Manufacturing and testing prototype of a gamma type Stirling engine for micro-CHP application

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Abstract. In this study, a gamma type Stirling engine was produced and tested for the micro-CHP system with a swept volume of compression 106 cc. The engine is tested by air and uses LPG fuel as a heat source. Air pressure at the beginning of the compression process is considered to be the ideal gas pressure of 0.987 bar. The best working characteristics of the machine were obtained in the first test with a temperature difference on the hot and cold side of an average of 74.7^{o}C. Maximum output and power output were obtained at 1.82 bar charge pressure of 242.6 rpm and 12.9 W. The results found were encouraging to begin the prototype gamma type Stirling engine for micro-CHP applications.

1. Introduction

Energy needs in the household sector in Indonesia increased from 116 million SBM in 2016 and predicted to be 483 million SBM in 2050. Figure 1 shows the final energy requirements according to the sector in Indonesia [1]. The increase in energy in this sector is due to the increasing use of electrical equipment to help with daily activities in the household. The electrical energy used by the people in Indonesia is obtained from the supply of the National Electricity Company (PLN). Today, Indonesia is still experiencing a shortage of electricity supply from PLN, which is characterized by rotating power outages and some remote areas that have not yet been electrified.

The use of electrical energy in the household sector is usually for the purposes of lighting, cooking, air conditioning, refrigerators, pumps, and other electrical equipment. Cooking is an activity of preparing food to eat by heating so that the food can be consumed. When the cooking process occurs it will produce heat energy which is mostly wasted into the environment. The hot waste still has the potential to be used to drive electric power plants. The system that works together to produce heat and power plants is known as the combined heat and power (CHP) system. Cooking activities in Indonesia generally use fuel available in their respective regions. The percentage of the main fuel for cooking in households is based on data from the Central Bureau of Statistics (BPS) for 2012 and 2016 in Indonesia as shown in Figure 2 [2]. Figure 2 shows that the most used fuel used for cooking is gas/elpiji 1 (LPG) and wood (biomass) as much as 72.38% and 21.57% in 2016.

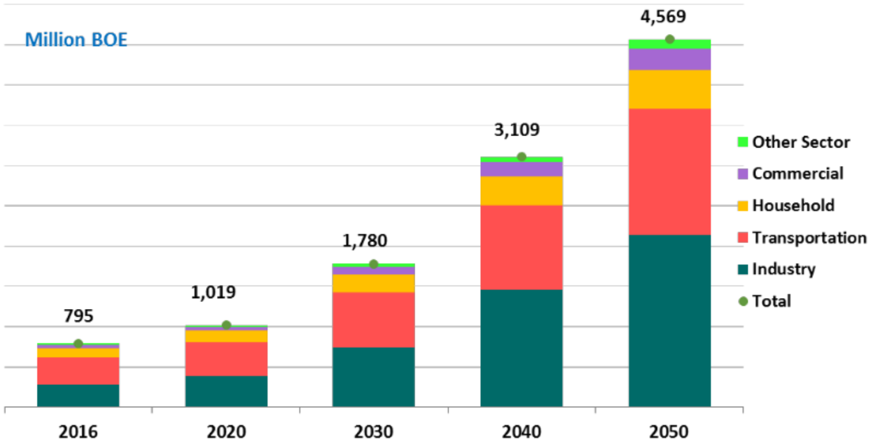

Figure 1. Final energy demand by sector[1]

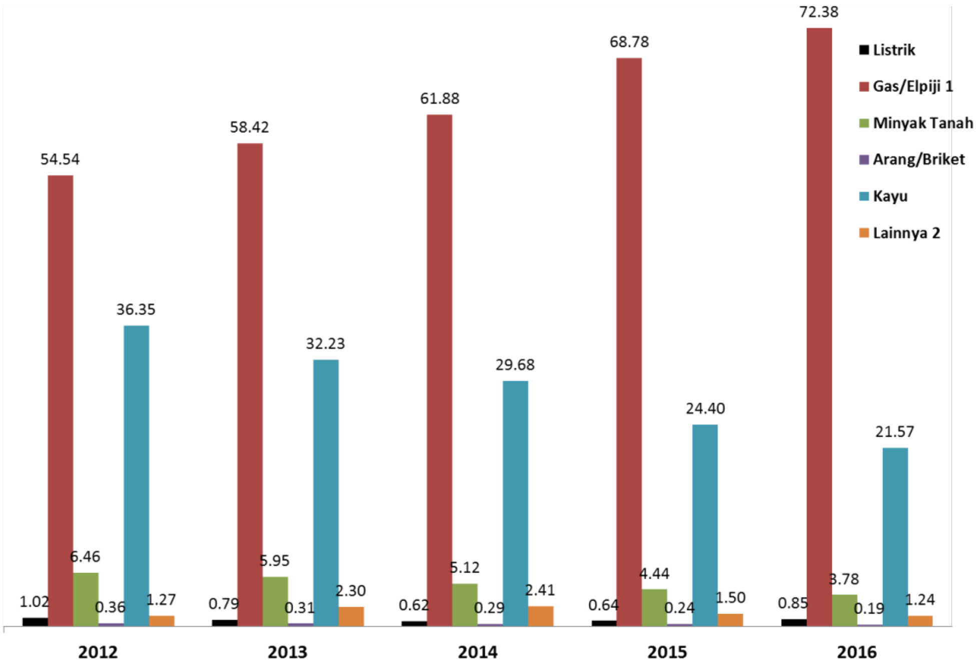

Figure 2. Percentage of the main fuel for cooking in Indonesia[2]

CHP is a good and efficient approach to produce heat energy and use electric power from one fuel source [3]. CHP technology is usually developed according to the type of fuel used, namely solid, liquid and gas. CHP has proven to be useful for both housing and industry because of its high overall thermal efficiency, reducing total power requirements and providing high-quality power with good reliability [4]. The traditional application of the CHP system enables higher energy performance than the production of heat and separate electrical energy [5]. The CHP system is categorized based on the size of electricity generation. The micro-CHP system produces electric power <10 kWe and small-CHP produces electric power 10-1000 kWe [6]. The application of the micro-CHP concept makes each home has its own heat and electricity generating unit [4].

The main driver of the electric generator from micro-CHP is usually the Stirling engine. The Stirling engine is selected for micro-CHP applications because it can be operated on a variety of fuels. In addition, the Stirling engine also has advantages, which are controlled combustion, long life, long maintenance time, high efficiency, low noise and vibration and low emissions [7–12]. Stirling machines are defined as thermal machines operated by cycles of compression and expansion of air or other gases (working fluids) at different temperatures so that there is a conversion of heat energy into mechanical work [13,14]. This machine was discovered about 80 years before the discovery of a Diesel engine by Robert Stirling in Scotland and was patented in 1816 with number 4081 [13-16].

Since the issue of fossil energy has diminished, the Stirling engine has returned to the attention of many researchers to develop. Much research has been done to see the ability of small-scale Stirling engines by utilizing heat from burning various kinds of fossil and renewable fuels to produce electricity less than 10 kWe. Implementation of gamma type Stirling engine by utilizing waste heat from cooking stoves in rural areas can reduce the electrical energy crisis [17]. Integration of alpha type Stirling engines with wood pellet combustion chambers is strongly influenced by the heat side heat exchanger with combustion heat source [18].

Design, fabrication, and evaluation of the gamma type Stirling engine to produce rural electrical energy with a capacity of 1 kWe. The engine is tested using helium as a working fluid and biomass as fuel. The test results show that the maximum power is 96.7 W obtained at a heat source temperature of 550^{o}C. The resulting pressure is 10 bar, 700 rpm rotation and engine thermal efficiency are 16% [19-21]. Integration of the Stirling engine with pellet burners is a promising alternative for generating heat and power for home use [22]. The Stirling engine heater which is placed in a fluidized bed combustor (FBC) increases efficiency for micro-CHP system applications [23]. The design and feasibility study of the integrated CHP system with heat pump (CHP-HP) shows that the proposed CHP-HP system is effective in cold climate zones by increasing additional heating energy consumption with waste heat obtained from the power generation unit (PGU) [24]. The power plant from the free-piston Stirling engine generator (FPSEG) that uses heat obtained from wood pellet combustion makes it possible to move the FPSEG to obtain electricity and hot water as output [25].

Based on literature studies from previous studies, it is seen that research on CHP based Stirling engines to produce heat and electricity promises to continue to be developed considering the potential for waste heat that continues to exist in every household. This study aims to create and test the ability of a gamma type Stirling engine prototype for micro-CHP applications.

2. Method

The first generation Stirling engine that has been designed by the author assisted by the Stirling Engine Research Team 2018 is the gamma type named mCHPSE-012018. Furthermore, this engine was made in the Engineering Timbul Workshop and tested at the Mechanical Engineering Laboratory, Institut Teknologi Medan. The engine that has been made and tested as shown in Figure 3.

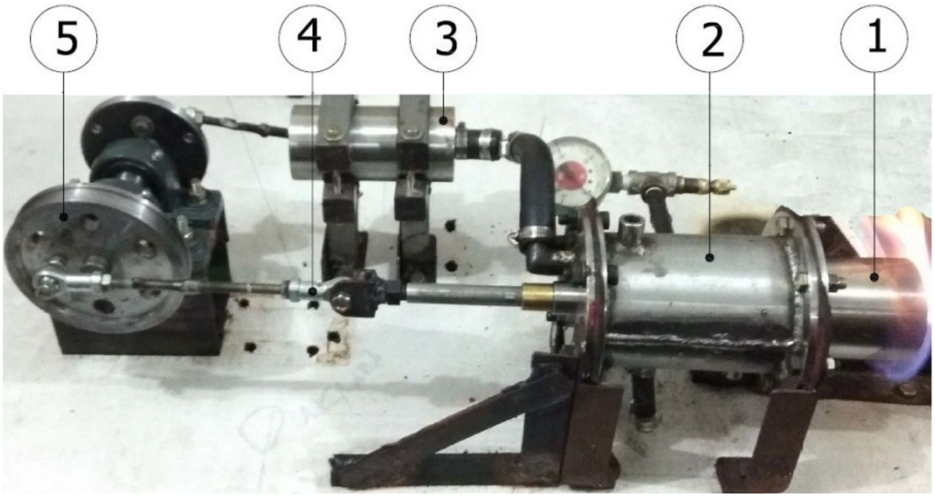

Figure 3. Prototype Stirling engine type gamma

This engine is also equipped with a water jacket and radiator for the cooling system. The size of the main components of the engine is shown in Table 1. This engine has been tested using air as a working fluid and LPG or in Indonesia better known as Elpiji for fuel. Measurements were made in 1-minute intervals for 1 hour as many as 3 times the test. During testing, there are several variables that have been measured, namely heat source temperature, the air temperature on the hot and cold side, and the flywheel round. Temperature measurements were carried out using Autonics temperature indicator T4WM-N3NKCC with a type K thermocouple sensor. While the engine flywheel rotation was measured using a Tachometer Krisbow brand type KW 06-563. The cooling water temperature is kept constant by the cooling system at 40^{o}C. Whereas all calculation analysis in this paper uses the ideal Stirling cycle approach. Calculation of all parameters in this paper is carried out using equations proposed by Wagner [26] and Wan Dawi et al. [27].

Table 1. Component dimensions of the Stirling engine prototype

No. Part	Component	Material and size	
1.	Heater	Material	: Stainless steel
		Diameter	: 66.5 mm
		High	: 75 mm
		Thickness	: 5 mm
2.	Displacer section (Displacer piston and cylinder)	Displacer Piston	
		Material	: Duralumin
		Diameter	: 50 mm
		High	: 54 mm
3.	Piston section (Power piston and cylinder)	Power Piston	
		Material	: Duralumin
		Diameter	: 54 mm
		High	: 130 mm
4.	*Connecting rods*	Distance	: 370 mm
5.	*Flywheel*	Material	: Cast iron
		Diameter	: 200 mm

3. Results and discussions

Based on the dimensions in Table 1, calculation of swept volume for displacer (V_{SE}) and power piston (V_{SC}), dead volume in expansion space (V_{DE}), dead volume in compression space (V_{DC}), pipe volume between expansion and compression space (V_R) , Dead total volume (V_D) and compression ratio (CR). The results of the calculations from all the parameters above can be seen in Table 2. Then proceed with the calculation of expansion volume, compression volume, and total volume. Data from the calculation of the three variables can be seen in graphical form as in Figure 4.

Table 2. Data from volume calculation results

V_{SE} (m^3)	V_{DE} (m^3)	V_{SC}(m^3)	V_{DC} (m^3)	V_R (m^3)	V_D(m^3)	CR
0.0001237	0.0000345	0.0001060	0.0000491	0.0000246	0.0001081	1.46

From the three tests that have been carried out, several important parameter values have been obtained which indicate the ability of the Stirling engine. The average heat source temperature values for each test are 431.5^{o}C, 419.5^{o}C, and 449.1^{o}C. The air temperature value in the expansion and compression section of the measurement results as shown in Figure 5. The heat and cold side temperature difference (ΔT) on average for each test are 74.7^{o}C, 42.3^{o}C, and 54^{o}C. The average flywheel rounds are 242.6 rpm, 197.9 rpm, and 221.2 rpm.

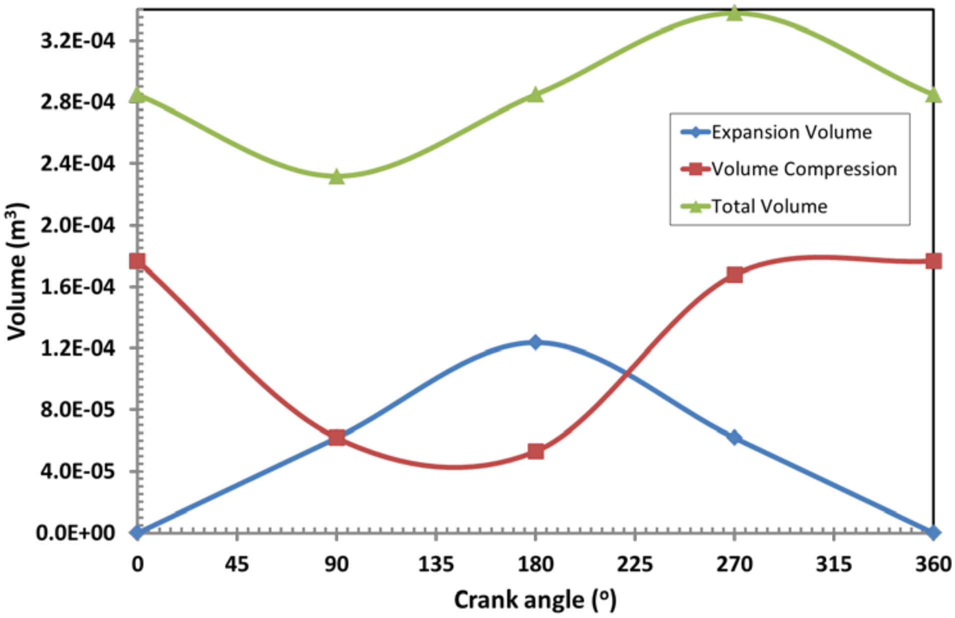

Figure 4. Volume as a function of the crank angle

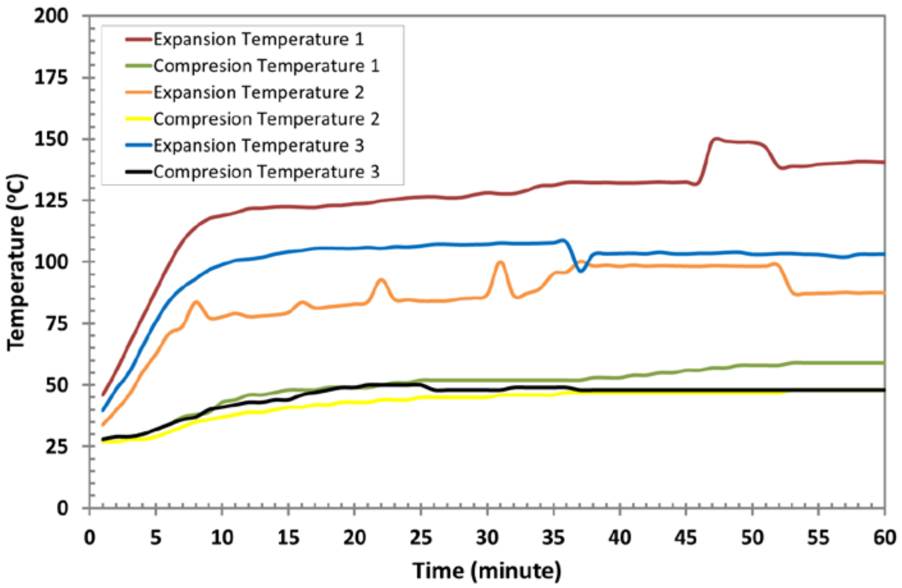

Figure 5. The temperature profile in the expansion and compression section

The thermal efficiency of the Stirling engine average (η_{th}) from the calculation results are 18.78%, 11.8%, and 14.5%, respectively. If the process that occurs is ideal, then the relationship between the volume and pressure of the Stirling engine is three times the test as shown in Figure 6. Every test, the air pressure at the beginning of the compression process is equal to the ideal gas pressure of 0.987 bar. The maximum pressure that can be achieved by the Stirling engine at three tests is 1.82 bars, 1.67 bars, and 1.73 bars, respectively. While the average power that can be generated from the calculation results for are 12.9 W, 7.32 W, and 9.4 W.

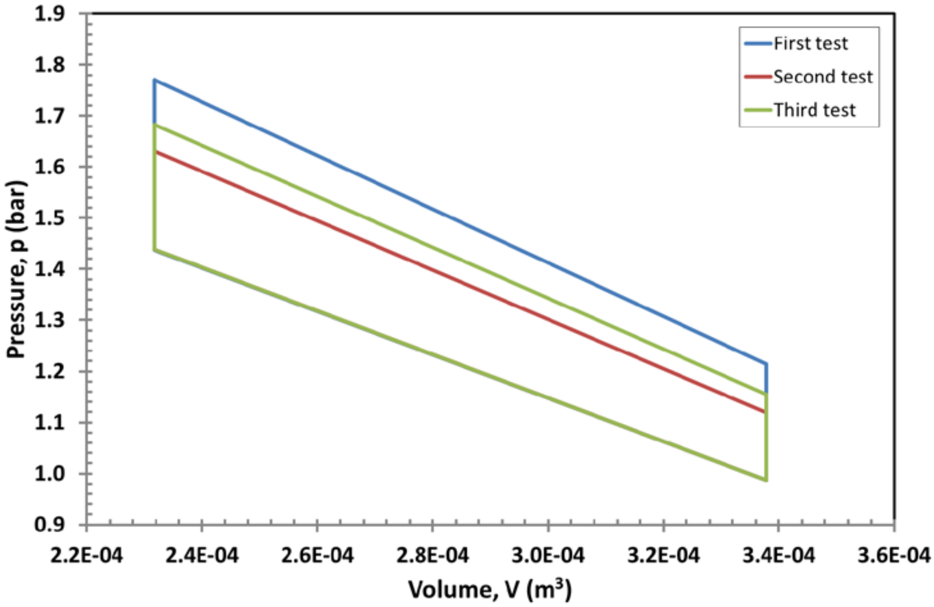

Figure 6. p-V diagram for the ideal process Stirling engine

4. Conclusions

Gamma type Stirling engine prototype has been made and tested. The results of the analysis show that the performance of the engine is still low and there is a high deviation between every the test. The main causes of thermal efficiency, working fluid pressure and low power are the differences in temperature changes that are not constant. So it is necessary to do some modifications, especially the addition of regenerators so that the temperature difference between the hot and cold sides is not too much changed like now. In addition, it is also necessary to consider the shorter design of connecting rods to increase the flywheel rotation.

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