Available online at: http://journal.uny.ac.id/index.php/jpms

Jurnal Pendidikan Matematika dan Sains, 14 (1), 2026, 1–10

Analysis of The Thermodynamics Problem-solving Process Based on Polya's Stages in High School Students

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Abstract

This research was motivated by the importance of problem-solving skills as part of the higher-order thinking skills required in physics learning, especially in complex and abstract thermodynamics materials. The complexity of materials, including internal energy, ideal gases, and the laws of thermodynamics, often caused difficulties for students in understanding and solving problems. This study aimed to analyze students' problem-solving skills in thermodynamics based on Polya's problem-solving stages. The research employed a survey method involving 36 students who completed a problem-solving test covering topics of internal energy, ideal gas, and the laws of thermodynamics. The overall problem-solving score was 53,59%, categorized as low. The highest achievement was in understanding the problem (64,8%, moderate), followed by devising a plan (54,01%, low), carrying out the plan (46,60%, low), and looking back (45,37%, low). These results indicated that students experienced difficulties in selecting appropriate concepts, applying relevant formulas, and evaluating solutions systematically. The findings suggested that students' problem-solving skills in thermodynamics remained weak and required more effective instructional approaches. This study contributed to the achievement of Sustainable Development Goal 4 (Quality Education) by highlighting the need to enhance problem-solving skills to improve the quality of physics education.

Keywords: *Polya, Problem-solving skills, Thermodynamics.*

How to Cite: Lutfiani, S., Liliawati, W., Samsudin, A., & Aviyanti, L. (2025). Analysis of the thermodynamics problem-solving process based on polya's stages in high school students. *Jurnal Pendidikan Matematika dan Sains, 14*(1), 1–10. https://dx.doi.org/10.21831/jpms.v14i1.90339

Permalink/DOI: ***DOI:*** . https://dx.doi.org/10.21831/jpms.v14i1.90339

INTRODUCTION

Education is one of the 17 goals of the Sustainable Development Goals (SDGs), and quality education is also a key factor contributing to a nation's progress (Hana et al., 2024). As an effort to achieve quality education, 21st-century education emphasizes the importance of developing individuals who are innovative, adaptive, and prepared to face global change. (Muyambo-Goto et al., 2023; Rahman, 2019). 21st-century education has brought about fundamental changes in the learning paradigm, particularly in the competencies that students must possess to address global challenges. 21st-century education requires students to have high-level skills (high-order thinking skills), one of which is problem-solving skills. Problem-solving skills are fundamental human activities that are crucial in learning because they can enhance self-confidence, improve daily decision-making, and accustom students to solving problems ranging from simple to complex (Hadi & Radiyatul, 2014; La'ia & Harefa, 2021; Yuhani et al., 2018). Problem-solving skills are essential for assisting students in comprehending concepts, the relationships between concepts, and their interconnections with other fields through the construction of problem representations to facilitate understanding (Amanda et al., 2020). Supporting students' problem-solving skills, solution planning, and the sequence of various stages involved in developing meaningful solutions to problems has become a challenge in learning, especially in physics (Chinofunga et al., 2025).

Physics is a science that requires a great deal of problem-solving (Pasigon, 2022). Physics learning is the process of studying nature and its phenomena through a series of activities to acquire, process, and transfer knowledge, attitudes, and skills that aim to improve analytical, logical, deductive thinking skills and problem solving by linking existing theories to complex problems related to everyday life (Darmawan et al., 2020; Napis, 2018; Nayazik, 2017; Setianingrum et al., 2016). The development of problem-solving skills, one of the higher-order thinking skills that is crucial for students to face the challenges of this century, is an essential part of physics learning (Docktor et al., 2015). Problem-solving skills are critical because everyone is constantly faced with various problems that require logical solutions. This ability is the primary key in understanding various complex and applicable physics concepts, including one of the important materials, namely thermodynamics.

Thermodynamics material, which encompasses abstract concepts such as internal energy, entropy, and thermodynamic processes, often causes confusion among students (Christensen et al., 2009). This is especially true for understanding and applying the material to solve problems because it is difficult to visualize directly. The complexity of the material, which encompasses numerous variables and relationships between concepts, as well as failures in analyzing and planning problem-solving strategies, are some of the causes of this difficulty (Mason & Singh, 2016). In line with Wantrilita & Rohaeti (2025), who revealed that many students struggle to understand thermodynamics concepts because they cannot see their direct applications in daily life. Hijriani & Hatibe (2021) also stated that factors influencing the difficulty of solving physics problems in students include the learning activities experienced by students and the learning in schools that have not effectively trained problem-solving skills. It is essential to understand the profile of students' problem-solving skills in thermodynamics material as a basis for creating more effective learning programs. Problem-solving skills can be examined through the general strategies employed in problem-solving (Siringoringo et al., 2018). For this reason, a systematic strategy to analyzing problem-solving skills can be adopted by referring to the theory proposed by (Polya, 1973).

According to Polya, there are four stages in problem-solving: understanding the problem, devising a plan, carrying out the plan, and reflecting on the outcome. Understanding the problem stage involves being able to clearly state what is known and what is being asked. The devising a plan stage involves finding the relationship between known and unknown data to develop a solution plan. The carrying out the plan stage involves implementing the solution plan and checking it at each step. Finally, the looking back stage is the ability to re-examine the steps taken to obtain the solution. The problem-solving stages, as outlined by Polya, have demonstrated their effectiveness in various learning contexts, particularly in physics learning (Okafor, 2019; Olaniyan & Govender, 2018). Research (Gok, 2014) shows that Polya's stage strategy can improve students' ability to solve physics problems. Research by Malik et al. (2019) states that learning with a problem-solving strategy that utilizes Polya's stages can enhance students' critical and creative thinking skills when solving complex physics problems.

An in-depth analysis of the problem-solving skill profile in thermodynamics using Polya's stages is crucial for several reasons. First, the analysis provides a detailed picture of the challenges students encounter at each stage of the problem-solving process. This information can serve as a basis for creating learning programs that are more tailored to students' needs and maximize their potential (Tawfik et al., 2020). Second, understanding how students think and the methods they use to solve thermodynamic problems can help teachers create more effective assessment instruments (Singh & Marshman, 2015). Third, identifying students' strengths and weaknesses in each stage of problem-solving can provide the basis for more targeted support and scaffolding. Research by Christensen et al. (2009) suggests that problem-solving skill profiles can reveal specific patterns of difficulty experienced by students in thermodynamic concepts, such as entropy, enthalpy, and thermodynamic processes. Furthermore, understanding how students apply Polya's stages in the context of thermodynamics can help them develop more effective problem-solving strategies. The analysis of problem-solving skill profiles can be helpful for assessment because it reveals errors and misunderstandings that often occur when learning thermodynamics, serving as a basis for innovation and improvement in thermodynamics learning.

This study focused on final-grade science students, as at this level, the topic of thermodynamics has been introduced, encompassing abstract concepts such as internal energy, entropy, and the laws of thermodynamics, which are often difficult for students to comprehend. It is expected that final-grade science students have developed adequate abstract thinking and formal reasoning abilities, enabling them to comprehend complex physics concepts such as those found in thermodynamics. The purpose of this study was to evaluate students' problem-solving skills in thermodynamics material, based explicitly on George Polya's problem-solving stage, which consist of understanding the problem, devising a plan, carrying out the plan, and looking back. This study does not aim to improve students' understanding, but rather focuses on how students apply these stages to solve problems related to thermodynamic concepts.

METHOD

This descriptive study used a survey method. The research subjects were 36 final-grade science students at a senior high school in Bandung Regency. The sampling technique used was simple random sampling, in which the classes involved were selected randomly from all existing classes, without any specific criteria limiting the selection of classes. Data collection was carried out using a test with a problem-solving skills test sheet. The test used was adopted from a study that had been declared valid and reliable to obtain information about students' physics problem-solving skills in thermodynamics (Ilma et al., 2024).

The test was in essay form with a total of three questions. Each question contained four stages of problem-solving skills according to Polya. The indicators for each question are shown in Table 1. All data obtained was then scored and analyzed. The scoring guidelines for students' physics problem-solving skills were adopted from Septriansyah et al. (2022), as shown in Table 2.

Table 1. Question indicators and problem-solving skills stages

No.	Question Indicator	Problem-Solving Skills Indicator
1	Analyzing the magnitude of the system's work based on the First Law of Thermodynamics	a. Students can write down the quantities given in the problem and the quantities being asked. b. Students can select the appropriate concepts and determine the correct equations. c. Students can perform calculations using the selected equations to obtain the correct results. d. Students can draw conclusions from the answers they have obtained.
2	Analyze the relationship between heat and work and their impact on internal energy.	
3	Analyzing the amount of heat by applying ideal gas processes based on the First Law of Thermodynamics	

Table 2. Scoring guidelines for problem-solving skills

Stage	Score	Description of Student Answers
Understanding the problem	0	No answer
	1	Incorrect answer
	2	The answer is correct but incomplete.
	3	Correct and complete answer
Devising a plan	0	No answer
	1	Incorrect answer
	2	The answer is correct but incomplete.
	3	Correct and complete answer
Carrying out the plan	0	No answer
	1	Incorrect answer
	2	The answer is correct but incomplete.
	3	Correct and complete answer
Looking back	0	No answer
	1	Incorrect answer
	2	The answer is correct but incomplete.
	3	Correct and complete answer

Based on the results of the data processing, students' physics problem-solving skills were interpreted according to the criteria proposed by Septriansyah (Septriansyah et al., 2022). The total score percentage was classified into five qualification category. A percentage score ranging from 85 to 100 indicates a very high level of problem-solving skills. Scores between 70 and 84,99 are categorized as high, while those between 55 and 69,99 are considered moderate. Meanwhile, scores ranging from 40 to 54,99 fall into the low category, and those between 0 and 39,99 are classified as very low. Next, the data were analyzed using descriptive statistics to provide an overview of student's problem-solving skills levels. Then, the student data was grouped by skill level and described.

RESULT AND DISCUSSION

Data on students' problem-solving skills are categorized into five groups, as shown in Table 3.

Table 3. Statistical description of student scores

Qualification	Amount	Percentage
Very low	8	22,22
Low	10	27,78
Moderate	13	36,11
High	3	8,33
Very high	2	5,56

Students' problem-solving skills are divided into five categories: very low, low, moderate, high, and very high. The majority of students, 13 (36,11%), fall into the medium category. However, the data show that the proportion of students with problem-solving skills in the low and very low categories is still quite large, namely 10 (27.78%) and 8 (22.22%), respectively. Thus, more than half of the students (50%) demonstrate problem-solving abilities that fall below the moderate category.

Furthermore, the research results related to the statistical description of students' problem-solving skills scores are shown in Table 4 below.

Table 4. Statistical description of student scores

Statistics	Total score
Ideal score	36
Maximum Score	31
Minimum Score	9
Average	18,97
Variance	29,74
Standard Deviation	5,45

Table 4 shows a statistical description of the students' problem-solving skill scores in the study. The highest and lowest scores obtained by students were 31 and 9, respectively, while the ideal score set was 36. The ideal score indicates the maximum score that should be achieved using ideal criteria. From all the collected data, an average of 18,97 was obtained, indicating a general trend in students' problem-solving abilities. In addition, the variance value of 29,74 indicates the level of dispersion of students' score data from the average. In contrast, the standard deviation of 5,45 indicates the extent to which students' scores deviate from the general average. These data provide an overview of the variation and trend in students' problem-solving skills in the study.

The distribution of data related to students' problem-solving skills is shown in Figure 1.

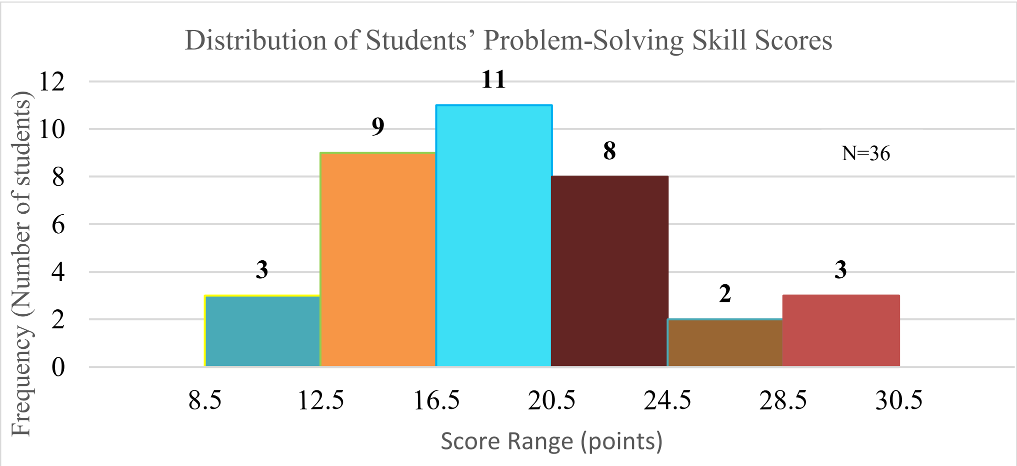

Figure 1. Histogram problem-solving skills

Figure 1 shows the distribution of problem-solving skills test scores. The lowest scores were in the 8,5-12,5 grade range, with three students, while the highest scores were in the 28,5-30,5 grade range, with three students. The highest scores were in the 16.5-20.5 grade range, with 11 students, and the lowest scores were in the 24.5-28.5 grade range, with two students. The assessment of students' problem-solving skills is reflected in the percentage of each indicator. The percentage value is obtained from a test consisting of 3 descriptive questions, each of which contains all indicators of problem-solving skills. The percentage of problem-solving skills obtained is categorized according to Septriansyah et al. 2022). The average test score results for each problem-solving skill indicator are presented in Table 5

Table 5. Average test scores, problem-solving skills stages skills indicator

Stage	Indicator	Percentage
Understanding the problem	Students can write down the quantities listed in the questions and the quantities asked for.	64,81
Devising a plan	Students can select concepts and determine the correct equations.	54,01
Carrying out the plan	Students can perform the calculation process using the selected equation to obtain correct results.	46,60
Looking back	Students conclude the answers they have made.	45,37
Average		53,59

Table 5 presents the average test scores of students for each problem-solving skill indicator across four stages. In the first stage, understanding the problem, students could write down the quantities listed in the problem and the quantities asked, with an average percentage of 64,81%, which is categorized as moderate. In the second stage, when devising a plan, students' ability to select concepts and determine the correct equation reached only an average percentage of 54,01%, which falls within the low category. Furthermore, in the third stage, when carrying out the plan, students' ability to perform the calculation process using the selected equation only reached an average percentage of 46,60%, which falls within the low category. In the final stage, looking back, students' ability to conclude the answers they had made had an average percentage of 45,37%, which falls within the low category. The data indicate that students' ability to understand problems is at a moderate level. In contrast, their abilities to devise plans, implement them, and review results remain at a low level. These findings suggest that greater attention should be given to these aspects in the learning process.

Overall, the profile of students' problem-solving skills falls into the low category. This is reinforced by the findings of Dumila et al. (2023), which indicate that students' problem-solving skills are low due to their limited ability to understand what is known and what is asked in a problem, to devise a problem-solving plan or appropriate mathematical equations, to solve the problem according to the plan, and to recheck the results by concluding. The understanding the problem stage achieved an achievement of 64.8% with moderate qualifications, which is the highest percentage among all indicators. This shows that most students have been able to identify important elements in the thermodynamic problems presented by the teacher, although not yet fully optimally. Students can write known data, such as pressure, volume, and changes in internal energy, and determine what is asked in the problem. However, the results of the analysis show that there are still shortcomings, as students tend to understand the problem in general but are not yet accustomed to expressing it in the form of physical symbols and complete with units. These results are relevant Dumila et al. (2023), which found that some students are unable to convert problem sentences into symbolic forms, while others have limited ability to understand problem components when presented in story form. Polya’s theory emphasizes that understanding the problem is the foundational step in the problem-solving process. Since this process is sequential in nature, failure to complete the first stage effectively can result in mistakes in the following stages. Several studies have also found that problem representation skills are essential for successful problem solving (Effendi, 2012; Farahhadi & Wardono, 2019). Similarly, Chinofunga et al. (2024) revealed that understanding the problem is the key to success in the next step of solving problems in learning. Students must first understand the "knowns" and "unknowns" of the problem, as well as what the problem demands. Therefore, although the understanding the problem stage achieved the highest achievement compared to other indicators, this achievement still needs to be reinforced through practice to navigate the subsequent stages of the problem-solving process successfully.

The devising a plan stage showed lower results, with a percentage of 54.01% at the low qualification level, indicating students' difficulties in selecting concepts and determining the correct equations. The results showed that many students had difficulty connecting the concepts of heat and work to internal energy in the concept of the First Law of Thermodynamics. In questions that required analyzing the relationship between quantities, most students had written the general formula but were unable to devise a specific formula to proceed to the next stage. Students had difficulty in determining concepts and tended to write general mathematical equations immediately without first developing a plan or deriving an equation based on an initial concept. This is in line with research by Nurkaeti (2018) showing that students experience difficulty in developing a plan and selecting the appropriate concept to solve the problem. Weaknesses at this stage indicate that students are not yet fully able to connect the data contained in the problem with relevant mathematical concepts. Lubis & Maysarah (2025) also found that students experience difficulties in systematically developing problem-solving strategies. Research conducted by Akbar et al. (2018) found that students face difficulties in converting verbal data into mathematical models. Students' skills in planning solutions still need improvement through more effective learning.

The carrying out the plan stage is the stage where students apply the strategies they have designed to obtain the correct solution. However, the study's results indicate that achievement at this stage is only 46.60%, particularly among those with low qualifications. Based on the selected equation, many students made errors when calculating the amount of heat in an ideal gas system. Many students were inconsistent in determining the positive and negative signs as signs of system work, so the final results were not appropriate. This suggests that most students struggle to implement the solution plan systematically and accurately. The quality of the plan implementation is highly dependent on the clarity and accuracy of the strategy developed in the previous stage. This stage is a continuation of the devising a plan stage. Given that students experienced difficulties in the previous stage, these challenges tend to persist in this stage. In line with Yayuk & Husamah (2020), the implementation stage is a process that is highly dependent on the previously prepared plan. At this stage, students are expected to be able to decompose information into mathematical form and apply the solution strategy through systematic calculation steps. This finding is also in line with Fatmawati et al. (2014) dan Simatupang et al. (2020), who found that students often make errors in calculations and the application of formulas. Errors in calculations and formula application indicate that learning tends to emphasize the result over the thought process. According to cognitive load theory as proposed by Sweller (1994), these difficulties may be attributed to the high cognitive load encountered when students are required to integrate physics concepts with mathematical procedures simultaneously. In this regard, repeated practice is crucial for improving students' procedural skills, allowing the implementation phase of the plan to develop with a meaningful understanding.

The final stage of the problem-solving process is looking back. At this stage, students are expected to be able to evaluate and reflect on the results of the solution. However, the results of the study indicate that this stage obtained the lowest percentage of 45.37% with low qualifications. Most students did not re-check the results of their work, such as whether the symbols of quantities and units were correct, whether the derivation from the general equation to the specific equation was correct, whether the substitution and calculation processes were correct, and whether the conclusions were correct. However, the results indicate a weak ability of students to draw conclusions based on the solution process and evaluate the answers obtained. So, basically, this stage requires the ability to reflect on the processes that have been carried out, starting from understanding the problem, developing a plan, and implementing the plan. The study Anwar & Amin (2013) shows that students rarely re-check their answers. This is supported by Widodo & Kartikasari (2017), who identified low student awareness of the importance of verifying results. In addition, Ulya (2016) also found that students' evaluation and reflection skills in problem-solving still require significant improvement. Weaknesses in the looking back stage indicate that the learning process has not thoroughly fostered a culture of reflective thinking. Learning that focuses on the result without allowing students to review their answers prevents them from drawing conclusions and verifying their results, thus hindering their development. Therefore, strengthening the looking back stage of the learning process is necessary.

Overall, it is necessary to strengthen the four stages of problem-solving skills proposed by Polya, namely understanding the problem, devising a plan, carrying out the plan, and looking back. Therefore, innovative, interactive, and learner-centered instructional approaches are essential to enhance students' problem-solving abilities. These efforts align with the Sustainable Development Goals (SDGs), particularly Goal 4 (*Quality Education*), which emphasizes the importance of improving the quality of education through learning that fosters higher-order thinking skills and the development of 21st-century competencies. In line with the opinion of Yusra et al. (2025), higher-order skills such as problem-solving are crucial, as they enable individuals to acquire deeper knowledge, address complex issues, and evaluate them from multiple perspectives. The implementation of innovative learning strategies, such as problem-based learning, discovery learning, and inquiry-based learning, represents a concrete step toward supporting the achievement of SDGs 4, which aims to ensure that all learners acquire the knowledge and skills necessary to promote sustainable development (Hana et al., 2024). Thus, improving problem-solving skills not only enhances learning outcomes but also contributes to global efforts to achieve quality education.

CONCLUSION

This study shows that students' problem-solving skills based on Polya's stages remain low, with an average score of 53,59%. The highest achievement was recorded in the understanding the problem stage (64,8%, moderate), while the lowest was in the looking back stage (45,37%, low). Students experienced particular difficulties in devising a plan and carrying out the plan, reflecting challenges in selecting concepts, applying equations, and evaluating answers. These results highlight the need for innovative teaching, curriculum development, improved teacher competency, and comprehensive assessment. Such efforts align with SDG 4, which promotes inclusive and quality education. Further research on innovative learning strategies is strongly recommended.

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