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Mapping the Mastery Level of Basic Thermodynamics Concepts among Chemistry Education Students

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ABSTRACT

Thermodynamics is a fundamental yet conceptually challenging topic that chemistry education students must master, particularly as future science teachers. This study aimed to map students' conceptual mastery across six core thermodynamic topics; gas systems and laws, kinetic theory of gases, state and state functions, systems and surroundings, thermodynamic processes, and the first law of thermodynamics, while identifying the most difficult areas and the misconceptions that arise. The study involved 125 students from the Chemistry Education Study Program who had completed the thermodynamics course. A 45-item multiple choice test was administered, and data were analyzed using descriptive statistics. Concept mastery was categorized into five levels (very high, high, medium, low, very low), and distractor analysis was used to uncover patterns of misconceptions.The results showed very high mastery in thermodynamic processes (93,92%), high mastery in gas systems and laws, kinetic theory of gases, state and state functions, and systems and surroundings (ranging from 79,80% to 84,80%), and moderate mastery in the first law of thermodynamics (72,93%). Common errors included confusion about sign conventions, energy flow, entropy, and the difference between state and process functions. The findings emphasize the importance of shifting from procedural to conceptual teaching strategies. Visual models, simulations, and diagnostic tools are recommended to address persistent misconceptions. This study contributes to improving thermodynamics instruction in chemistry teacher education and serves as a reference for further research on conceptual change in science learning.

INTRODUCTION

Thermodynamics is a foundational aspect of chemistry that explains energy transformations in physical and chemical processes. Its principles are essential not only for understanding topics like phase transitions and chemical equilibrium, but also for interpreting everyday phenomena. For chemistry education students, who are expected to become future educators, a strong conceptual understanding of thermodynamics is critical for academic success and effective science teaching (Gaskell & David E, 2024; Natalis & Leyh, 2025). Despite its importance, thermodynamics is consistently cited as one of the most challenging areas for students to master. This is due to its abstract nature and the complexity of concepts like entropy and energy transfer, which are often disconnected from observable phenomena (Gao & Chaudhari, 2021; Haglund et al., 2015). Studies have also shown that traditional teaching methods, focused on equations and calculations, fail to foster deep conceptual understanding (Baran & Sozbilir, 2018; Bray & Tangney, 2015). As a result, students frequently develop misconceptions or fragmented knowledge.

Moreover, research that specifically examines the mastery level of thermodynamic concepts among chemistry education students remains limited. Most existing studies focus on general chemistry or physics students, without accounting for the dual role chemistry education students play as both learners and future instructors (Holme et al., 2015; Treagust et al., 2018). This gap in the literature hinders the development of instructional strategies tailored to their needs. This study seeks to address the lack of specific data on thermodynamic concept mastery among chemistry education students by systematically mapping their understanding across five core topics: gas systems and laws, the kinetic theory of gases, state and state functions, thermodynamic processes, and the first law of thermodynamics. The research aims to identify which concepts are well understood, which pose persistent difficulties, and what common misconceptions exist.

By providing a detailed overview of students' conceptual strengths and weaknesses, the findings from this study are intended to support the development of more effective, contextual, and conceptually grounded learning strategies. Furthermore, the results can serve as a foundation for improving curriculum design, refining instructional methods, and creating diagnostic tools tailored to chemistry education students. Ultimately, this study contributes to enhancing the quality of thermodynamics education in teacher preparation programs.

METHODS

Research Design

This study employs a qualitative descriptive approach aimed at mapping the level of mastery of basic thermodynamic concepts among students in the Chemistry Education Study Program. This approach enables researchers to explore students' conceptual understanding in depth through answer analysis and narrative interpretation techniques. By doing so, the study can identify the level of conceptual mastery, highlight the most challenging thermodynamic concepts for students, and uncover common misconceptions that may arise in their understanding

Research Target

The participants in this study comprised 125 undergraduate students enrolled in the Chemistry Education Program. A purposive sampling technique was employed, with inclusion criteria requiring that students had successfully completed coursework in chemical thermodynamics. The selected participants were drawn from the 2020 and 2021 academic cohorts.

Research Data

The type of data collected in this study is quantitative, which is interpreted qualitatively. The instrument used was a multiple choice test designed to map the level of students' understanding of basic thermodynamic concepts. Data were collected from students' test responses administered after they had completed learning activities related to the fundamental concepts of thermodynamics. The analysis aimed to categorize levels of conceptual mastery and explore the nature of student misconceptions.

Research Instruments

The research instrument consisted of a multiple-choice test comprising 50 items, constructed in accordance with the learning objectives of the chemical thermodynamics course. The items covered key conceptual domains such as systems and surroundings, state functions, thermodynamic processes, thermodynamic laws, internal energy and heat, and entropy. The development process involved expert validation to ensure the accuracy and relevance of the items.

Validity was assessed using Pearson's product-moment correlation between each item score and the total test score. Items with a correlation coefficient greater than the critical value were deemed valid. Out of the 50 items, 45 were valid were found to be invalid, Thus, the total number of items used in the research was 45.

The reliability of the test was measured using Cronbach's Alpha, yielding a coefficient of 0.890, which indicates high internal consistency. The difficulty index ranged from 0.00 (very difficult) to 0.96 (very easy), with most items falling within medium to easy categories. The discrimination index ranged from 0.000 to 0.557, with the majority of the items categorized as having adequate to good discriminating power, demonstrating the instrument's ability to differentiate between varying levels of student understanding.

Data Analysis

This study employed a qualitative descriptive approach to analyze the level of mastery of basic thermodynamic concepts among students in the Chemistry Education Study Program. Data were obtained from a multiple-choice conceptual test administered after students had completed the relevant instruction. Student test scores were analyzed to identify patterns of understanding, areas of conceptual difficulty, and the presence of misconceptions.

Descriptive analysis was conducted by examining the frequency of correct and incorrect responses for each item. Based on these patterns, students' levels of conceptual mastery were categorized using Table 1, which provides percentage intervals and corresponding categories adapted from Arikunto in Maksum et al., (2017).

Table 1. Categories of Concept Mastery

Percentage	Category
90%–100%	Very High
75%– 89%	High
60%–74%	Medium
40%–59 %	Low
0%-39 %	Very Low

This classification provided a structured framework for describing students' conceptual profiles and interpreting the variation and depth of their mastery across the group. To further identify misconceptions, a distractor analysis was employed. This involved analyzing the most frequently chosen incorrect options to determine which concepts were consistently misunderstood. The repeated selection of specific distractors by many students served as an indicator of misconceptions and helped pinpoint the conceptual areas requiring reinforcement.

RESULTS AND DISCUSSION

This study aims to map the level of mastery of basic thermodynamic concepts among students in the Chemistry Education study program. Data were collected through multiple-choice tests designed to assess students' understanding of six key thermodynamics topics: gas systems and laws, the kinetic theory of gases, states and state functions, systems and surroundings, thermodynamic processes, and the first law of thermodynamics. Based on the analysis of the test results, students were categorized into three levels of concept mastery: high, medium, and low. Additionally, distractor analysis was performed to identify common misconceptions. The findings from both the concept mastery categorization and distractor analysis provide insights into the extent of students' understanding and highlight areas where conceptual difficulties remain in learning thermodynamics. The results, including the percentage of student concept mastery and the corresponding mastery categories, are presented in the table below:

Table 2. Percentage Results and Level of Concept Mastery

Basic Concepts of Thermodynamics	Percentage of Concept Mastery	Level of Concept Mastery
Gas systems and gas laws	83,93%	High
Kinetic theory of gases	79,80%	High
State and state functions	83,60%	High
Systems and surroundings	84,80%	High
Thermodynamic processes	93,92%	Very High
The first law of thermodynamics	72,93 %	Medium

Based on the data in Table 2, it can be seen that most students demonstrated a level of conceptual mastery in the very high category, particularly in the topic of thermodynamic processes, which achieved the highest percentage of 93,92%, placing it in the very good category. This indicates that students are relatively able to understand the differences between isochoric, isobaric, isothermal, and adiabatic processes, as well as their energy implications. In the other four topics, such us gas systems and gas laws, the kinetic theory of gases, state and state functions, and systems and environments, student mastery was also classified as high, with percentages ranging from 79,80% to 84,80%. However, the topic of the first law of thermodynamics had a score of only 72,93%, placing it in the moderate category. This suggests that some students still struggle to understand the relationship between heat, work, and energy changes in a system.

Mastery of Gas System Concepts and Gas Laws

The mastery level for gas systems and gas laws was 83,93%, categorized as good. Students generally demonstrated the ability to apply fundamental gas laws, such as Boyle’s, Charles’, Avogadro’s, and Dalton’s. However, notable misconceptions appeared in two items involving molecular interactions under high pressure and the compressibility of real gases. Many students incorrectly identified “cohesive forces” as acting between neutral gas molecules under high pressure, reflecting a confusion between intermolecular interactions and bulk liquid behavior. Others wrongly believed that real gases are more compressible at high pressure due to attractive forces, when in fact, they deviate from ideal behavior and become less compressible. These misconceptions reflect inaccurate mental models of gas behavior, as also found Madden et al., (2011). Nurulwati et al., (2024) emphasized that students struggle with the ideal gas equation due to its abstract, mathematical nature and limited use of visual supports.

From a constructivist learning perspective, students’ misconceptions often arise when their prior knowledge or everyday experiences conflict with scientifically accepted models. This challenge becomes more significant when students are required to integrate macroscopic observations with molecular-level reasoning, as often seen in gas law topics. (Martinez et al., 2021) demonstrated that the cognitive demands of such tasks can overload working memory, especially in the absence of instructional scaffolding like guided simulations or screencasts. Without these supports, students tend to rely on memorized associations rather than develop meaningful conceptual understanding. Mayer (2009) multimedia learning theory reinforces the importance of integrating visual and verbal information to promote the construction of coherent mental models. Consequently, students may misinterpret molecular interactions, misuse terminology such as ‘cohesion’, or struggle with with abstract representations. To effectively address these persistent misconceptions, instruction should incorporate conceptual simulations, multiple representations (macroscopic, microscopic, and symbolic), and formative assessments that elicit and refine students' thinking.

Mastery of the Kinetic Theory of Gas Concept

Students demonstrated a high level of mastery (79,80%) in the kinetic theory of gases, showing that most were able to explain and apply key principles such as the relationship between pressure, temperature, volume, and molecular kinetic energy in both ideal and real gases. The concept was assessed through four questions, three categorized as high mastery, and one as sufficient.

The lower-performing item i that when a system involves determining the value of the gas constant R from experimental data or by using the Boltzmann constant. Many students answered incorrectly due to confusion with unit conversions and exponential notation (e.g., $J \cdot mol^{-1} \cdot K^{-1}$ vs. $erg \cdot mol^{-1} \cdot K^{-1}$). These findings are consistent with Usu et al., (2019), who reported that many students struggle with interpreting and applying physical constants due to a lack of understanding in unit analysis and dimensional relationships. Yilzid, (2023) further noted that when constants are presented in exponential form or without context, students tend to memorize the numerical values without internalizing their meaning or application. This leads to procedural recall rather than conceptual understanding. From a constructivist perspective, such misconceptions arise because students fail to link macroscopic and microscopic representations of gas behavior. Without strong conceptual bridges, formulas involving constants like k and become abstract and prone to misapplication.

Cognitive Load Theory, as applied by Meissner & Bogner, (2013), explains that symbolic reasoning involving constants and units can impose excessive cognitive demands when not supported by appropriate instructional design. They argue that without visual scaffolding or structured problem-solving guidance, students experience high intrinsic and extraneous cognitive load, which impairs conceptual integration. In line with Mayer's Multimedia Learning Theory, instruction that includes multiple representations, such as unit flowcharts, conceptual diagrams, or interactive simulations, can significantly improve student understanding of gas constants by providing meaningful connections between numeric, symbolic, and conceptual levels. While the overall mastery was high, this specific weakness highlights the need for more deliberate instruction on constants, units, and their scientific meanings. Activities involving unit tracking, symbolic derivations, and macroscopic to microscopic connections should be embedded across thermodynamics instruction.

Mastery of the Concept of State and State Function

The concept of state and state functions achieved a high mastery score of 83,60%. Students generally demonstrated an ability to distinguish between intensive and extensive variables, apply state equations, and differentiate between state and process functions. However, a closer analysis of students' responses reveals persistent misconceptions, particularly in identifying thermodynamic variables that depend on the process path and distinguishing them from actual state properties. For instance, many students incorrectly classified process-dependent variables, such as heat and work, as state functions, and misidentified Helmholtz free energy as not being a state function. These misconceptions suggest a fundamental misunderstanding, where students perceive heat and work as intrinsic system properties, rather than energy transfers that depend on the path taken. Similar patterns were observed in recent studies by Brundage et al., (2024) who reported that even advanced students often confuse path-dependent and state-dependent variables, especially when interpreting thermodynamic equations conceptually.

From a learning theory standpoint, such misconceptions are consistent with the constructivist view, which holds that learners interpret new information through the lens of prior experiences. When students approach thermodynamic concepts with intuitive or everyday notions of “energy” and “heat,” these ideas may conflict with scientific definitions unless conceptual restructuring occurs (Foroushani, 2019). The abstract and equation heavy nature of thermodynamics also contributes to cognitive overload, particularly when concepts such as internal energy, enthalpy, and free energy are introduced simultaneously. Cognitive Load Theory supports this, emphasizing that excessive intrinsic load can lead students to rely on memorized associations rather than meaningful understanding.

Additionally, Zhu & Xiang (2022) found that a lack of visual and contextual support, such as energy diagrams or process animations limits students' ability to differentiate between state and process functions. Their study of student reasoning about heat engines revealed that learners often view energy exchanges as substance like and fail to apply formal thermodynamic definitions when interpreting physical processes. Despite the high overall score, these findings indicate that students' conceptual understanding remains superficial. Instruction should go beyond definitions and equations by incorporating visual representations, contrastive reasoning tasks, and guided inquiry. By explicitly addressing common misconceptions and providing conceptual scaffolding, educators can foster a more robust and transferable understanding of state and process functions in thermodynamics.

Mastery of the Concept of Systems and Environments

The concept of systems and environments received a score of 84,80%, which falls into the high category. That's indicates general competence in identifying system types, boundary conditions, and system-environment interactions. However, distractor analysis revealed a common misconception: many students labeled walls that block both energy and mass as "partition walls" instead of correctly identifying them as "adiabatic walls." This points to a superficial understanding of boundary conditions and a weak grasp of how walls regulate the exchange of energy and matter. This finding is consistent with Brown & Singh (2022), who found that many students misinterpret thermodynamic boundaries, particularly when analyzing heat and work interactions on PV diagrams. Their research emphasized that these misconceptions are rooted not in lack of terminology, but in underdeveloped conceptual frameworks. From a learning theory perspective, these errors reflect the influence of prior, intuitive notions, where students map everyday ideas of "walls" onto scientific categories.

According to Taber, (2021), such alternative conceptions persist because learners often lack opportunities to confront and restructure prior knowledge through guided conceptual conflict. Rather than relying solely on general frameworks such as Cognitive Load Theory or Multimedia Learning Theory Meissner & Bogner, (2013) argues for the use of targeted instructional design that incorporates analogical reasoning and visual schematics to improve comprehension in complex scientific domains. They showed that using structured graphic organizers and contrastive visuals, such as diagrams comparing adiabatic and diathermal boundaries, helps reduce confusion and enhance knowledge retention.

Mastery of Thermodynamic Process Concepts

The concept of thermodynamic processes received a score of 93,92%, placing it in the very high category. Students generally demonstrated the ability to distinguish between different thermodynamic processes, namely isothermal, isobaric, isochoric, adiabatic, and isentropic, and analyze them in terms of state variables such as temperature, pressure, volume, entropy, and heat transfer. This finding aligns with Adila et al. (2018), who reported that students can typically recall definitions of these processes and recognize their basic characteristics. However, a deeper analysis of students' response patterns reveals persistent misconceptions that indicate a fragile conceptual foundation. For instance, on an item asking which process involves no entropy change, many students incorrectly selected the adiabatic process. While adiabatic processes do not involve heat transfer ($Q = 0$), entropy remains unchanged only when the process is also reversible, that is, isentropic. This misconception, assuming "no heat" implies "no entropy change", was also documented by Brundage et al., (2024), who found that even upper-level physics students struggle to dissociate heat flow from entropy change and often conflate adiabatic with isentropic processes.

Another common error was selecting isothermal as the process occurring at constant pressure, indicating confusion between thermodynamic variables. This type of error suggests that students may rely on memorized associations rather than relational reasoning. Georgiou & Sharma, 2015)observed that such confusion is widespread, especially when instruction lacks visual or conceptual scaffolding. Without diagrams or dynamic models, students often misapply concepts under verbal-only instruction. From a learning theory perspective, these misconceptions can be explained using diSessa's Knowledge-in-Pieces framework, which suggests that students build understanding from fragmented, experience-based knowledge units or "p-prims (diSessa, 2018). In this case, intuitive beliefs like "no heat means no change" may work in everyday contexts but mislead students when applied to abstract thermodynamic systems. Effective strategies might include visual simulations of thermodynamic systems, structured argumentation that connects claims to evidence and theoretical warrants, and conceptual conflict discussions that target and correct intuitive but incorrect understandings.

Mastery of the First Law of Thermodynamics Concept

The concept of the First Law of Thermodynamics received the lowest average score of 72.93%, placing it in the moderate category. The learning objectives for this concept include the ability to understand and apply the principle of energy conservation in thermodynamic systems, including the relationship between heat (Q), work (W), and internal energy (ΔU). Although students were generally able to recall basic definitions, many had difficulty correctly applying the law, especially in formulating the equation $\Delta U = Q - W$ and assigning the appropriate signs to heat and work. The distractor analysis revealed that students frequently made errors in determining the direction of energy transfer, indicating a lack of understanding regarding when energy is entering or leaving the system. These findings are consistent with previous studies (Suroso in Sudarmo et al., 2018; Brown & Singh, 2021) which report that students often use formulas mechanically without fully grasping the conceptual meaning behind them.

From a conceptual standpoint, these errors suggest that students still perceive heat and work as separate, unrelated quantities, rather than as interconnected components of internal energy change. As noted by Loverude et al., (2002), students often fail to view energy as a conserved quantity that can be transferred in different forms. For instance, some assume that some assume that if a system performs work, its internal energy must always decrease, without considering whether heat is added to the system to compensate. According to Constructivist Learning Theory, such misconceptions may stem from prior experiences and intuitive beliefs about "energy" and "work" that are inconsistent with scientific models. diSessa's Knowledge-in-Pieces framework (diSessa, 2018) further explains that students often rely on intuitive fragments, such as "positive means gain" or "work removes energy", which can interfere with formal reasoning if not explicitly challenged during instruction.

In addition, Cognitive Load Theory offers insight into why students tend to rely on memorization. The First Law involves processing multiple abstract variables simultaneously, which can overwhelm students' working memory, especially in the absence of supporting visuals or guided reasoning strategies. To address these issues, learning activities should incorporate energy flow diagrams, bar charts, and structured argumentation tasks that help students visualize the relationships between heat, work, and internal energy. This approach not only promotes conceptual understanding but also helps students develop the reasoning skills necessary to apply the First Law more accurately and meaningfully.

The findings show that while students generally demonstrated high mastery in most thermodynamics topics (particularly thermodynamic processes) conceptual weaknesses persist, especially in understanding the First Law of Thermodynamics. Distractor analysis revealed recurring misconceptions across topics, indicating that many students rely on memorized rules rather than deep conceptual understanding. These results highlight the need for instructional strategies that integrate visual representations, simulations, and formative assessments to address misconceptions and support meaningful learning in thermodynamics.

CONCLUSION AND RECOMMENDATIONS

This study shows that, in general, students in the Chemistry Education study program have a good level of mastery of basic thermodynamic concepts, with most topics falling in the high to very high category. The highest mastery was recorded in the topic of thermodynamic processes (93,92%), reflecting a strong understanding of various types of processes and their characteristics. The other four topics, gas systems and gas laws, kinetic theory of gases, state and state functions, and systems and environments, also showed encouraging results, with an average score above 79%. However, there were significant conceptual weaknesses in the topic of the First Law of Thermodynamics, which only reached the moderate category (72,93%). The main errors were found in the understanding of the signs of heat and work, as well as the direction of energy flow, indicating lingering misconceptions about sign conventions and energy interpretation within the system. Additionally, several misconceptions were identified in the topic of gas systems and gas laws, particularly in distinguishing between ideal and real gases and understanding the constants and units in the kinetic theory of gases.

Based on the results of this study, improvements in learning should focus on the topic of the First Law of Thermodynamics, emphasizing the understanding of the concepts of heat, work, and internal energy, as well as the use of appropriate sign conventions. The use of visual media, simulations, and multiple representations is recommended to clarify the concepts of ideal gases, real gases, and the kinetic theory of gases. Learning should also actively involve students through discussions, problem-solving, and strengthening the relationships between concepts to reduce misconceptions and enhance overall understanding.

Future research should consider developing a more comprehensive diagnostic instrument, not only in the form of multiple-choice questions but also incorporating descriptive questions or interviews to gain deeper insights into students' conceptual understanding and misconceptions.

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