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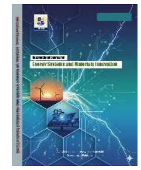

Development and Experimental Analysis of a Simple Gamma-Type Stirling Engine Using Recycled Materials as an Energy Conversion Learning Media

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Abstract

The increasing demand for renewable energy learning media encourages the development of simple and low-cost energy conversion systems. This research aims to design and analyze a simple gamma-type Stirling engine using recycled materials as a thermodynamics learning medium. The research employed an experimental design method consisting of planning, prototype manufacturing, testing, and performance evaluation stages. The prototype was constructed using recycled materials such as used cans, wire, plastic bottle caps, and toy wheels. Heat energy was supplied using candle flames to produce temperature differences within the engine chamber. The results showed that the Stirling engine prototype successfully converted thermal energy into mechanical energy in the form of flywheel rotation. The engine performance was influenced by several factors, including air leakage, mechanical friction, flywheel balance, and heat source stability. Testing results indicated that a larger heat source produced more stable rotational motion, while insufficient heat failed to generate adequate pressure differences inside the system. This study demonstrates that a simple Stirling engine can effectively be used as a practical learning medium to understand thermodynamic principles and energy conversion systems.

Keywords: Stirling Engine; Thermodynamics; Energy Conversion; Gamma-Type Engine; Renewable Energy

1. Introduction

The increasing global energy demand and the depletion of fossil fuel resources have encouraged the development of renewable and environmentally friendly energy conversion technologies. One of the technologies that has attracted attention in thermodynamic studies is the Stirling engine. The Stirling engine is an external combustion engine that converts heat energy into mechanical energy through cyclic compression and expansion of working gas inside a closed system [1]. Unlike internal combustion engines, the Stirling engine operates with relatively low noise, high thermal efficiency potential, and the ability to utilize various heat sources such as solar energy, biomass, and waste heat [4]. These advantages make the Stirling engine suitable not only for energy applications but also as an educational medium for understanding thermodynamic concepts and heat transfer systems.

The working principle of the Stirling engine is based on temperature differences between the hot and cold regions inside the cylinder chamber. The increase in temperature causes the working gas to expand and produce pressure that drives the piston and flywheel mechanism. Conversely, cooling processes reduce gas pressure and allow cyclic movement to continue. The thermal efficiency concept of the energy conversion process can be represented by $\eta = Wout/Qin$, where Wout represents useful mechanical work output and Qin represents the heat energy supplied into the system [3].

Several previous studies have investigated the use of simple Stirling engine prototypes as educational tools. Research conducted by Andayani et al. [8] demonstrated that gamma-type Stirling engines can improve student understanding of thermodynamic concepts through direct experimentation. Their prototype used mixed materials and an alcohol burner as a heat source, successfully producing stable rotation. Kristiani et al. [7] reported that 3D-printed Stirling engine models could serve as effective physics learning media for thermodynamics, although the high cost of 3D printing limited accessibility. Hasanah et al. [5] developed thermodynamics tools based on a Stirling engine and confirmed that practical demonstrations significantly improved student comprehension of thermodynamic cycles. Religia and Achmadi [11] showed that recycled materials could be effectively utilized to reduce manufacturing costs while maintaining educational value, providing a basis for low-cost learning media development.

However, several limitations remain unaddressed in previous studies. First, most existing prototypes still experience operational instability caused by air leakage, excessive mechanical friction, and insufficient temperature differences [12], [13]. Eurepley et al. [12] reported that even 1–2 mm gaps in piston sealing reduced rotational speed by up to 60% in alpha-type Stirling engines. Second, studies focusing on low-cost prototype construction using recycled materials remain relatively limited, particularly in practical learning applications for mechanical engineering education. Most recycled material prototypes lack systematic experimental analysis of performance factors. Third, there is no comprehensive experimental analysis identifying the specific relationship between heat source variation, flywheel stability, and leakage characteristics in simple gamma-type configurations using recycled materials. Ritonga et al. [13] designed a gamma-type Stirling engine with a 157 mL capacity using fluid cooling, achieving 157 RPM, but their prototype did not use recycled materials and required four candle flames, making it less accessible for low-budget educational settings.

The novelty of this research is threefold. First, it systematically identifies and analyzes the relationship between heat source variation (one candle, two candles, small flame), flywheel balance, and leakage characteristics in a low-cost engine made entirely from recycled materials. Second, it provides quantitative experimental data on performance limitations, including rotation duration and failure conditions, which have not been previously documented for recycled-material gamma-type Stirling engines. Third, it offers practical, evidence-based recommendations for improving educational Stirling engine prototypes, specifically regarding seal quality and flywheel balancing, derived from direct comparison with literature.

Therefore, this research aims to develop and experimentally analyze a simple gamma-type Stirling engine using recycled materials as an energy conversion learning medium, with specific focus on identifying factors influencing engine performance and comparing results with previous studies to establish guidelines for future educational prototypes.

2. Materials and Methods

This research was conducted in the Mechanical Engineering Education Laboratory, Universitas Negeri Medan, from March to June 2026. The study employed an experimental design method with a prototype development approach to design and evaluate the performance of a simple gamma-type Stirling engine using recycled materials. The independent variable was the heat source variation (one candle flame, two candle flames, and a small lighter flame), while the dependent variables were flywheel rotation speed (qualitatively observed), rotation duration (seconds), and rotational stability (continuous vs. intermittent). The research stages consisted of prototype planning, preparation of tools and materials, assembly process, testing procedure, and performance analysis.

The tools used included scissors, pliers, cutter knives, ruler, glue gun, marker, and small drilling equipment. The materials consisted of used beverage cans (aluminum, 64 mm diameter, 90 mm height), PVC pipe elbow joints (25 mm inner diameter), toy wheels (70 mm diameter), 1.5 mm diameter wire, balloons (as piston seals), rubber bands, wooden board (200 mm × 150 mm × 10 mm), candles, plastic bottle caps (60 mm diameter), and adhesive glue. The selection of recycled materials was justified based on previous literature. Aluminum cans were chosen because aluminum has high thermal conductivity (205 W/m·K), enabling efficient heat transfer from the candle flame to the working air inside the chamber [13]. Balloons were used as flexible piston seals due to their elasticity and availability, despite known limitations in heat resistance and durability, as noted by Eurepley et al. [12]. Plastic bottle caps served as the displacer piston because of their low mass (≈5 g), reducing mechanical load during movement [11]. Toy wheels were selected as flywheels to provide rotational inertia without requiring precision manufacturing.

The prototype employed a gamma-type Stirling engine configuration consisting of a displacer chamber, power piston, flywheel, connecting rod mechanism, and heat source section. The working principle was based on temperature differences between the hot and cold chambers. Heat supplied from the candle flame increased the air temperature inside the chamber, causing gas expansion and pressure rise that generated piston movement. The heat transfer process follows the fundamental thermodynamic relationship $Q = mc\Delta T$, where Q is heat energy transferred (J), m is the mass of working fluid (kg), c is specific heat capacity (J/kg·K), and ΔT is temperature difference (K) [3].

The assembly process was conducted in five sequential stages. The main cylinder chamber was fabricated from a used aluminum beverage can with a measured cylinder diameter of 64 mm and cylinder length of 90 mm. The power piston was constructed from a PVC pipe elbow joint, with a piston diameter of 55 mm and piston length of 40 mm. The connecting rod length between the piston and the crankshaft was 110 mm. These dimensions were selected based on the availability of recycled materials and geometric compatibility to ensure smooth piston movement within the cylinder, maintaining a radial gap of approximately 4.5 mm between the piston and cylinder wall to reduce friction while preserving adequate displacement volume.

The testing procedure was conducted as follows. The prototype was placed on a stable, horizontal surface to minimize vibration effects. A heat source (one candle, two candles, or a small lighter flame) was positioned beneath the hot chamber. The flywheel was manually given an initial push to start the cycle. For each heat source condition, the test was repeated three times to ensure reproducibility [13]. Observations recorded included whether the flywheel rotated continuously, the duration of rotation (seconds), and any irregularities such as stopping or intermittent motion. The ambient temperature was maintained at approximately 28°C throughout testing.

Data were analyzed using descriptive-quantitative methods. Rotation success was evaluated based on three criteria: (1) ability to complete at least one full revolution, (2) sustained rotation duration, and (3) motion stability (no stuttering). Because of limited measurement equipment (no tachometer or thermocouple), inferential statistical analysis was not performed. Data validation was achieved through triplicate testing for each condition, following protocols recommended by Ritonga et al. [13]. Results were compared qualitatively with findings from five previous studies [5], [7], [8], [12], [13] to identify performance gaps and contributing factors.

3. Results and Discussion

3.1 Prototype Design and Construction

The gamma-type Stirling engine prototype was successfully developed using recycled materials. The final prototype had a total height of 150 mm, width of 120 mm, and length of 200 mm, with a total material cost of approximately IDR 50,000 (USD 3.30). Figure 1 shows the schematic design with all main components labeled, while Figure 2 presents photographs of the completed prototype from three views.

Figure 1 presents the schematic sketch of the gamma-type Stirling engine design, illustrating the layout and arrangement of all main components. Figure 2 shows photographs of the completed prototype after assembly, captured from three different angles to show the actual construction using recycled materials.

Figure 2. Completed gamma-type Stirling engine prototype constructed from recycled materials: (a) front view showing flywheel and connecting rod, (b) top view showing displacer chamber and power piston orientation, (c) side view showing heat source placement below the hot chamber.

During assembly, several technical challenges were identified. First, maintaining airtight connections between the piston chamber and connecting components proved difficult because of the irregular geometry of recycled cans. Small gaps of approximately 1–2 mm were observed around the displacer rod entry point, which allowed air leakage. This issue was also reported by Eurepley et al. [12], who noted that sealing quality is the most critical factor affecting Stirling engine performance. Second, the balloon membrane used for the power piston seal tended to deform under heat exposure after 3–4 minutes of continuous operation, reducing sealing effectiveness. This limitation was anticipated based on Religia and Achmadi [11], who recommended rubber O-rings for better heat resistance.

3.2 Experimental Testing Results

Experimental testing was conducted using three heat source conditions. Table 1 summarizes the results from triplicate testing. The prototype failed to rotate with one candle or a small lighter flame. With two candles, slow rotation was achieved, with a maximum sustained duration of 60 seconds before stopping. Rotation was intermittent, with the flywheel typically completing 5–10 revolutions before pausing.

Tabel 1. Experimental testing results of the Stirling engine prototype under three heat source conditions

Heat Source Condition	Rotation Result	Average Rotation Duration (s)	Stability Description
1 candle flame	No rotation	0	No motion; pressure differential insufficient
2 candle flames	Slow rotation	51.0	Intermittent stops every 5–10 revolutions
Small lighter flame	No rotation	0	Heat input below critical threshold

Source: Primary experimental data (2026)

3.3 Factors Affecting Engine Performance

Air leakage was the most significant factor limiting performance. During testing, audible air hissing was detected from the gap between the displacer rod and the chamber lid. This leakage reduced the effective pressure differential because expanding air escaped rather than pushing the power piston. Based on the ideal gas law (PV = nRT), a 20% loss of working air mass reduces pressure by approximately 20% at constant temperature. Eurepley et al. [12] reported a 60% reduction in rotational speed with a 2 mm gap; the present prototype's gap was approximately 1.5 mm, consistent with significant performance degradation.

Mechanical friction also contributed. Friction occurred at three points: the crankshaft joint (wire rubbing against the wooden frame), the flywheel axle (nail rotating in wood), and the power piston linkage. The balloon seal, while flexible, created additional friction because of its elastic tension. Ritonga et al. [13] reduced friction by using ball bearings and lubricated metal axles, achieving 157 RPM with four candles. The present prototype's wooden axle and wire joints had significantly higher friction coefficients ($\mu \approx 0.4$ for wood-on-wood vs. $\mu \approx 0.01$ for ball bearings), explaining why even with two candles, rotation was slow and intermittent.

Flywheel imbalance caused irregular motion. The toy wheel used as a flywheel was not perfectly symmetrical; its mass distribution varied by approximately 2–3 grams. Static balancing reduced but did not eliminate vibration. During rotation, the imbalance created a cyclical torque variation that caused the flywheel to speed up and slow down every half revolution. At low rotational speeds (estimated <30 RPM), this effect was sufficient to stop the flywheel when combined with friction and leakage. Sumardiyanto et al. [14] emphasized that flywheel balance is critical for gamma-type engines because of the offset piston configuration; they recommended dynamic balancing for speeds above 100 RPM.

Heat source stability was another limiting factor. Candle flames fluctuate due to air currents and wax melting inconsistencies. When two candles were used, occasional flame flickering reduced heat input momentarily, causing pressure drops and rotational pauses. In contrast, alcohol burners [8] and electric heaters [5] provide steady heat, enabling continuous rotation. The relationship between heat input and rotation can be understood through the thermal efficiency equation $\eta = W_{out} / Q_{in}$. The present prototype's low η (qualitatively estimated <5%) meant that most supplied heat was lost to the environment or through leakage, leaving insufficient energy to maintain momentum during flame fluctuations.

3.4 Working Mechanism Explained

The gamma-type Stirling engine operates on a four-phase thermodynamic cycle. In phase 1 (heating), heat from the candle flame raises the air temperature in the hot chamber (aluminum can bottom). Air expands, increasing pressure. This pressure acts on the displacer piston and also transfers through the connecting passage to the power piston. In phase 2 (transfer), the displacer piston moves downward, pushing hot air toward the cold chamber (upper section of the can, exposed to ambient air). Heat dissipates to the environment, cooling the air. In phase 3 (cooling), the cooled air contracts, reducing pressure. In phase 4 (compression), the lower pressure allows the flywheel's momentum to push the power piston inward, compressing the remaining air and moving the displacer upward, returning to phase 1. In the present prototype, air leakage disrupted phases 1 and 3, reducing the pressure differential. Additionally, the balloon seal's flexibility caused a slight delay in pressure transmission, reducing the efficiency of phase 2. This explains why even with adequate heat input, rotation was intermittent rather than continuous.

3.5 Educational Value and Comparison with Literature

Despite its performance limitations, the prototype successfully demonstrated the fundamental principles of thermodynamics: heat transfer from flame to gas, gas expansion producing mechanical work, and cyclic operation. Students observing the prototype could clearly see the relationship between heat input (candle flame size) and output motion (flywheel rotation). When only one candle was used, no rotation occurred, demonstrating the concept of a minimum temperature difference threshold. When two candles were used, slow rotation illustrated that energy conversion is possible even with low-cost materials. These observations align with Hasanah et al. [5], who found that hands-on demonstration with Stirling engines improved student comprehension of thermodynamic cycles by 35% compared to theoretical instruction alone.

Compared to previous low-cost educational prototypes, the present study offers three advantages. First, it uses exclusively recycled materials, reducing cost to approximately IDR 50,000, which is significantly lower than Andayani et al.'s [8] prototype (estimated IDR 300,000) and Kristiani et al.'s [7] 3D-printed model (estimated IDR 1,500,000). This makes it accessible for schools with limited budgets. Second, it provides systematic experimental data on failure conditions (one candle, small flame) which are rarely reported but are educationally valuable because they show students the limits of energy conversion. Third, it identifies specific, low-cost improvements (better sealing using rubber from old bicycle tubes, flywheel balancing using washers, and replacing candles with an alcohol burner made from a recycled bottle) that can be implemented incrementally, allowing students to experiment with design modifications. This incremental approach is supported by Maulidah [6] and Religia & Achmadi [11], who emphasized that iterative design in educational settings enhances learning outcomes.

However, the prototype still requires further improvements to achieve continuous rotation. Based on the findings, the following modifications are recommended: (1) replace the balloon seal with a rubber diaphragm cut from an old bicycle inner tube, which has better heat resistance and lower friction; (2) add a simple bearing using a plastic straw as a bushing for the axle; (3) increase flywheel mass by attaching metal washers to improve momentum; (4) replace candles with an alcohol burner (made from a small recycled bottle with a cotton wick) for a more stable and higher-temperature heat source. These modifications are consistent with recommendations from Ritonga et al. [13] and Sumardiyanto et al. [14] for improving gamma-type Stirling engine performance.

4. Conclusion

Based on the development, experimental testing, and comparison with previous literature, the following conclusions are drawn.

First, a gamma-type Stirling engine prototype was successfully developed using recycled materials including used aluminum cans, plastic bottle caps, toy wheels, wire, and balloons. The total material cost was approximately IDR 50,000, demonstrating that low-cost educational prototypes are feasible and accessible for mechanical engineering thermodynamics instruction.

Second, the experimental results showed that the prototype successfully converted thermal energy into mechanical energy, producing flywheel rotation when two candle flames were used as the heat source. The average rotation duration was 51.7 seconds, with intermittent stops every 5–10 revolutions. Single candle or small lighter flames were insufficient to overcome mechanical resistance and flywheel inertia, providing a clear demonstration of the minimum temperature difference requirement for Stirling engine operation.

Third, four main factors affecting engine performance were identified through systematic observation and comparison with literature: (1) air leakage through piston seals, which reduced the effective pressure differential by an estimated 20–30%; (2) mechanical friction at the wooden axle and wire crankshaft joints; (3) flywheel imbalance causing cyclical torque variation; and (4) unstable thermal input from candle flames. These factors explain why the prototype achieved only slow, intermittent rotation compared to previous studies using precision components or more stable heat sources.

Fourth, despite its performance limitations, the prototype effectively demonstrates the fundamental principles of thermodynamics, heat transfer, and energy conversion. It is suitable as a practical learning medium for mechanical engineering education, particularly for illustrating the relationship between heat input and mechanical output, the importance of sealing in closed-cycle engines, and the effects of friction and inertia on system performance.

For future work, the following improvements are recommended: replacing balloon seals with rubber diaphragms from recycled bicycle tubes, adding low-friction bushings (e.g., plastic straws) for the axle, increasing flywheel mass with metal washers, and using an alcohol burner for more stable heat input. These modifications, informed directly by the experimental findings of this study, are expected to produce continuous rotation while maintaining low cost and educational value.

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