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Design and Optimization of LPG Safety Cap using Finite Element Method

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ABSTRACT

This paper presents a comprehensive study on the design and optimization of LPG safety caps, aimed at enhancing safety, reducing material consumption, and optimizing performance. The project employs SolidWorks simulation tools to conduct research and concept design phases. The primary objective is to ensure product safety while minimizing costs through Finite Element Analysis (FEA). The final product undergoes rigorous evaluation for performance and consumer safety. Three main goals guide this investigation: to scrutinize existing LPG safety cap designs, minimize material usage, and simulate the optimal design for enhanced safety. Analysis of the current design reveals vulnerabilities, including theft of LPG gas from sealed cylinders and escalating HDPE prices. Proposed designs simplify the current model and economize material consumption, successfully addressing the second objective. Through simulation, an optimal design (Design 8) emerges with superior characteristics compared to the existing model. Design 8 demonstrates a reduced total weight, higher safety factor, and lower maximum von Mises stress value. Notably, it exhibits enhanced safety and resilience, mitigating failure risks under stress conditions. The findings highlight the potential for creating stronger and safer designs while minimizing material requirements. In conclusion, Design 8 emerges as a superior alternative to the current design, boasting advantages in weight reduction, stress tolerance, safety factor, and optimization potential. This study underscores the significance of utilizing advanced computational methods to refine engineering designs for improved safety and efficiency in LPG safety caps.

Keywords:

LPG safety cap; FEA; Design optimization; HDPE; Stress analysis

1. Introduction

The safe storage and transportation of liquefied petroleum gas (LPG) are paramount considerations in ensuring the integrity and reliability of LPG systems, particularly in contexts such as Malaysia, where LPG serves as a subsidized domestic resource [1-3]. At the heart of these systems lie

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safety caps, essential components designed to protect against the entry of moisture, dirt, dust, or other contaminants that could compromise the quality and safety of the stored gas. Additionally, safety caps serve to prevent the sudden release of gas under high pressure, mitigating the risk of accidents and ensuring operational safety [1].

Moreover, in subsidized domestic contexts like Malaysia, where LPG is provided for household use, the security of LPG resources becomes a significant concern [4]. There is a need to safeguard against unauthorized access to the gas, which may include individuals attempting to tamper with or steal the gas by removing and replacing the safety cap. To address this concern, safety caps are designed to be tamper-evident, ensuring that once opened, they cannot be resealed or reused, thus maintaining the integrity and security of the LPG supply chain.

However, the material typically used in safety cap production, such as High-Density Polyethylene (HDPE), faces challenges due to the depletion of petrochemical resources, resulting in increased material costs [5-8]. This necessitates a re-evaluation of safety cap designs to optimize material usage as part of sustainability efforts. By modifying design parameters to reduce material consumption while maintaining or enhancing functionality and mechanical strength, it is possible to mitigate the impact of rising material costs and contribute to sustainability goals.

Furthermore, the LPG subsidy program in Malaysia underscores the importance of efficient LPG utilization and management [4]. LPG must be carefully controlled as a subsidized resource for domestic usage to ensure equitable distribution and prevent misuse. This further emphasizes the critical role of safety caps in safeguarding the integrity of the LPG supply chain and maintaining safety standards. In light of these critical functions and challenges, this paper aims to address the imperative of optimizing safety cap designs for LPG systems in Malaysia. By systematically analysing various design iterations and evaluating their performance in terms of material usage reduction, mechanical strength enhancement, and tamper resistance, this study endeavours to contribute to the advancement of safety cap technology, ultimately promoting enhanced safety, efficiency, security, and sustainability in LPG handling operations.

2. Methodology

2.1 3D Models

The methodology employed in this study aimed to optimize safety cap designs for LPG systems in Malaysia, focusing on reducing material costs while maintaining primary functionality and mechanical strength. The process utilized Solidworks software as a Computer-Aided Engineering (CAE) tool to simulate and evaluate various design iterations, considering a pulling force equivalent to an average normal pulling force of 200N [9,10]. Figure 1 shows the existing design for the LGP safety cap. This safety cap is used for their domestic cylinder LPG. The dimensions of this existing design were measured with a diameter of 37mm and a height of 10mm. The material was assigned to the model utilizing Solidworks software, which precisely depicts its material characteristics and enables thorough analysis within simulations. In this study, High-Density Polyethylene (HDPE) was employed. A total of 10 samples were analysed and compared with the existing design. The initial step involved measuring the dimensions and characteristics of the current safety cap design, including weight and structural features. Using these measurements as a baseline, the design was digitally reconstructed in Solidworks software to create a virtual model for further analysis. Subsequently, the digital model was redesigned with various modifications to optimise material usage while ensuring safety and mechanical strength requirements adherence. These modifications included adjustments to geometry, material thickness, and reinforcement patterns to achieve the desired balance between material reduction and performance enhancement. Following the redesign process, each iteration of the safety cap design was simulated using Solidworks software. The simulations involved applying a pulling force equivalent to an average normal pulling force of 200N to mimic real-world conditions. Key performance metrics such as Von Mises stress, safety factor, displacement, and stress reduction were evaluated during the simulation process.

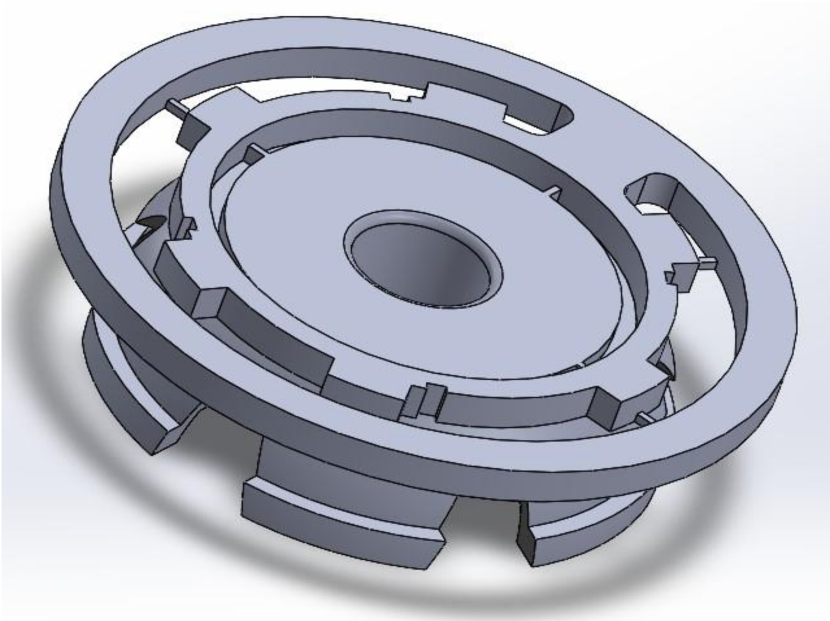


Fig. 1. Benchmark design of LPG Safety Cap using Solidworks software

2.2 Mechanical Properties

Table 1 lists the mechanical properties of HDPE material. HDPE is a thermoplastic polymer characterized by its high stiffness and rigidity, as indicated by its elastic modulus of 10.7 x 10^5 kN/m^2. With a Poisson's ratio of 0.410, HDPE exhibits a slight tendency to contract laterally when subjected to longitudinal stress [11]. The shear modulus of HDPE is 3.7 x 10^5 kN/m^2 underscores its resistance to shear deformation. HDPE's relatively high mass density of 952 kg/m^3 contributes to its strength and durability, making it suitable for applications requiring lightweight yet robust materials. Furthermore, the 2.21 x 10^4 kN/m^2 tensile strength highlights its ability to withstand tension before experiencing permanent deformation or failure. These properties collectively position HDPE as a versatile material widely employed in packaging, construction, and automotive industries due to its exceptional combination of strength, stiffness, chemical resistance, and low moisture absorption.

Table 1
Mechanical properties of HDPE

Property	Value
Elastic modulus	10.7 x 10^8 N/m^2
Poisson's ratio	0.410
Shear modulus	3.7 x 10^8 N/m^2
Mass density	952 kg/m^3
Tensile strength	2.21 x 10^7 N/m^2

2.3 Total Displacement

Total displacement as shown in Figure 2, quantifying the overall movement or deformation of a structure or component in finite element analysis (FEA) or any other methods [12-14], are crucial for engineers to assess structural integrity effectively. This measure encompasses displacements in all three directions (x, y, and z) at specific points within the structure or component. By summing the displacements in each direction, engineers can discern potential issues like excessive deformation or instability. When calculating total displacement, the magnitude of the displacement vector is utilized, where the displacement magnitude equals the square root of the sum of displacement squares in each direction.

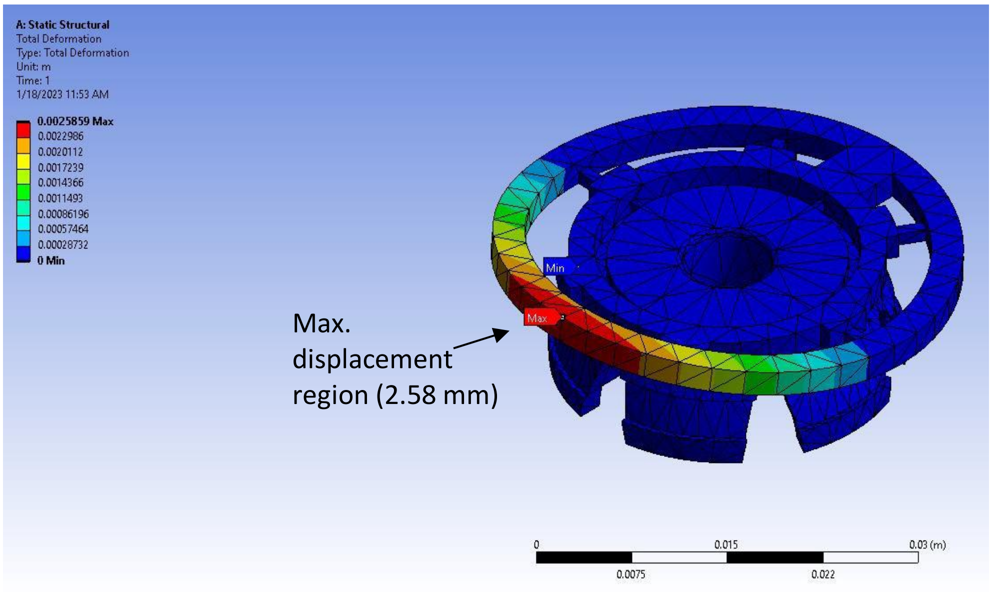


Fig. 2. Total displacement of Benchmark design

Notably, total displacement is a scalar value, disregarding displacement direction, and is often integrated with other displacement measures, such as principal displacements and maximum shear displacements, for a comprehensive understanding of the displacement state. In the context of this study, the maximum displacement observed is 2.58 mm, indicating the extent of deformation experienced by the safety cap under the simulated loading conditions.

2.4 Von Mises Stress

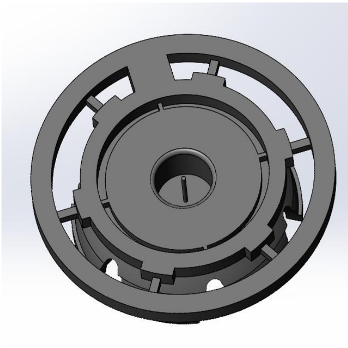
Von Mises stress analysis provided insights into stress distribution throughout the component, identifying potential failure points and areas requiring reinforcement. Safety factor calculations ensured adequate protection against failure under the applied pulling force. Displacement analysis assessed structural response to the pulling force, aiding in evaluating stability and deformation characteristics. Stress reduction analysis quantified improvements in reducing stress levels compared to the current design, demonstrating the effectiveness of the redesign efforts in enhancing mechanical strength.

Through this systematic methodology, the study aimed to evaluate and optimize safety cap designs for LPG systems, utilizing advanced simulation techniques to inform design decisions and achieve cost-effective yet robust solutions, while considering the impact of a pulling force equivalent to an average normal pulling force of 200N.

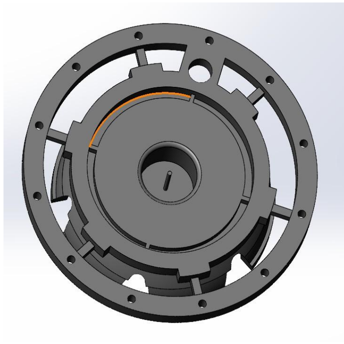
3. Results and Discussion

3.1 Preliminary Study

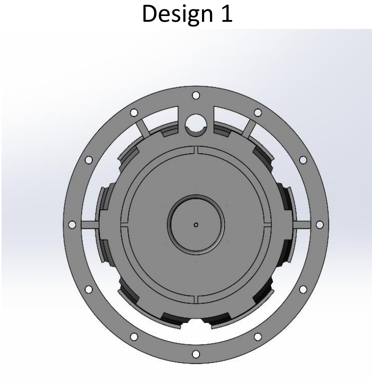
The modifications to the LPG safety cap design progress through ten stages as shown in Figure 3. Initially, Design 1 adds two stems to accommodate increased stress. Design 2 reduces material by drilling twelve 1mm holes in a circular pattern and a 3mm hole in a larger stem. Design 3 retains these features from Design 2 but reverts the modification from Design 1. Design 4 maintains the modifications of Design 2 while reducing the mass of the load-applied surface and adding four 1.5mm slots. Design 5 combines features from Designs 2 and 4. Design 6 resembles the current design but includes six 1mm slots. Design 7 combines features from Designs 4 and 6. Design 8 combines features from Designs 5 and 6. Design 9 eliminates connecting stems. Design 10 combines features from Designs 8 and 9, omitting connecting stems.



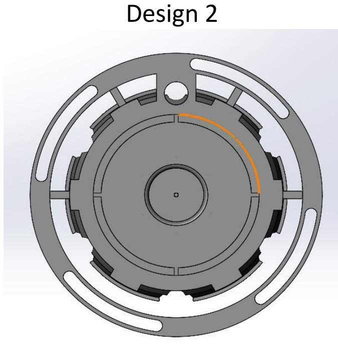
Design 1



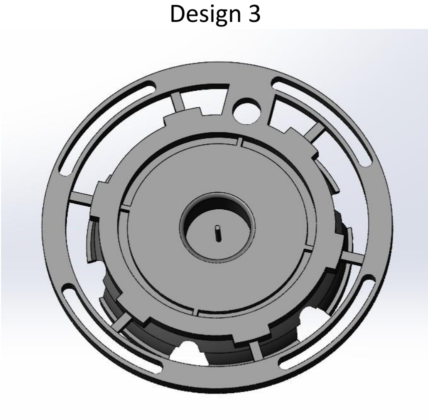
Design 2



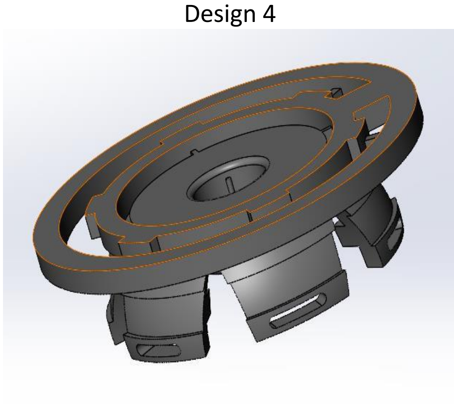
Design 3



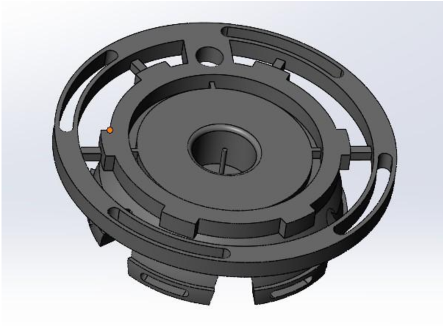
Design 4



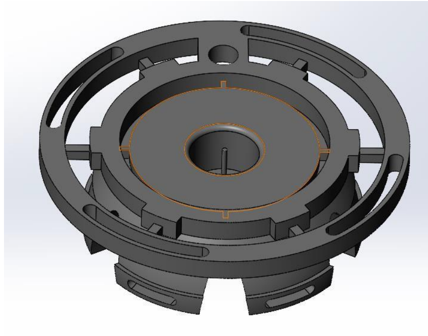
Design 5



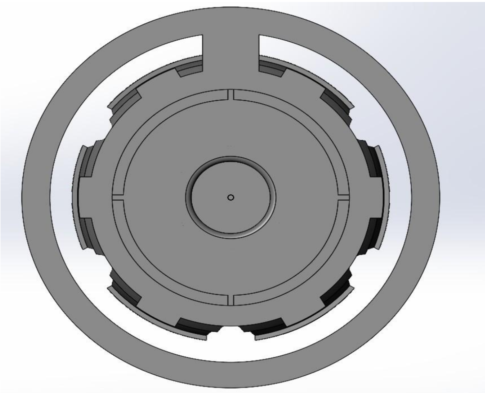
Design 6



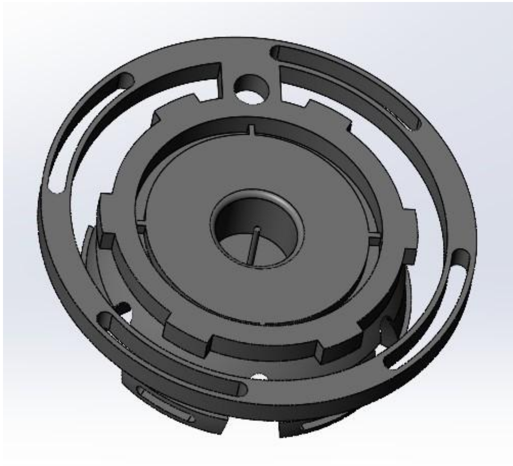
Design 7



Design 8



Design 9



Design 10

Fig. 3. The modifications to the LPG safety cap design progress through ten stages

3.2 Structural Analysis
3.2.1 Von-Mises stress analysis

Table 2 provides a comprehensive overview of 10 different designs for a safety cap intended for use with LPG. Each design is evaluated based on three key parameters: the maximum Von Mises stress experienced, the mass of the design, and the factor of safety. Among the designs, Design 10 stands out with the highest recorded maximum Von Mises stress, indicating potential vulnerability to failure under operational conditions. Conversely, Design 1 exhibits the lowest stress level, suggesting superior structural integrity and resilience. The remaining designs fall within a range of stress values, showcasing variations in performance and robustness. When considering mass, most designs demonstrate consistency with minor fluctuations across the board. This suggests that alterations in design have not significantly impacted the overall weight of the safety cap, maintaining stability in this aspect throughout the iterations. Perhaps the most crucial aspect of the evaluation is the factor of safety. Designs with higher factors of safety, such as Design 1 and Design 8, present enhanced reliability and safety margins, offering greater assurance of performance under operational loads. On the other hand, designs with lower factors of safety, like Design 9 and Design 10, indicate potential concerns regarding structural integrity and may require further optimization to ensure adequate safety levels.

Between Design 1 and Design 8, Design 8 emerges as the preferable choice. Design 8 showcases a substantial reduction in Von Mises stress compared to Design 1, indicating improved structural integrity and durability. This reduction suggests that Design 8 may better withstand operational stresses, potentially leading to a longer lifespan and increased reliability. Additionally, Design 8 features a notable increase in the factor of safety, providing greater safety margins and assurance of performance under varying conditions. Despite these enhancements, both designs maintain similar masses, suggesting that Design 8 achieves these improvements without significantly increasing material usage or overall weight. Thus, Design 8 offers superior performance in stress reduction and safety enhancement, making it the preferable option for practical implementation.

Between Design 1 and Design 8, Design 8 emerges as the preferable choice. Design 8 showcases a substantial reduction in Von Mises stress compared to Design 1, indicating improved structural integrity and durability. This reduction suggests that Design 8 may better withstand operational stresses, potentially leading to a longer lifespan and increased reliability. Additionally, Design 8 features a notable increase in the factor of safety, providing greater safety margins and assurance of performance under varying conditions. Furthermore, Design 8 achieves these improvements while also reducing material usage compared to the current design by approximately 9%. Despite these enhancements, both designs maintain similar masses, suggesting that Design 8 achieves these improvements without significantly increasing overall weight. Thus, Design 8 offers superior performance in stress reduction, safety enhancement, and material usage reduction, making it the preferable option for practical implementation.

Table 2
A comprehensive comparison of ten design iterations

Design	Max. Von Mises Stress	Mass	Factor of Safety
Current Design	1.45×10^7	2.32	1.52
Design 1	5.77×10^6	2.33	4.32
Design 2	8.037×10^6	2.75	2.75
Design 3	3.237×10^7	2.29	0.68
Design 4	2.699×10^7	2.15	0.81
Design 5	8.982×10^6	2.15	2.46
Design 6	1.585×10^7	2.26	1.39
Design 7	2.666×10^7	2.08	0.83
Design 8	6.79×10^6	2.09	3.25
Design 9	4.061×10^7	2.32	0.54
Design 10	1.228×10^8	2.07	0.18

3.3 Mass Reduction and Stress Reduction Analysis

Table 3 represents a comprehensive comparison of ten design iterations, focusing on their respective impacts on mass reduction and stress reduction compared to the current design. Notably, Design 10 stands out with the highest recorded stress reduction of 108.30 MPa, showcasing significant improvements in structural integrity. Conversely, Design 9 demonstrates the most substantial stress reduction of 26.11 MPa despite not achieving a mass reduction, suggesting an efficient utilization of existing materials to enhance performance. Designs 3, 4, and 7 also exhibit notable stress reductions ranging from -17.90 MPa to -12.16 MPa, indicating substantial improvements in structural resilience. Among these designs, Design 8 emerges as particularly noteworthy, achieving a balanced performance with a substantial stress reduction alongside a significant mass reduction. This balanced approach signifies an efficient optimization of material usage while enhancing structural integrity, making Design 8 a compelling choice for further consideration and potential implementation.

Table 3
Mass and Stress Reduction

Design	Mass Reduction (g)	Stress Reduction (MPa)
Design 1	-0.01	8.73
Design 2	-0.43	6.46
Design 3	0.03	-17.90
Design 4	0.17	-12.50
Design 5	0.17	5.52
Design 6	0.06	-1.35
Design 7	0.24	-12.16
Design 8	0.23	7.71
Design 9	0	-26.11
Design 10	0.25	-108.30

Design 8 emerges as the preferred choice due to its balanced performance in both mass reduction and stress reduction, alongside other factors. Design 8 achieves a notable reduction in mass by 0.23 grams, indicating efficient material usage, while also demonstrating a significant stress reduction of 7.71 MPa compared to the current design. This reduction in stress signifies an improvement in structural integrity, suggesting that Design 8 may better withstand operational stresses, leading to increased reliability and longevity. Furthermore, Design 8 maintains similar masses to other designs, indicating that the improvements achieved in stress reduction have been realized without significantly increasing material usage or overall weight. The selection of Design 8 over other iterations is supported by its comprehensive improvements in both material usage reduction and stress reduction, making it a compelling choice for practical implementation.

4. Conclusions

In conclusion, this research aimed to optimize safety cap designs for LPG systems in Malaysia by reducing material costs while maintaining primary functionality and mechanical strength. Through a systematic analysis of various design iterations and evaluations of key performance metrics, including Von Mises stress, mass, safety factor, displacement, and stress reduction, significant insights were gained. The findings indicate that modifications to design parameters can effectively reduce material usage without compromising safety or structural integrity. Particularly noteworthy was the development of Design 8, which demonstrated a balanced performance with substantial stress reduction and material usage reduction, making it a preferable option for practical implementation. Furthermore, the utilization of Solidworks software as a CAE tool proved instrumental in simulating and evaluating design iterations, providing valuable insights for engineers and designers. Overall, this research contributes to the advancement of safety cap technology, promoting enhanced safety, efficiency, and sustainability in LPG handling operations in Malaysia and beyond. Future studies may further explore optimization strategies and evaluate long-term performance under varying operating conditions to refine safety cap designs for improved effectiveness and reliability.

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