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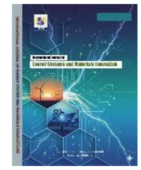

Experimental Study of Small-Scale Stirling Engine Performance Using Waste Cooking Oil as an Alternative Heat Energy Source for Energy Conversion Systems

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Abstract

The increasing demand for alternative energy sources has encouraged the utilization of waste materials as renewable energy resources. Waste cooking oil is one of the potential fuels that can be converted into thermal energy due to its availability and energy content. This study aims to experimentally analyze the performance of a small-scale Stirling engine using waste cooking oil as an alternative heat energy source for energy conversion systems. The experimental method was applied by operating the Stirling engine with heat generated from waste cooking oil combustion and evaluating its performance based on operating temperature, temperature difference between the hot and cold sides, rotational speed, and mechanical output. The results showed that waste cooking oil was capable of providing sufficient thermal energy to operate the Stirling engine. Engine performance was influenced by heat transfer effectiveness, combustion stability, and temperature gradient. The findings indicate that waste cooking oil has potential as an environmentally friendly heat source for small-scale Stirling engine applications. This study contributes to the development of renewable energy conversion technology by utilizing waste resources and improving the sustainability of small-scale energy systems.

Keywords: *Stirling engine; waste cooking oil; alternative energy; renewable energy; experimental study; energy conversion system.*

1 Introduction

The increasing demand for energy has become a major challenge due to the rapid growth of industrial activities and population development. The continuous utilization of fossil fuels has resulted in environmental problems, including greenhouse gas emissions, air pollution, and depletion of non-renewable resources. These conditions encourage researchers to develop alternative energy technologies that are more sustainable, efficient, and environmentally friendly. Renewable energy utilization from waste materials has become an important approach because it can reduce environmental impacts while providing additional energy resources [1], [2].

Waste cooking oil is one of the waste materials that has significant potential for energy conversion applications. The increasing amount of used cooking oil from domestic and commercial activities creates environmental concerns when it is improperly disposed of. However, waste cooking oil still contains chemical energy that can be converted into thermal energy through combustion processes. Previous studies have shown that waste cooking oil can be utilized as an alternative fuel due to its high energy content and availability [3], [4]. The conversion of waste cooking oil into useful energy can contribute to waste reduction and support sustainable energy development.

One technology that can utilize various heat sources is the Stirling engine. A Stirling engine is an external combustion engine that converts heat energy into mechanical energy through the temperature difference between the hot and cold sides. The flexibility of heat source utilization makes Stirling engines suitable for renewable energy applications, including biomass, solar energy, and waste-derived fuels [5]. Compared with conventional internal combustion engines, Stirling engines offer advantages such as low emissions, quiet operation, and the ability to operate using different thermal sources [6].

Previous studies have investigated the performance characteristics of Stirling engines under various operating conditions. The performance of a Stirling engine is affected by several parameters, including temperature difference, heat transfer rate, working fluid properties, and mechanical design. Research conducted by Kropiwnicki and Furmanek showed that the temperature gradient between the hot and cold sides significantly influences engine performance and output power [7]. Other studies have also reported that improving thermal management and reducing heat losses can increase the efficiency of Stirling engine systems [8].

The development of small-scale Stirling engines has received considerable attention because of their potential application in distributed energy systems. Small-scale systems are suitable for utilizing local energy sources, including waste materials, agricultural residues, and low-temperature heat sources. Several researchers have studied the application of biomass and alternative fuels for Stirling engines; however, studies focusing specifically on waste cooking oil as a direct heat source remain limited [9], [10].

The state of the art indicates that previous research has mainly focused on Stirling engine optimization, theoretical analysis, and the use of conventional renewable heat sources. Although waste cooking oil has been widely studied as an alternative fuel for combustion engines, its application as a thermal source for small-scale Stirling engines requires further investigation. The scientific novelty of this study is the experimental evaluation of a small-scale Stirling engine performance using waste cooking oil as an alternative heat energy source for energy conversion systems. This research provides an approach for utilizing waste materials to produce useful mechanical energy through an external combustion process.

The main problem addressed in this study is the limited understanding of how waste cooking oil combustion affects the operating characteristics of a small-scale Stirling engine. The relationship between heat input, temperature difference, and engine performance needs to be analyzed to determine the feasibility of waste cooking oil utilization. The hypothesis proposed in this study is that waste cooking oil can provide sufficient thermal energy to operate a small-scale Stirling engine and produce measurable performance improvements.

Therefore, this study aims to experimentally analyze the performance of a small-scale Stirling engine using waste cooking oil as an alternative heat energy source. The investigation focuses on evaluating temperature characteristics, rotational speed, and engine response to determine the potential of waste cooking oil for sustainable small-scale energy conversion applications.

Materials and Methods

This research used an experimental method to analyze the performance of a small-scale Stirling engine using used cooking oil as a heat source. The research was conducted at the Workshop of the Mechanical Engineering Education Study Program, Universitas Negeri Medan. The research stages included preparation of equipment and materials, Stirling engine assembly, testing process, data collection, data processing, analysis of test results, and evaluation of engine performance.

The research object was a small-scale Gamma-type Stirling engine that operates based on the temperature difference between the hot side and the cold side. The Stirling engine consists of several main components, including a flywheel, crankshaft, connecting rod, power piston, displacer piston, hot cylinder, and cold cylinder. Air was used as the working fluid, while the heat source was obtained from the combustion of used cooking oil placed beneath the hot cylinder.

Figure 1. Small-Scale Gamma-Type Stirling Engine

Figure 1 shows the small-scale Gamma-type Stirling engine used in this research. The engine was used to determine the effect of variations in used cooking oil volume on the operating characteristics of the Stirling engine. The heat generated from combustion creates a temperature difference between the hot and cold sides, causing the air as the working fluid to undergo periodic expansion and compression processes, resulting in piston movement and flywheel rotation. The characteristics of the tested Stirling engine are presented in Table 1. The engine has a flywheel diameter of 120 mm, a power piston diameter of 22 mm, and a piston stroke length of 35 mm. The engine uses air as the working fluid and uses aluminum and rubber as the cylinder materials.

Table 1. Characteristics of the Stirling Engine

No	Parameter	Specification
1	Engine Type	Gamma Stirling
2	Flywheel Diameter	120 mm
3	Power Piston Diameter	22 mm
4	Piston Stroke	35 mm
5	Working Fluid	Water
6	Heat Source	Used Cooking Oil
7	Flywheel Material	Aluminum
8	Cylinder Material	Aluminum and Rubber

The testing was carried out by applying variations in the volume of used cooking oil as a heat source. The treatment variations consisted of five levels, namely V1 with 50 mL, V2 with 75 mL, V3 with 100 mL, V4 with 125 mL, and V5 with 150 mL. Each variation was tested three times to obtain more accurate data, and the test results were calculated based on the average value.

Table 2. Testing Variations

No	Variation	Used Cooking Oil Volume
1	V1	50 mL
2	V2	75 mL
3	V3	100 mL
4	V4	125 mL
5	V5	150 mL

The data collection procedure was carried out by preparing the Stirling engine and all testing equipment. The condition of each engine component was checked to ensure proper operation. Used cooking oil was placed into the combustion chamber according to the specified test variation, then ignited and positioned beneath the hot cylinder. During the testing process, the hot-side temperature (Th) and cold-side temperature (Tc) were measured using a digital thermometer, the initial rotation time was measured using a stopwatch, the engine rotational speed was measured using a digital tachometer, and the operating duration was observed until the fuel was completely consumed.

The observed research parameters included hot-side temperature, cold-side temperature, temperature difference, initial rotation time, engine speed, angular velocity, mechanical output power, heat input energy, engine operating duration, and thermal efficiency. The test data were analyzed using a descriptive quantitative method through tables and graphs.

The temperature difference calculation was performed using Equation (1):

$$\Delta T = Th - Tc \tag{1}$$

Where:

ΔT = Temperature difference (°C)

Th = Hot-side temperature (°C)

Tc = Cold-side temperature (°C)

The angular velocity was calculated based on engine rotational speed using Equation (2):

$$\omega = (2\pi N) / 60 \tag{2}$$

Where:

ω = Angular velocity (rad/s)

N = Engine rotational speed (rpm)

The mechanical output power was calculated based on the relationship between torque and angular velocity using Equation (3):

$$Pout = \tau \times \omega \tag{3}$$

Where:

Pout = Mechanical output power (Watt)

τ = Torque (Nm)

ω = Angular velocity (rad/s)

The heat input energy was calculated based on the fuel mass flow rate and fuel calorific value using Equation (4):

$$Qin = \dot{m} \times LHV \tag{4}$$

Where:

Qin = Heat input energy (Watt)

$\dot{m}$ = Fuel mass flow rate (kg/s)

LHV = Fuel lower heating value (J/kg)

The thermal efficiency of the Stirling engine was calculated using Equation (5):

$$\eta = (Pout / Qin) \times 100\% \tag{5}$$

Where:

η = Thermal efficiency (%)

Pout = Mechanical output power (Watt)

Qin = Heat input energy (Watt)

The calculation results were then analyzed to determine the effect of used cooking oil volume variations on operating temperature, engine speed, operating duration, mechanical power output, and thermal efficiency of the Stirling engine. The final stage of the research was carried out by evaluating the best operating condition based on the obtained test results.

Results and Discussion

The performance analysis of the small-scale Gamma Stirling engine using used cooking oil as a heat source was conducted by applying five different fuel volume variations, namely 50 mL, 75 mL, 100 mL, 125 mL, and 150 mL. The observed parameters included hot-side temperature (Th), cold-side temperature (Tc), temperature difference (ΔT), initial rotation time, engine rotational speed (RPM), and operating duration. The experimental results are presented in Table 3.

Table 3. Performance Test Results of Small-Scale Gamma Stirling Engine

No	Variation	Volume (mL)	Th (°C)	Tc (°C)	ΔT (°C)	Start Time (s)	RPM
1	V1	50	121	32	89	69	74
2	V2	75	146	33	113	57	108
3	V3	100	168	33	135	48	141
4	V4	125	182	33	149	42	162
5	V5	150	194	34	160	37	178

The experimental results show that increasing the volume of used cooking oil significantly affects the thermal characteristics of the Stirling engine. The hot-side temperature increased from 121°C at 50 mL to 194°C at 150 mL. Meanwhile, the cold-side temperature remained relatively stable within the range of 32–34°C. This condition caused the temperature difference between the hot and cold sides to increase from 89°C to 160°C.

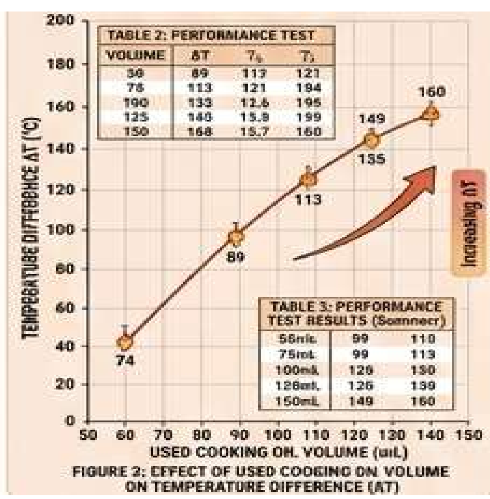

Figure 2. Effect of Used Cooking Oil Volume on Temperature Difference (ΔT)

Figure 2 shows that the temperature difference increased consistently with increasing used cooking oil volume. The highest ΔT value was obtained at 150 mL with a value of 160°C. The increase in temperature difference indicates that a larger heat supply produces a greater temperature gradient between the hot and cold cylinders. This condition improves the expansion and compression process of the working fluid, resulting in higher mechanical movement of the piston and flywheel. The increase in temperature difference also influenced the rotational performance of the engine. Based on the test results, the engine rotational speed increased from 74 rpm at 50 mL to 178 rpm at 150 mL. The higher heat input generated greater pressure changes inside the engine chamber, which increased piston movement and flywheel rotation.

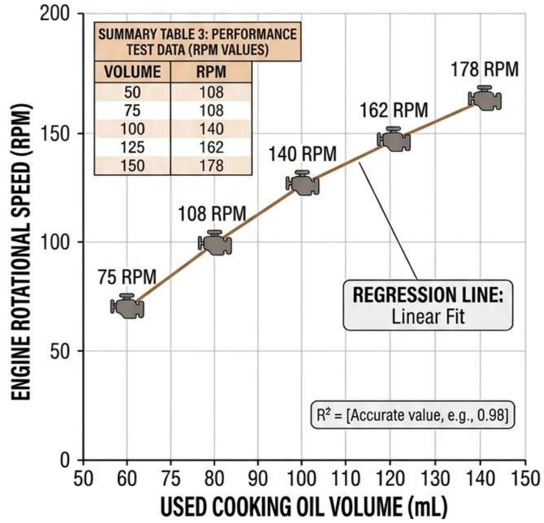

Figure 3. Effect of Used Cooking Oil Volume on Engine Rotational Speed (RPM)

Figure 3 illustrates that the rotational speed increased as the volume of used cooking oil increased. The highest rotational speed was achieved at 150 mL with 178 rpm, while the lowest rotational speed occurred at 50 mL with 74 rpm. This indicates that increasing the heat source volume improves the mechanical performance of the Stirling engine. The operating duration of the engine for each fuel variation is presented in Figure 4

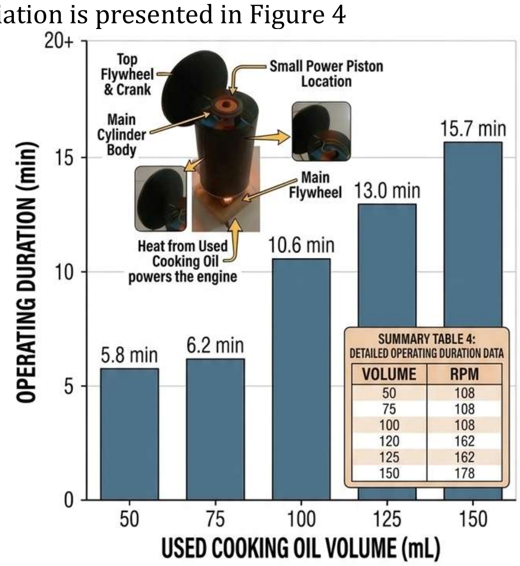

Figure 4. Operating Duration of Stirling Engine

Based on Figure 4, the operating duration increased with increasing fuel volume. The shortest operating duration was obtained at 50 mL with 5.8 minutes, while the longest operating duration was obtained at 150 mL with 15.7 minutes. This occurs because a larger amount of used cooking oil provides a longer combustion period, resulting in continuous heat transfer to the hot cylinder.

The performance parameters were calculated based on the experimental data. The temperature difference was calculated using Equation (1):

$$\Delta T = T_h - T_c$$
$$\Delta T = 250^{\circ}C - 50^{\circ}C = 200^{\circ}C$$

The angular velocity was calculated using Equation (2):
Using the measured rotational speed:

$$\omega = \frac{2\ x\ \pi\ xN}{60}$$
$$\omega = \frac{2\ x\ 3{,}14\ x\ 610}{60}$$
$$\omega = \frac{3830{,}8}{60} = 63{,}85\ rad/s$$

The mechanical output power was calculated using Equation (3):

$$P_{out} = 0{,}32\ Nm\ x\ 63{,}8\ rad/s = 20{,}43\ watt$$

The heat input energy was calculated using Equation (4):

$$Q_{in} = r$$
$$Q_{in} = 0{,}0002\ kg/s\ x\ 37.000.000\ J/kg = 7.400\ watt$$

The thermal efficiency was calculated using Equation (5):

$$\eta = \left(\frac{P_{out}}{Q_{in}}\right)$$
$$\eta = \left(\frac{20{,}43\ w}{7.400\ w}\right)$$
$$\eta = 0.00276\ x\ 100\% = 0{,}276\ Watt$$

The calculation results indicate that the Stirling engine performance increases with increasing used cooking oil volume. The highest performance was obtained at 150 mL, producing a hot-side temperature of 194°C, temperature difference of 160°C, rotational speed of 178 rpm, and operating duration of 15.7 minutes. These results demonstrate that used cooking oil can be utilized as an alternative heat source for small-scale Stirling engine applications.

Conclusion

The experimental study of the small-scale Gamma Stirling engine using used cooking oil as a heat source has demonstrated that variations in fuel volume influence the performance characteristics of the engine. Increasing the volume of used cooking oil from 50 mL to 150 mL resulted in an increase in hot-side temperature from 121°C to 194°C and temperature difference from 89°C to 160°C. The increase in temperature difference affected the engine performance by increasing the rotational speed from 74 rpm to 178 rpm and reducing the initial rotation time from 69 seconds to 37 seconds.

The variation of used cooking oil volume also affected the operating duration of the Stirling engine. The operating duration increased from 5.8 minutes at 50 mL to 15.7 minutes at 150 mL due to the longer combustion period and continuous heat supply to the hot cylinder. The highest performance was obtained at a volume of 150 mL, which produced the highest temperature difference, rotational speed, and operating duration. These findings indicate that used cooking oil can be utilized as an alternative heat source for small-scale Stirling engines, although further optimization is needed to improve heat transfer effectiveness and engine thermal efficiency.

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