledge graphs have been shown to support personalized learning, curriculum design and concept mapping in education [8]. Rather than forcing students to memorize isolated fragments, the graph reveals the links among knowledge points, allowing students to see, for example, how the equation of state of ideal gases is connected to the flow of gases, or how the laws of black-body radiation are connected to the greenhouse effect. When a student fails at a later node, the graph can trace back to the prerequisite nodes, enabling dynamic reconstruction of the learning path. This transfers the burden of organizing fine-grained knowledge from the classroom to the AI system, so that the limited hours can focus on the core chains.

4.2. Progressive AI-assisted engineering case library

To address the disconnection between the course and the mechanical engineering profession, a progressive case library is built, containing engineering scenarios drawn from the mechanical domain, such as the temperature field simulation of single-abrasive grinding (linked to heat conduction) and the cooling system simulation of a reduction gearbox (linked to convective heat transfer). The cases are organized into a chain that follows the learning guidance of "observe phenomena—grasp concepts and laws—analyze processes—apply to engineering—innovate". This chain matches the clear extension paths of the two parts of the course and converts them from abstract deductions into concrete, discipline-relevant problems, thereby improving receptivity. The case library also carries value elements, forming a chain from "stimulating low-carbon awareness" to "building the idea of ecological civilization" and then to "arousing the sense of mission for a strong technological nation".

4.3. Intelligent teaching analysis platform and precise learning diagnosis

To address the low and uneven receptivity of students, an intelligent teaching analysis platform is introduced to process learning data generated before, during and after class. Through online preview tests, in-class quizzes and homework, the platform identifies in real time the knowledge points that are weakly mastered, so that the teacher can re-explain them immediately or adjust the pace. This realizes a feedback loop from diagnosis to adjustment, which was difficult to achieve under the traditional coverage-driven teaching. Compared with the learning-centred mode that relies on activity data from teaching platforms [2], the AI platform further automates the identification of weak links and reduces the teacher's workload of manual statistics.

4.4. Knowledge-ability-value multi-dimensional evaluation

Corresponding to the transformation chain in Section 3.3, a multi-dimensional evaluation system is designed to assess knowledge, ability and value simultaneously. Knowledge is evaluated through conventional tests; ability is evaluated through the modeling and calculation of engineering cases; and value attainment is evaluated with the help of knowledge graphs and natural language processing based sentiment analysis, which identifies keywords and emotional tendencies in students' discussions and reports. The results are used to push different cases or resources to students with different learning styles, approaching an individualized education. This evaluation system echoes the AI-empowered smart teaching models reported in recent studies, which emphasize data-based and continuous evaluation [5].

4.5. Value education and ideological-political integration

Value education is treated not as an add-on but as an integral component of the design. Ideological-political elements are embedded in each knowledge point: the perpetual-motion machine leads to the first law of thermodynamics and a scientific attitude; the energy-efficiency labels of air conditioners lead to energy-saving awareness; the steam catapult of aircraft carriers leads to a sense of mission for a strong technological nation; and the satellite fairing and the greenhouse effect lead to radiative heat transfer and environmental responsibility. Prior work has shown that student-centred ideological-political teaching in this course improves engagement [6]. In the AI era, sentiment analysis makes this value education dynamically adjustable, so that value guidance and technology empowerment reinforce each other.

5. A Worked Example: AI-Empowered Course Design for "Flow of Gases and Vapours"

This section illustrates how the proposed framework is applied, taking the chapter "Flow of Gases and Vapours" as a worked example. With its clear but under-absorbed extension path, this chapter is a representative case of the dilemma described in Section 2.

5.1. Knowledge structure and atomization

The chapter studies how a gas accelerates in a nozzle, a variable cross-section duct, and how a nozzle is designed and checked. Its core content can be decomposed into a set of atomic knowledge points: the mass-conservation (continuity) equation, the reversible-adiabatic process equation, the energy equation, the speed of sound and the Mach number, the mechanical condition for velocity change, the geometrical condition for velocity change, the critical pressure ratio, nozzle selection, and flow-rate calculation. These atoms are linked into a chain: the three fundamental equations yield

the mechanical condition — a velocity increase is the result of a pressure drop — and the geometrical condition $dA/A = (Ma^2 - 1)\, dc_f/c_f$, which dictates the nozzle shape: a convergent nozzle for subsonic flow, a divergent nozzle for supersonic flow, and a convergent-divergent (Laval) nozzle for acceleration across the speed of sound. The critical pressure ratio (0.528 for diatomic ideal gases, 0.546 for superheated steam and 0.577 for saturated steam) then determines the nozzle type, and finally the outlet velocity and mass flow rate are calculated. In the knowledge graph, these atoms are linked backward to their prerequisites — the ideal-gas equation of state and the first law of thermodynamics — and forward to engineering scenarios such as turbojet engines, rocket nozzles, supersonic wind tunnels and vector-thrust nozzles.

5.2. AI-assisted learning path

The chapter follows the "observe phenomena — grasp concepts and laws — analyze processes — apply to engineering — innovate" chain, with AI support embedded at each stage, as shown in Figure 2. (1) Observe phenomena: before class, the platform pushes videos of a rocket launch, a turbojet engine and a vector-thrust nozzle demonstration, together with the guiding question "how does a gas accelerate in a nozzle?", so that students arrive with a concrete physical image. (2) Grasp concepts and laws: the three fundamental equations and the concepts of the speed of sound and the Mach number are introduced, and the knowledge graph shows how the equations are connected and traces back to prerequisites for students who need them. (3) Analyze processes: the mechanical and geometrical conditions are derived, and an AI-generated animation visualizes how the cross-section must change with the Mach number, making the abstract relation intuitive. (4) Apply to engineering: nozzle selection and flow-rate calculation are practised; the case library pushes discipline-relevant cases such as a supersonic wind tunnel and a vector-thrust nozzle, and students complete a design-calculation exercise for a convergent-divergent nozzle. (5) Innovate: students connect the chapter to mechanical engineering, for example to high-pressure jet cooling in machining or to pneumatic tools, and reflect on energy saving, so that knowledge, ability and value advance together.

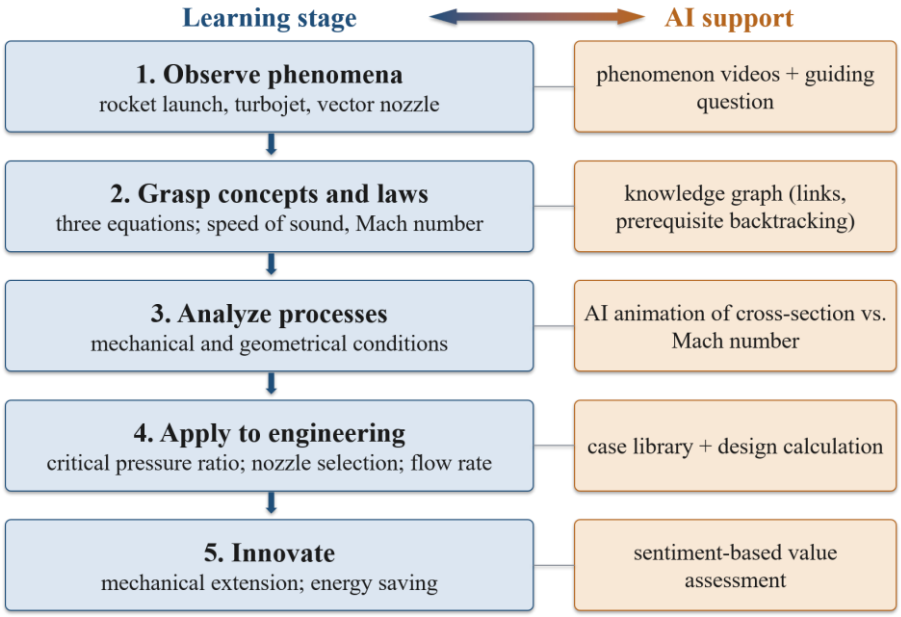


Figure 2. AI-empowered learning path for the chapter "Flow of Gases and Vapours".

5.3. Proposed course arrangement

The chapter is allocated two class hours, organized into before-class, in-class and after-class phases, as summarized in Table 1.

Table 1. Proposed two-class-hour arrangement for the chapter "Flow of Gases and Vapours".

Phase	Main content	AI support	Assessment
Before class (online)	Phenomenon videos (rocket launch, turbojet, vector nozzle) and guiding question; pre-class quiz on prerequisites	Knowledge-graph prerequisite backtracking; guided videos	Pre-class quiz
In class (2 class hours)	Three fundamental equations; speed of sound and Mach number; mechanical and geometrical conditions; critical pressure ratio; nozzle selection; flow-rate calculation	Knowledge-graph links; animation of cross-section vs. Mach number; selection decision support	In-class quiz; nozzle-selection exercise
After class (online)	Design-calculation exercise of a convergent-divergent nozzle; mechanical-engineering cases; open-ended exploration	Case library; precise diagnosis; sentiment-based value assessment	Design-calculation report; case discussion

6. Discussion: Principles to Uphold and Expected Outcomes

The application of AI to course design must be governed by several principles, otherwise technology may undermine rather than serve education. First, teacher leadership must be maintained: AI organizes, diagnoses and recommends, but the teacher remains the designer of the course and the guide of value. Second, value guidance must not be diluted: AI should serve the cultivation of engineering ethics and social responsibility rather than merely improve scores. Third, data security and privacy must be respected, since learning diagnosis relies on the collection of student data. Fourth, the use of technology should be appropriate: AI should be introduced where it genuinely resolves a difficulty, and not for its own sake. These principles are consistent with those proposed for AI-empowered smart teaching [5].

Qualitatively, the proposed framework is expected to produce several outcomes. It should reduce the classroom burden of knowledge transmission and leave room for thinking and application; it should improve the absorption of the two parts' extension paths by converting them into discipline-relevant cases; it should make teaching adaptive through precise diagnosis; and it should embed value education into the whole process. The construction plan of the course sets out a staged roadmap from case collection, platform construction and evaluation system development to iterative improvement, and designates the publication of teaching-research papers as one of the assessment indicators. Quantitative verification of teaching effectiveness, such as comparison of examination performance and student feedback before and after the reform, will be the subject of subsequent empirical studies.

7. Conclusion

This paper addresses the dilemma of a tight-credit-hour foundational course whose content is dense, whose knowledge points are fine-grained, and whose clear extension paths are nevertheless difficult for students to absorb. It proposes that, in the AI era, course design should shift from a coverage-driven logic to a structure-driven and AI-assisted logic, and it presents a design framework

for Fundamentals of Thermal Engineering built on a dual-track progressive architecture and four pillars: knowledge-graph-based atomization, a progressive engineering case library, an intelligent analysis platform and multi-dimensional evaluation, all governed by the principles of teacher leadership, value guidance, data security and appropriate use of technology. The framework is expected to improve teaching effectiveness by matching each AI capability to a specific difficulty of the course. As a set of design ideas and guiding principles, it also offers a reference for the course design of other foundational engineering courses under the constraints of limited credit hours.

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