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Article

Fostering Students' Concept Mastery through STEM-Engineering Design Process in Thermal Energy and Heat Transfer Topic

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ABSTRACT
This study aims to investigate the effect of STEM-EDP on students' concept mastery in thermal energy and heat transfer topic. Employing a quasi-experimental design, the study incorporates pretest and posttest across both an experiment class and a control class. The Experimental class using the STEM-EDP while control class using the conventional as the learning approach. The study encompasses 35 seventh-grade students for each class from one of Junior High School in Bandung, Indonesia. The instruments include an objective test that spans cognitive levels from C1 to C5 based on the Bloom Taxonomy. The result shows that there are significant differences between experimental and control class in both concept mastery. This is evident from the p-values of 0.03 in independent t-test results for concept mastery. In terms of improvement, the N-Gain of experiment class for concept mastery stands at 0.22, characterizing a low improvement. While, the N-gain of control class is 0.08, also characterizing as a low improvement. In light of these outcomes, it is reasonable to consider STEM-EDP as a valuable pedagogical approach within Junior High School in fostering a deeper understanding of scientific concepts especially in thermal energy and heat transfer topic.

INTRODUCTION

The advancement of science and technology underscores the need for better-prepared human resources capable of addressing complex global challenges. It is clear that relying solely on knowledge and abilities within a single area of expertise is no longer sufficient to address these intricate issues. Instead, a transdisciplinary approach that integrates various fields of knowledge and skills is imperative to tackle the multifaceted challenges ahead (Budwig & Alexander, 2020). Emphasizing 21st-century abilities, such as problem-solving, in education reforms empowers individuals to tackle real-world issues effectively. As we seek to raise individuals who can contribute meaningfully to the resolution of global issues, education reforms are being implemented to cater to this evolving context (Uzel & Bilici, 2021). In light of these reforms, education systems worldwide emphasize the acquisition of problem-solving and creative thinking skills by individuals. Indonesia has a curriculum called kurikulum merdeka, this curriculum has an aim which is expected to help develop several student's skills, it also said in (Law Number 20 of 2003 concerning the National Education System Article 3) that indonesian student should posses several skill, which is strong faith and reverence for the Almighty, exhibit virtuous character, maintain good health, knowledgeable, capable, creative, independent, and become democratic and responsible citizens. These skills are not merely confined to academic settings but are expected to be integrated into individuals' daily lives, guiding their decision-making and problem-solving in various domains (Uzel & Bilici, 2021; Demir, 2015; Ernst & Haynie, 2010; Wells, 2008). By nurturing a generation of thinkers and problem-solvers, societies can forge ahead with confidence, knowing that they have the human capital to meet the demands of an increasingly intricate world. Through such reforms, education becomes a catalyst for positive change and progress on a global scale.

The process of mastering concepts is closely tied to learning activities and signifies a deep and meaningful understanding of the subject material. Mastery of a concept reflects the students' capacity to not only comprehend the meaning of the learning but also to apply it effectively in their daily lives (Astuti, 2020; Shidiq, Rochintaniawati, & Sanjaya, 2017). As Anderson and Krathwohl (2001) underline, understanding ideas may strengthen students' intellectual skills and provide them with problem-solving abilities essential for meaningful learning experiences. According to Meyer and Land (2006) and Clohessy (2021), students achieve concept mastery when they effectively assimilate new information into their existing cognitive framework. This integration process often results in a more comprehensive and enriched concept as prior knowledge synergizes with new insights (Batlolona, Baskar, Kurnaz, & Leasa, 2018). When students achieve concept mastery, they not only grasp the theoretical aspects of a subject but can also effectively apply the knowledge to real-life situations. This integration of learning into practical contexts fosters meaningful and applicable knowledge, empowering students to tackle challenges.

A significant connection between concept mastery and problem-solving was highlighted by Amanda, Sumitro, Lestari, & Ibrohim (2021). This finding underlines the importance of a strong grasp of foundational concepts for effective problem-solving. This sentiment is echoed by Gunawan et al. (2020), who observed that many students faced challenges during the initial stages of problem-solving, mainly attributed to their limited understanding of underlying concepts. The lack of concept mastery among students can be attributed, in part, to the learning strategies employed by teachers (Pujani, Suma, Sadia, & Wijaya, 2018). In many cases, the learning process revolves around traditional lecturing, with minimal opportunities for student collaboration and interactive learning. Furthermore, teaching materials may be insufficient or lacking in variety, limiting the scope for comprehensive understanding and application of concepts.

The key to overcoming the challenges of low concept mastery lies in adopting an appropriate learning approach that prioritizes student engagement, critical thinking, and creativity. STEM is an interdisciplinary educational method that emphasizes science, technology, engineering, and math (Fajrina, Lufri, &Ahda, 2020; Bybee, 2010). STEM education can also enhance the quality of human resources (Toma & Greca, 2018; Asmuniv, 2015). Students have the chance to comprehend difficulties in the actual world based on those multidisciplinary disciplines through STEM (Dugger, 2010). One general model of the creative process that can be used in STEM classes is the engineering design process (EDP) model (Householder & Hailey, 2012). Research to assess the engineering design process model found that an outreach challenge program might help rural secondary school students develop their problem-solving, creativity, and thinking abilities (Winarno et al., 2020; Siew, Goh, & Sulaiman, 2016). Lin, Wu, Hsu, and Williams (2021) noted that the engineering design process focuses on solutions and the construction of prototypes, which impels students to encounter the process of creative and critical thinking as well as problem-solving skills.

Numerous researchers have highlighted the engineering design process as a promising approach for tackling challenges in the fields of STEM (Nurtanto, Pardjono, &Ramdani, 2020; Farmer, Allen, Berland, Crawford, & Guerra, 2012; Householder & Hailey, 2012; Hynes et al, 2011). In this regard, Siew, Goh and Sulaiman (2016) has proposed a comprehensive seven-step engineering design process. These steps encompass identifying the need or problem, researching the need or problem, drawing or sketching possible ideas or solutions for the problem, selecting the best possible solutions, designing and constructing a prototype, testing and evaluating the solutions, and communicating the solutions. Throughout the seven stages of the engineering design process, learners are actively encouraged to develop and refine their creative and critical thinking abilities. This dynamic engagement in STEM activities nurtures students' problem-solving skills, empowering them to tackle real-world challenges with confidence and ingenuity.

One of the notable advantages of incorporating the engineering design process into STEM education lies in its emphasis on fostering a solutions-oriented mindset (Siew et al., 2016; Spires, Himes & Krupa, 2020). By engaging in the construction of prototypes, students are prompted to encounter the iterative process of creative and critical thinking, along with honing their problem-solving skills. This approach instills in learners the understanding that there are multiple avenues to find solutions, as they actively participate in brainstorming to identify problems and propose innovative solutions. Moreover, the engineering design process challenges participants to seek the optimal solution while working within specific constraints. This requirement demands a synthesis of critical thinking and problem-solving skills as students navigate the complexities of decision-making and resource management.

Numerous research studies have demonstrated the positive impact of engineering design process-oriented STEM activities on students' academic success (Dedetürk, Kirmizigül, and Kaya's, 2021; Doppelt Mehalik, Schuun, Silk, & Krysinski, 2008; Ercan & Sahin, 2015; Gülhan & Şahin, 2016; Wendell & Rogers, 2013). These findings highlight the close relationship between scientific conceptual knowledge and engineering design. STEM Engineering design (STEM-EDP) entails integrating both scientific content knowledge and the skills necessary for scientific inquiry and engineering design (National Research Council [NRC], 2012). STEM-EDP challenges students to identify problems, understand physics concepts, and devise effective solutions (Tank, Rynearson, & Moore, 2018), building on previous research (English & King, 2015; NRC, 2014).

Furthermore, researchers have identified several characteristics that constitute "engineering thinking," including systems thinking, adaptability, problem-finding, creative problem-solving, visualization, and improvement (Karatas-Aydin & Isiksal-Bostan, 2023; Lucas & Hanson, 2014). Some studies, like Park, Park, and Bates's (2018) research on explaining the concept of volume using the engineering design process, show that students grasp the concept correctly but not entirely while engaging in engineering practices. This highlights the value of using engineering activities to convey complex ideas and concepts related to physics, providing students with engaging and motivating learning experiences. Nevertheless, Dedetürk, Kirmizigül, and Kaya's (2021) research provided compelling evidence of how engineering design process-oriented STEM activities can significantly enhance students' conceptual understanding levels in the physics of sound.

From an early age, students begin to develop alternative ideas about heat, temperature, and heat transfer, often influenced by their direct experiences with warm and cold objects (Luce & Callanan, 2020; Schnittka, 2010). These early conceptions can persist throughout their educational journey and may prove challenging to change. Heat transfer is indeed a scientific topic that holds practical relevance in our everyday lives, and it is no exception when it comes to education in Indonesia (Anam, Widodo, & Sopandi, 2017; Batlolona et al., 2018). Understanding the principles of heat transfer is not only relevant from a scientific standpoint but also has practical applications in our daily lives. As students grasp the fundamentals of heat transfer, they gain the potential to apply this knowledge to create more useful and innovative products in the future.

Research has established that engineering design process-oriented integrated STEM activities have a positive impact on students' achievement levels in science (Dedetürk, Kirmizigül, and Kaya's, 2021;Ercan & Sahin, 2015; Harwell et al., 2015; Wendell & Rogers, 2013).The significance of incorporating the STEM-EDP into regular classroom practices is underscored by its ability to actively involve students in authentic problem-solving. According to Shume et al. (2022), educators express an increased commitment to empowering students with more responsibility throughout the problem-solving process, allowing them additional time to grapple with the iterative nature of design. This aligns with existing research findings, such as those by Bowen et al. (2021), which highlight that teachers exhibit higher motivation to integrate the EDP into their instructional methodologies. Similarly, Hanif, Wijata, Winarno, and Salsabila (2018) undertook a comparable research endeavor, concentrating on the implementation of STEM-Project Based Learning to investigate students' concept mastery within only higher order thinking skills which is C3 until C5, with pre-experimental (using one class) specifically within the light and optic topic. However, in this research, delves into students' concept mastery using the STEM-EDP across a wider range of cognitive levels, spanning from C1 to C5 with quasi-experimental (using two classes). Furthermore, the scope of the topic extends to thermal energy and heat transfer. Hence, this study aims to investigate the effect of STEM-EDP on students' concept mastery in thermal energy and heat transfer topic.

By incorporating the engineering design approach into the teaching and learning process, particularly within the context of thermal energy and heat transfer, students have the opportunity to enhance their concept mastery. A crucial aspect of this research is its aim to assist educators in effectively implementing the engineering design process within their teaching strategies. The objective is to cultivate students' concept mastery in the specific domain of thermal energy and heat transfer.

METHODS

The quasi-experimental method was employed to assess students' concept mastery pertaining to the topic of thermal energy and heat transfer. This methodology was chosen due to the inherent requirement for comparison between two distinct classes. Quasi-experimental designs are particularly advantageous in scenarios where comparison groups can be well-matched, thereby reducing the initial disparity between experiment and control classes. In this research, the chosen research design is the pre- and posttest design, a method frequently selected to scrutinize the disparities between pretest and posttest outcomes stemming from a specific intervention or treatment. Creswell (2012) stated that this research allows for a systematic examination of the effects of the treatment on the subjects' performance. A visual representation of this design is illustrated in Table 1 below.

Table 1. Pre- and Posttest Design

Group	Pretest (O_1)	Treatment	Posttest (O_2)
Experiment class	O_1	X	O_2
Control class	O_1		O_2

As depicted in Table 1, the variables O_1 and O_2 signify the measurements, while the symbol X represents the administered treatment which is STEM-EDP. The essence of this research design hinges on not merely assessing whether individuals subjected to the treatment exhibit enhanced performance but, more importantly, determining if their improvements surpass those observed in participants who were not subjected to the treatment (Creswell, 2012).

The participants involved in this research consisted of 7th-grade students from a junior high school, comprising a total of 70 students with 35 students for each class. The study was conducted at a private junior high school in Bandung, which implemented the Kurikulum

Merdeka and had not yet covered the topic of thermal energy and heat transfer. The age range of the participants varied between 12 and 13 years old. Additionally, the distribution of the sample was characterized by gender, as highlighted in the breakdown provided in Table 2.

Table 2. Detail of The Sample Based on Gender

Gender	Frequency	Percentage
Male	27	39%
Female	43	61%
Total	70	100%

In evaluating students' concept mastery, an objective test was administered. This test was designed based on Bloom's Revised Taxonomy and was used to gauge students' grasp of the subject matter before and after the implementation of STEM-EDP. Before the revision, the objective test consisted of 30 multiple-choice questions, encompassing cognitive domains such as C1 (remembering), C2 (understanding), C3 (applying), C4 (analyzing), and C5 (evaluating). The original blueprint for the scientific literacy objective test is presented in Table 3.

Table 3. Blueprint of Concept Mastery Objective Test Before Revision
Subtopik the Cognitive Process Dimension

Subtopik	The Cognitive Process Dimension				
	C1	C2	C3	C4	C5
Temperature			12, 13		27, 30
Heat				21	
Heat Capacity	2		14, 15		
Latent Heat	1	4,7	16, 17		26
Conduction		9		22, 24	
Convection		8, 10, 11		19, 18, 25	
Radiation	3			20, 25	29
Expansion		5, 6		23	28

To ensure the validity and reliability of the objective test, expert judgment was sought, and the test was validated by administering it to a group of 27 students who had already studied the thermal energy and heat transfer topic. The validation process involved analyzing the results using ANATES, which encompassed measures of validity, discriminating power (DP), difficulty level (DL), correlation, and acceptance. The compilation of test items is displayed in Table 4.

Table 4. Objective Test Analysis

Question Number	DP	DL	Correlation	Acceptance
1	42.86	Medium	0.4	Accepted
2	28.57	Medium	0.282	Accepted
3	71.43	Medium	0.286	Accepted
4	57.14	Medium	0.378	Accepted
5	28.57	Very Easy	0.222	Accepted
6	57.14	Medium	0.385	Accepted
7	71.43	Medium	0.580	Accepted
8	57.14	Hard	0.340	Accepted
9	28.57	Medium	0.201	Accepted
10	42.86	Medium	0.345	Accepted
11	57.14	Medium	0.430	Accepted
12	85.71	Medium	0.753	Accepted
13	100	Medium	0.747	Accepted
14	71.43	Medium	0.501	Accepted
15	42.86	Medium	0.398	Accepted

Question Number	DP	DL	Correlation	Acceptance
16	57.14	Medium	0.440	Accepted
17	14.29	Medium	0.304	Accepted
18	71.43	Hard	0.608	Accepted
19	14.29	Medium	0.153	Rejected
20	57.14	Hard	0.524	Accepted
21	57.14	Medium	0.505	Accepted
22	28.57	Hard	0.184	Rejected
23	71.43	Medium	0.514	Accepted
24	42.86	Medium	0.476	Accepted
25	14.29	Medium	0.204	Accepted
26	42.86	Hard	0.304	Accepted
27	42.86	Hard	0.307	Accepted
28	14.29	Medium	0.206	Accepted
29	57.14	Medium	0.528	Accepted
30	20.57	Medium	0.231	Accepted

Upon validation, it was found that two out of the 30 questions in the objective test needed to be rejected. Consequently, the final blueprint for the objective test was refined to include 28 questions, as illustrated in Table 5.

Table 5. Blueprint of Concept Mastery Objective Test After Revision

Subtopik	The Cognitive Process Dimension				
	C1	C2	C3	C4	C5
Temperature			12, 13		25, 28
Heat				20	
Heat Capacity	2		14, 15		
Latent Heat	1	4,7	16, 17		24
Conduction		9		22	
Convection		8, 10, 11		18, 23	
Radiation	3			19, 23	27
Expansion		5, 6		21	26

Ensuring the reliability of the test items is crucial in any assessment process. Reliability refers to the consistency of scores or responses across different administrations of the instrument and among different sets of items (Revelle & Condon, 2019; Fraenkel, Wallen, & Hyun, 2011). The assessment of the reliability of the test items is presented in Table 6.

Table 6. Objective Test Reliability

Subject	Score
Average	13.85
Standard Deviation	5.88
Reliability Test	0.79

From the data provided in Table 6, it is evident that the test items exhibited a reliability coefficient of 0.79. This signifies a high level of reliability, implying that the questions within the test can be consistently relied upon to measure students' concept mastery. Consequently, all the questions within the test can be considered appropriate research instruments for collecting data both before and after the treatment.

The evaluation of students' concept mastery involved utilizing Microsoft Excel for computational purposes and SPSS for statistical analysis. In order to assess the hypotheses, the Independent t-test was employed for concept mastery. The rationale behind choosing the Independent t-test for concept mastery was because all the data in the concept mastery in a normal distribution. Additionally, the computation of the N-Gain score was conducted to determine the extent of improvement (Meltzer, 2002).

$$\text{N} - \text{gain Score (g)} = \frac{\text{posttes score} - \text{pretest score}}{\text{maximum score} - \text{pretest score}}$$

The N-Gain score was calculated using the formula provided. Subsequently, the interpretation of the N-Gain score was cross-referenced with an interpretation table tailored for this purpose. According to Meltzer (2002), the interpretation of the N-Gain score is detailed in the Table 7 presented below.

Table 7. Interpretation of N-Gain Score

N-gain score	Interpretation
$g < 0.3$	Low
$0.3 \leq g \leq 0.7$	Medium
$g > 0.7$	High

Drawing from the insights gleaned from Table 6, the outcome scores were subsequently interpreted by referring to the same table. This interpretative process serves as the foundation for conducting the subsequent analysis and drawing meaningful conclusions based on the acquired insights.

The learning process is conducted in offline settings, involving four distinct classes of 7th grade students. Data collection was carried out in 7 meeting with 100 minutes for each meeting. The researcher assumes the role of both educator and facilitator during the teaching and learning sessions. It's important to note that throughout the research, the language employed is Indonesian. This decision is aligned with the language of instruction used within the school environment, where Indonesian is the primary language of communication among the students. The detailed breakdown of each instructional session is thoroughly documented and provided in Table 8, which serves as a comprehensive reference for the entire process.

Table 8. The Implementation Activities

Meetings	STEM-EDP Stages	Activities
1_{st} meetings	Identify the need or problem	1. At the beginning of the class, students were required to complete the pretest, which included both the objective test and the SIT-V assessment. 2. Students were then tasked with identifying the specific problem that needed to be addressed, a crucial step in the problem-solving process.
2_{nd} and 3_{rd} meetings	Research the need or problem	1. Through engaging in research, students deepened their understanding of the identified problem, setting the foundation for effective solutions.
4_{th} meeting	Draw/sketch possible ideas/solutions for the problem & Select Possible Solution	1. Drawing upon their scientific knowledge, students engaged in brainstorming sessions to generate potential solutions for the identified problem.
5_{th} meeting	Design and construct a prototype	1. Using a combination of scientific expertise and creative thinking, students leveraged their skills to design innovative solutions tailored to the problem at hand.
6_{th} meeting	Test and Evaluate the solution & Communicate the solution	1. Following the design phase, students moved on to the practical testing and evaluation of their proposed solutions, allowing them to assess the efficacy of their designs. They also communicated the results of their testing.
7_{th} meeting	-	1. Towards the conclusion of the class, students were prompted to complete the posttest, encompassing both the objective test and the SIT-V assessment.

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RESULTS AND DISCUSSION

To gauge the students' concept mastery, an objective test based on Bloom's Revised Taxonomy was utilized, which included a Pre-test and a Post-test. The Pre-test was administered to evaluate the students' existing knowledge before any intervention, while the Post-test was aimed at determining whether there was an improvement in cognitive mastery following the implementation of the engineering design process. The objective test measured various cognitive levels, namely C1 (remembering), C2 (understanding), C3 (applying), C4 (analyzing), and C5 (evaluating).

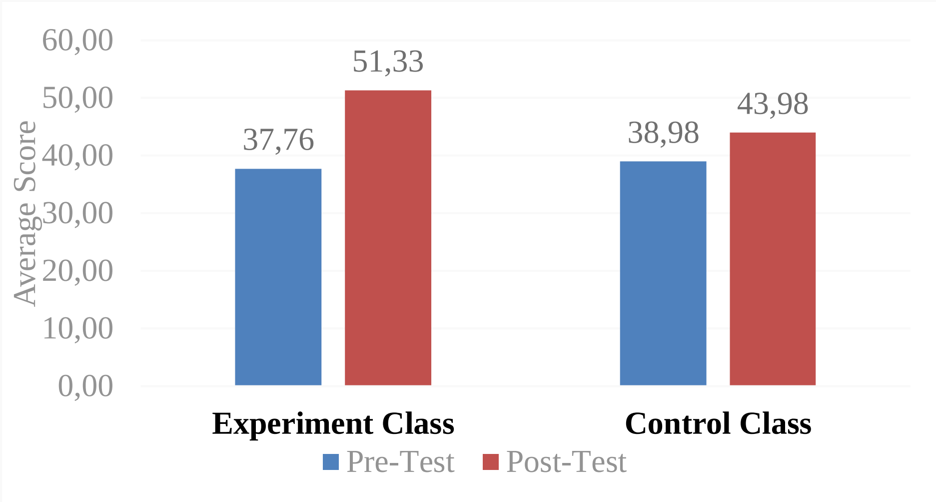

Figure 1. Comparisons of Concept Mastery Average Score between Experiment Class and Control Class Before and After Treatment

Figure 1 provides a visual representation of the significant improvement in the experiment class's scores when compared to the control class. Given the confirmation of normal distribution for both the pre-test and post-test scores in experiment and control class, the suitable statistical analysis to employ is the independent t-test. This choice is informed by the outcome of the prerequisite tests, as elucidated in Table 9.

Table 9. Recapitulation of Students' Concept Mastery Hypothesis Test

Component	Pre-Test		Post-Test	
	Experiment Class	Control Class	Experiment Class	Control Class
	Independent t-test		Independent t-test	
Signification (Sig α=0.05)	0.648		0.03	
Information	H_0 accepted		H_0 rejected	
Conclusion	There is no significant different		There is significant different	

In Table 9, the independent t-test results for the pre-treatment phase indicate that the null hypothesis (H_0) is accepted, while the alternative hypothesis (H_1) is rejected. The calculated independent t-test score is 0.648, which is greater than the significance level ($\alpha = 0.05$). This suggests that there is no significant difference in the students' concept mastery based on the pre-test scores between the experiment class and the control class before the treatment was administered. However, in the post-treatment phase, the independent t-test test yields a promising result with a score of 0.03, which is lower than the significance level ($\alpha = 0.05$). This indicates that there is a significant difference in the students' concept mastery between the experiment class and the control class after they received the treatment or intervention.

The findings from the independent t-test are further supported by the N-Gain score comparison between the experiment class and the control class, as depicted in Figure 2 The N-Gain scores demonstrate a notable improvement in the experiment class's concept mastery compared to the control class.

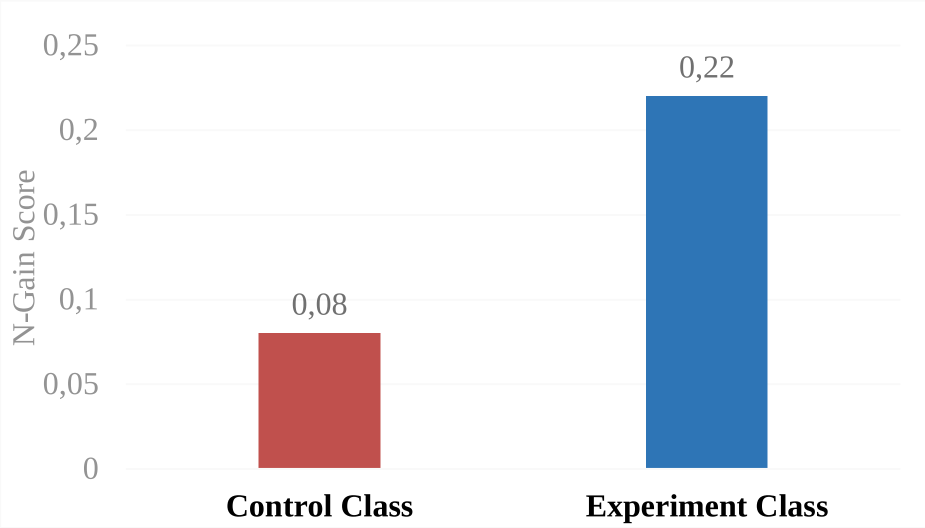

Figure 2. Comparisons of Concept Mastery N-Gain Score between Experiment Class and Control Class

The information presented in Figure 2 reveals crucial insights about the N-Gain scores in both the experiment class and the control class. Specifically, the N-Gain score in the experiment class is calculated to be 0.23, whereas in the control class, it stands at 0.08. The N-Gain score of the experimental class indicates a low level of improvement in concept mastery. However, when we compare this score to the N-Gain in the control class, the experimental class's N-Gain is relatively higher. On the other hand, the control class's N-Gain score also falls into the category of low improvement, indicating a modest increase in their concept mastery after undergoing the treatment. While both classes experienced low improvements in concept mastery, the experimental class showed a more significant gain compared to the control class. This suggests that the implementing EDP in the experimental class had a more pronounced impact on their learning outcomes than the approach used in the control class.

The engineering design process, as adapted from Siew et al. (2016), was implemented in the experiment class using the Save the Penguins (STP) curriculum. This curriculum, developed through the Virginia Middle School Engineering Education Initiative, challenges students to create a dwelling that reduces heat transfer to prevent a penguin-shaped ice cube from melting (Schnittka, Bell, & Richards, 2010). These steps encompass activities such as identifying the problem, conducting research, generating sketches for potential solutions, selecting the most promising ideas, creating prototypes, evaluating the effectiveness of the solutions, and ultimately communicating their findings.

In the initial phase of this learning model, students are tasked with identifying the problems associated with the challenge at hand. During this phase, students are introduced to the environmental conditions affecting penguins and the role of engineering in addressing climate change and energy consumption. They engage in group discussions to brainstorm possible solutions to the problem, aiming to meet specific criteria and limitations (Figure 3). To facilitate their understanding, the researcher provides relevant information and encourages creative thinking.

Figure 3. Identify The Problem Activity

In the process of generating the problem, students are expected to think like engineers, exploring ways to reduce energy use through the design of more energy-efficient buildings. To aid their conceptualization, students are required to create storyboards that visually depict the necessary steps for understanding each part of the "Save the Penguins" project. These storyboards serve as formative assessments, helping students break down key concepts and evaluate their progress at different stages of the lessons (Bartholomew, Yauney, Wolfey, & Park, 2022; Schnittka, 2010). Figure 4 shows one of the example made by the students.

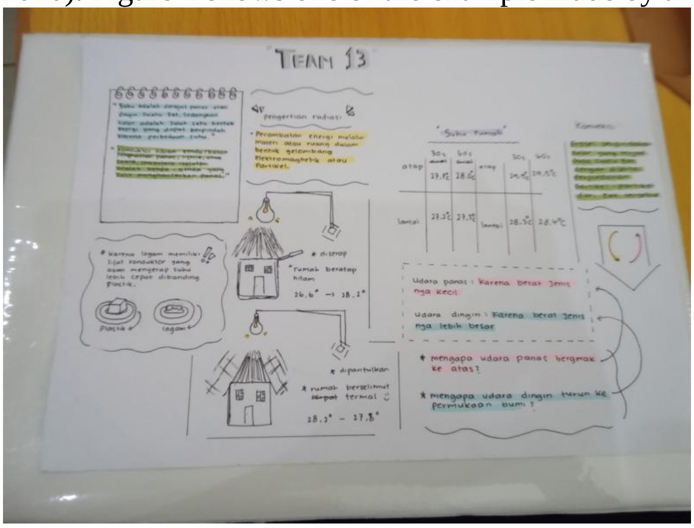

Figure 4. Storyboard

According to Syukri, Halim, Mohtar, and Soewarno, (2018), the identification and resolution of problems hold paramount importance in the engineering design process. Thus, it becomes essential to conduct studies that define and analyze the science concepts required for engineering education within the realm of science education. During this process, students identify the needs of the problem and articulate the science and mathematics content essential for their solution development (Fan & Yu, 2017; Arık & Topçu, 2020). As students engage in engineering design-based activities, they are exposed to the iterative and exploratory nature of the engineering process. By exploring various possibilities and embracing creativity, they learn to approach problems from diverse angles, culminating in the development of practical and ingenious solutions.

Following the phase of problem identification, it becomes imperative to understand the nature of the identified need or problem itself. During this crucial stage, students are entrusted with the responsibility of comprehending the intricacies of the problem, its underlying requirements, and devising a range of potential solutions (Nurtanto et al., 2020; Katehi, Pearson, &Feder, 2009). In this crucial stage, students are encouraged to apply their scientific knowledge rather than relying solely on trial and error methods. By doing so, they have the opportunity to assess their understanding of science content while also grasping essential engineering concepts (Nurtanto et al., 2020; Boesdorfer & Greenhalgh 2014).

To support students in gaining the necessary science and mathematics concepts required for developing effective design solutions, teaching and learning activities are thoughtfully organized. Within this phase, five demonstrations are provided as guiding tools. The initial demonstration centers around heat transfer, allowing students to develop an understanding of insulation, heat, and temperature (Figure 5). Subsequent demonstrations delve into different aspects of heat transfer, addressing key points such as the direction of heat transfer that emphasizing it occurs from warmer to cooler objects, the varying heat conductive properties of materials which highlighting how certain substances are better conductors of heat than others, the concept of radiation absorption and reflection by certain materials, and last the phenomenon of convection in fluids (liquids or gases) to illustrating how they sink or rise based on temperature changes.

Figure 5. Research The Problem Activity

Through these demonstrations, students are given the opportunity to engage with hands-on experiences and observe real-life examples related to heat transfer. This immersive approach allows them to internalize scientific principles and form a strong foundation for the subsequent phases of the engineering design process. Once students have gained a solid understanding of heat transfer, the next step in the engineering design process is to present them with the challenge: to construct a dwelling that will protect a penguin-shaped ice cube from melting. This task requires students to think creatively and draw upon their scientific knowledge to devise potential solutions. To begin, students must decide on the materials they will use for their dwellings. In this phase, scientific inquiry comes into play as students conduct tests to assess the effectiveness of different materials in preventing heat transfer (Figure 6).

Figure 6. Draw/Sketch Possible Ideas/Solutions For The Problem Activity

To begin, students are presented with a variety of materials, including felt, foam, cotton balls, paper, shiny Mylar, and aluminum foil, which they will use to test for their effectiveness in preventing heat transfer. They can compare these materials by conducting experiments under a 100-watt lamp shining on a black surface, such as a black countertop or plastic tray. Equipped with thermometers and timers, the students can accurately measure and record the temperature changes to fairly evaluate the performance of each material under the given conditions. As the students explore the different materials and observe their effects on heat transfer, they start to generate ideas and formulate potential solutions for building the ideal dwelling to preserve the penguin-shaped ice cube (Schnittka et al. 2010). Throughout this process, scientific inquiry plays a crucial role, encouraging the students to think critically and analytically while drawing conclusions based on their observations.

In this step, students collaborate in groups to brainstorm various solutions to the problem, pooling their ideas and insights together. They engage in dynamic discussions, weighing the pros and cons of each concept, and collectively decide on the most promising solutions. From this collaborative effort, they develop a plausible real-world solution that addresses the challenge at hand. Their proposed designs are then elaborated further through initial sketches and models (Han & Shim, 2019).

After that, students engage in discussions to assess how well each solution aligns with the criteria and constraints set for the problem (Nurtanto et al., 2020; Hynes et al., 2011). They analyze the strengths and weaknesses of each option, seeking to identify the most effective and efficient approach. Creativity plays a significant role in this step, as students are encouraged to explore various solutions and think outside the box. As mentioned by Lee and Kolodner (2011) and Bozkurt Altan and Tan (2021), creative designers and problem solvers should consider different approaches and draw from the solutions used for similar problems that could be applied to the current challenge. Moreover, during the evaluation process, students may encounter constraints or limitations that require them to adapt or modify their original ideas. They may need to think innovatively to work around these constraints while still ensuring that their solution remains viable and effective.

After selecting the best possible solution for the problem, the students put their knowledge into action by designing and constructing their own prototypes to protect the penguin-shaped ice cubes from melting. This hands-on phase is where the students truly take on the role of "engineers," drawing inspiration from real-world applications of materials used in buildings and structures to prevent heat transfer. As they embark on this engineering challenge, they are reminded that engineers play a crucial role in designing cutting-edge materials for buildings, schools, and various structures to effectively control heat transfer (Figure 7).

Figure 7. Design and Construct The Prototype Activity

Just like professional engineers, the students will create prototypes to visually present their designs and showcase their intricate details. Prototypes serve as a tangible representation of their ideas and provide a means to test and evaluate the functionality and efficiency of their proposed solutions (NRC, 2012). The prototypes developed by the students can take various forms, such as two-dimensional or three-dimensional models, depending on the complexity and nature of their designs (NAE [National Academy of Engineering] & NRC, 2009). These prototypes allow the students to better visualize their ideas and bring their concepts to life.

Throughout this phase, the students will face challenges and make modifications as they refine their prototypes. This iterative process enables them to think critically and creatively, just like professional engineers who continuously improve their designs to achieve optimal results. As the students engage in this exciting phase of the engineering design process, they not only apply their scientific knowledge and engineering skills but also develop their problem-solving abilities and creativity.

After the students have successfully designed and constructed their prototypes to protect the penguin-shaped ice cubes, the next crucial step in the engineering design process is to test and evaluate their solutions. Testing is essential to gather data and assess the performance of their design artifacts. The information obtained from testing will be used to evaluate the strengths and weaknesses of their solutions, enabling them to make informed decisions for further improvements and refinements.

To evaluate their dwellings, the students will place their prototypes in a specially prepared oven that simulates various forms of heat transfer. The oven, designed using a large plastic storage bin lined with aluminum foil on four sides and painted black on the bottom, is equipped with one 100W lights to allow for conduction, radiation, and convection to occur. The experiments conducted in this preheated oven will provide valuable data on the performance of their designs and how well they can prevent the penguin-shaped ice cubes from melting. After all the penguin-ice-cube masses are measured and the testing is complete, the students will gather to share and discuss their results. Some groups may have successfully saved at least half of their penguin ice cube, demonstrating the effectiveness of their designs, while others may have only managed to retain a few grams of the ice cube (Figure 8).

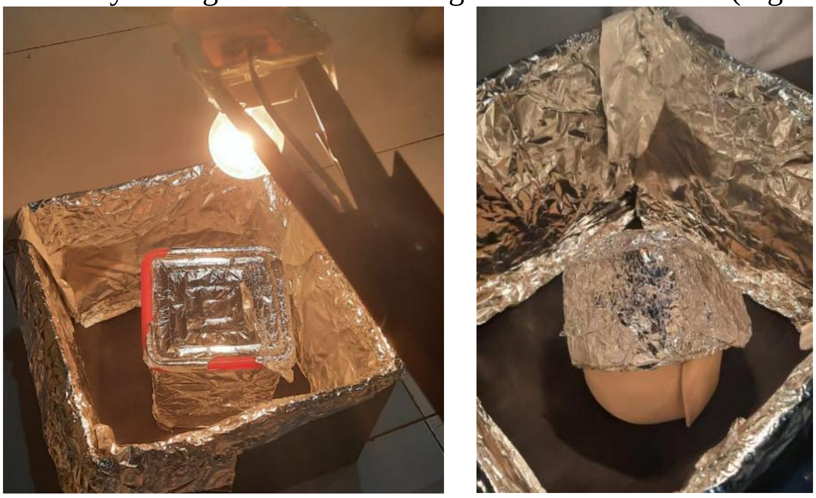

Figure 8. Test And Evaluate The Solutions Activity

The testing and evaluation phases are critical in the engineering design process as they revolve around prototypes. Prototypes serve as essential tools for testing out designs before finalizing the actual product or solution. Understanding the significance of prototypes, the teachers have guided the students to use these tools effectively during the testing and evaluation phase. Research indicates that students' testing and improving the prototypes they develop during the engineering design process can have a significant positive impact on their conceptual understanding (Dedetürk et al., 2021). The evaluation process is closely tied to the success of the solution and its potential for improvement (Nurtanto et al., 2020; Hynes et al., 2011). By carefully analyzing the data gathered during testing, the students can identify areas that require further refinement and make necessary adjustments to enhance the effectiveness of their designs.

After successfully testing their prototypes, students are now tasked with effectively conveying their ideas and findings to others.Communication is an essential skill for engineers, as they need to collaborate with colleagues, stakeholders, and clients to bring their designs and solutions to life. Similarly, students in the engineering design process must learn to articulate their concepts clearly and persuasively. In this step, students share their innovative ideas, design solutions, and the reasoning behind their choices with their peers and possibly even with teachers or professionals in the field. This process emulates how engineers interact and collaborate with other engineers to gather feedback, exchange ideas, and refine their designs (Nurtanto et al., 2020; Mentzer, 2011).

By engaging in this communication phase, students have the opportunity to receive valuable feedback from their peers. When students share and receive feedback on their product, it becomes a valuable opportunity for them to reflect on their knowledge and understanding (Nurtanto et al., 2020; Krajcik & Czerniak, 2007). The process of sharing and critiquing allows students to gain new perspectives, identify strengths and weaknesses in their work, and deepen their understanding of the subject matter.

These analyze align with the results as Sharunova, Wang, Kowalski, and Qureshi (2020) provides evidence supporting the strong connection between engineering design activities and cognitive development. The study conducted by Winarno et al. (2020) likely presents evidence supporting the positive impact of the STEM approach with EDP on students' conceptual understanding. The results may demonstrate that students who experienced this integrated learning approach exhibited higher levels of comprehension and retention of scientific concepts. Furthermore, integrating STEM-engineering design processes into the secondary school curriculum has been found to have significant benefits for students' understanding of basic concepts and principles within various disciplines, as well as their problem-solving abilities (Dedetürk et al., 2021; Nurtanto et al., 2020; Parnell, Deibel, & Atman, 2010; Brophy, Klein, Portsmore, & Roger 2008; Diefes-Dux, Zawojewski, & Hjalmarson, 2010; English & Mousoulides, 2011; Stoner, Stuby, & Szczepanski, 2013).

The Effect of STEM-Engineering Design Process in Students' Concept Mastery on Each Cognitive Level

To comprehensively examine students' concept mastery, it is essential to analyze the progress made in each test item across various cognitive domains. For this research, the test items were designed following the Bloom's Taxonomy Revision by Anderson & Krathwohl (2001). The taxonomy consists of five levels, each representing a different cognitive skill: C1 (remembering), C2 (understanding), C3 (applying), C4 (analyzing), and C5 (evaluating). These levels are chosen based on the fundamental competencies that need to be assessed. To delve deeper into the discussion, Figure 9 presents the N-Gain scores of each cognitive aspect.

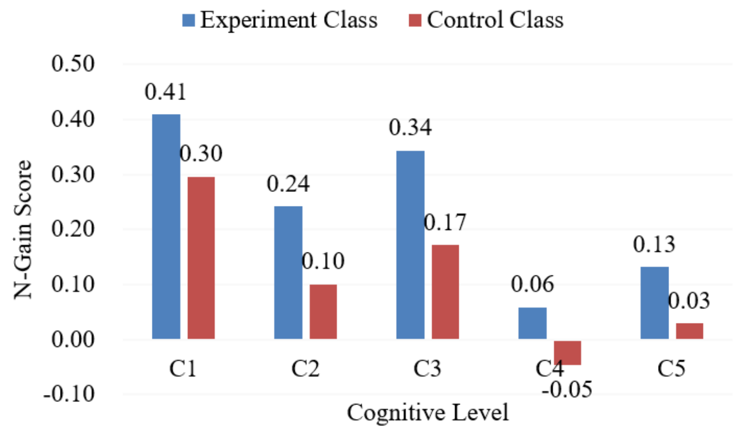

Figure 9. Comparisons of N-Gain Score between Experiment Class and Control Class in Each Cognitive Levels

The analysis of Figure 9 reveals significant disparities in the N-Gain scores across cognitive levels between the experiment class and the control class. This difference can be attributed to the experiment class's emphasis on fostering conceptual understanding. This disparity can be attributed to the experiment class's focus on nurturing conceptual understanding, particularly evident in C1, C2, and C3, where the students in the experiment class exhibit the highest N-Gain scores. This substantiates the notion that implementing STEM-EDP can effectively enhance the students' lower-order thinking skills, aligning with the understanding that the design element can play a pivotal role in bolstering the retention of scientific concepts in their long-term memory(Li et al., 2019; Siew, Amir, and Chong (2015).

However, the trend shifts in C4 and C5, with a decline in N-Gain scores. This can be ascribed to the increased complexity of the test items within the C6 dimension. This outcome aligns with Bloom's Taxonomy revision, which proposes that as the cognitive dimension rises, so does the difficulty of thinking abilities (Qaswari & BeniAbdelrahman, 2020; Anderson & Krathwohl, 2001). Consequently, it can be deduced that the higher the cognitive dimension, the more intricate the objective test becomes.

These findings also align with the research conducted by Sharunova et al. (2020), which also emphasizes the importance of cognitive levels throughout the engineering design process. The close relationship between scientific conceptual knowledge and engineering design becomes evident through these results. Moreover, the study by Rachmayati, Kaniawati, and Hernani (2020) further reinforces the positive impact of STEM education on students' concept mastery, validating the significance of incorporating engineering design principles in science education. The integration of engineering design in the learning process goes beyond theoretical knowledge; it fosters a dynamic interplay between scientific content knowledge and the essential skills required for scientific inquiry and engineering design (NRC, 2012). This integration allows students to engage in practical problem-solving scenarios, where they apply scientific principles to create innovative solutions.

Conversely, the control class also presents noteworthy N-Gain results. Positive impacts are evident in C1, C2, C3, and C5, indicating the effectiveness of the teaching approach. However, a negative N-Gain in C4 suggests a potential deficiency in deep analytical engagement within the control class. This variance might stem from the absence of comprehensive critical analysis methods within the control class's teaching approach. As a result, students in the experiment class demonstrated higher N-Gain scores across cognitive levels, showcasing a deeper understanding and proficiency in conceptual knowledge and problem-solving skills.

The Effect of STEM-Engineering Design Process in Students' Concept Mastery on Each Sub Topic

The Heat transfer and Thermal Energy material consists of eight subtopics: Temperature, heat, heat capacity, latent heat, conduction, convection, radiation, and expansion. These subtopics are part of the Kurikulum Merdeka, the latest curriculum introduced by the Indonesia Ministry of Education, Technology, and Culture. Figure 10 visually presents the comparison of the N-Gain scores between the experiment class and the control class for each subtopic.

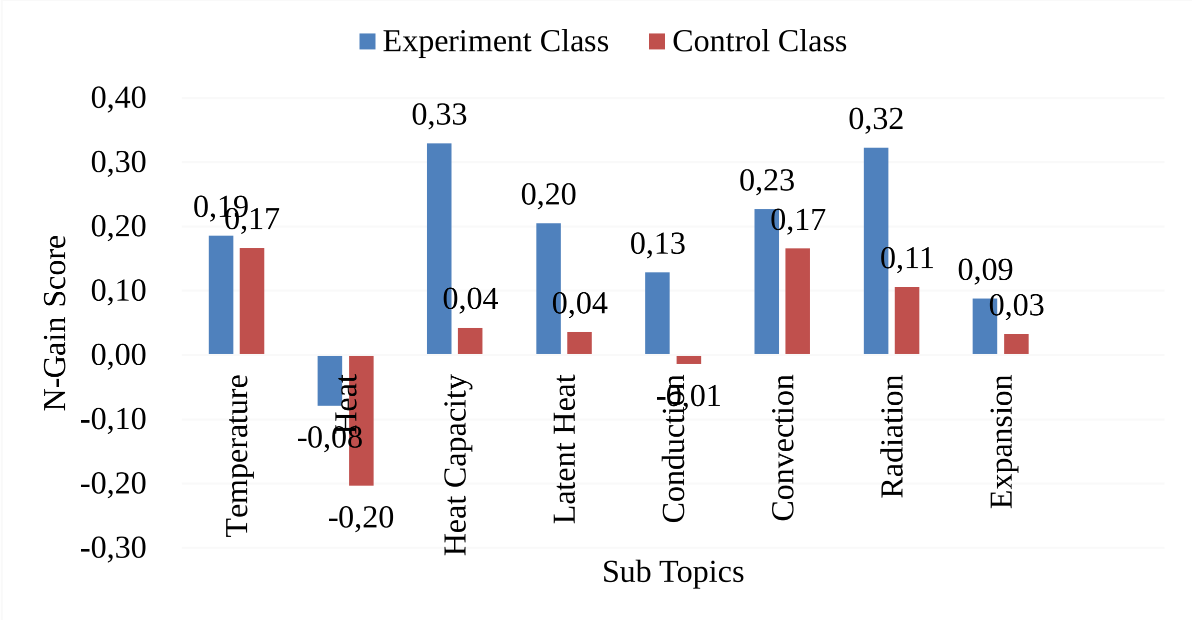

Figure 10. Comparisons of N-Gain Score between Experiment Class and Control Class in Each Sub Topic

As illustrated in Figure 10, the most prominent N-Gain scores are observed in topics related to heat capacity, latent heat, and heat transfer, particularly within the experiment class. This phenomenon can be attributed to the enhanced understanding facilitated by demonstrations and practical applications in these specific topics. This observation corroborates the idea that integrating the engineering design process into the learning journey prompts students to confront unique challenges that push them to identify issues, delve deeper into their comprehension of physics concepts, and craft effective solutions (Tank et al., 2018).

This teaching strategy aligns harmoniously with prior research that emphasizes the advantages of incorporating engineering design principles into science education. Previous studies like those conducted by the NRC (2014) underscore the positive influence of infusing science learning with engineering design activities, which in turn leads to a more profound grasp of scientific principles.

However, a relatively modest N-Gain is evident in the heat-related topic for both the experiment and control classes. This could be attributed to the limited number of questions related to this topic and a shortage of comprehensive discussions surrounding the subject matter. Additionally, the N-Gain decrease in the topic of conduction within the control class might indicate a lack of in-depth exploration in this particular area within the chosen teaching approach.

CONCLUSION

The STEM engineering design process that used have seven step, identifying the need or problem, researching the need or problem, drawing or sketching possible ideas or solutions for the problem, selecting the best possible solutions, designing and constructing a prototype, testing and evaluating the solutions, and communicating the solutions. Upon evaluating both the pretest and posttest results for concept mastery, the N-Gain observed in the experiment class reflects a low improvement, quantifying to 0.22. While the control class in 0.08, quantifying as low improvement. On the other hand, the Independent t-test score for concept mastery stands at 0.03, signaling the acceptance of the null hypothesis (H_0), which implies a notable distinction between the control and experiment classes. Subsequently, the analysis of concept mastery, stratified by cognitive levels, reveals that the highest N-Gain in experimental class is achieved in the C1 category, marking a medium improvement with a value of 0.41, whereas the lowest N-Gain is in the C4 category, signaling a slight increase of 0.06, which is classified as a low improvement. By dissecting the concept mastery based on subtopics, students show the most significant enhancement in the heat capacity subtopic with a N-Gain of 0.33, categorized as a medium improvement, while the least improvement is noted in the heat subtopic with a N-Gain of -0.08, signifying no substantial advancement.

It is evident that students' concept mastery displayed noticeable development following the application of the treatment. Students exhibited high levels of engagement in various activities such as discussions, demonstrations, and the creation of products. Furthermore, students demonstrated a heightened ability to articulate the concepts of thermal energy and heat transfer, linking these concepts to real-world phenomena. The incorporation of demonstrations served to present authentic phenomena, fostering a higher level of student participation and active involvement in the teaching and learning process.

Recommendation

For future research endeavors related to the implementation of the STEM engineering design process within the thermal energy and heat transfer topic, several recommendations can be made. First, it is recommended that future researchers include a more comprehensive set of questions in the objective test, ensuring representation across all aspects of the topic. Second, this could be achieved by preparing a larger pool of questions during the validation process, allowing for substitution if any questions are rejected. To optimize students' performance, it is advisable to allocate more time for them to complete the test. Extending the time for test completion could enhance students' ability to thoroughly engage with and provide well-considered responses. Second, future researchers planning to incorporate demonstrations should possess a solid understanding of the topic to ensure clear and effective delivery. Adequate mastery of the demonstration material will enable researchers to communicate concepts coherently, facilitating a better learning experience for the students. Last, for future researchers, it is recommended to employ the Rach Model for a more comprehensive analysis of the research questions. Utilizing this model allows for a clear examination of the validity, reliability, and differentiability of each question. By incorporating this analytical approach, researchers can enhance the robustness of their assessments, ensuring that the questions employed are not only valid and reliable but also effectively distinguish between varying levels of knowledge or skills.

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