Performance Analysis of Stirling Engine Type Alpha Using Thermodynamic Approach Based on Schmidt Theory

Raden Hengki Rahmanto[1*], *Yopi* Handoyo[1], and *Fahrizal Zain* Asrori[1]

[1]Department of Mechanical Engineering, Universitas Islam 45, Bekasi, Indonesia

Abstract. Environmental concern and the impact on climate change have spawned various technological innovations for high efficiency engines that save fuel and produce less carbon emissions. Technological innovations that operate on a closed cycle can use variety of heat sources, produce no emissions and very high efficiency was Stirling engine. This research aims to design a Stirling engine type Alpha with a capacity of 228 cc with a phase angle of 90 degrees, then analyze its performance in the form of power indicators and thermal efficiency indicators and determine the effect of the increase in temperature difference between the compression chamber temperature and the expansion chamber temperature towards engine rotation speed. The method used to analyze engine performance is the Schmidt method, which is a Stirling engine performance analysis method based on isothermal expansion and ideal gas compression. The result of this research is that the Stirling engine which is designed starts working when the compression chamber temperature is 31.9 degrees Celsius and the expansion chamber temperature is 482.2 degrees Celsius. The highest engine speed is 598 rpm which is obtained at a compression chamber temperature of 45.5 degrees Celsius and an expansion chamber temperature of 662.4 degrees Celsius. The engine power indicator is 194.6 watt at 598 rpm, while the thermal efficiency indicator is 65.94 percent. Based on the experimental data, it is also known that the increase in temperature difference between the compression chamber temperature and the expansion chamber temperature causes an increase in engine rotation speed.

1 Introduction

Many technology companies are currently competing to develop an environmentally friendly engine technology innovation, along with growing concern for the environment and the effects of climate change. The intended technological innovation, not only in the use of alternative fuels but also in increasing engine efficiency in order to save fuel and produce less exhaust emissions. Among the many innovations that have appeared, the Stirling engine is one of the oldest and most superior engine technologies because it closely addresses contemporary issues [1].

* Corresponding author: hengki.rahmanto@gmail.com

The Stirling engine is a closed-cycle, regenerative engine that can run on a variety of heat sources because it is externally heated. The ideal Stirling cycle theoretically has the same thermal efficiency as the Carnot cycle, according to the thermodynamic analysis [2, 9]. The Stirling engine is a type of external combustion engine, so it does not depend on certain types of fuel such as Otto or Diesel engines. In other words, a variety of heat sources can be used, including nuclear energy, solar energy, burning biomass, and burning solid, liquid, and gaseous fuels. Due to the fact that it is an external combustion engine, the reaction that results from the combustion of fuel and oxygen is very efficient and sustainable and results in minimal exhaust emissions of NOx, SOx, CO, and other pollutants [3].

This is interesting, because the Stirling engine can be the answer to the limited use of fossil fuels. Even with these capabilities, this engine can use heat energy sources that last a long time such as nuclear reactions to unlimited sources of heat energy from the sun, this of course can make the Stirling engine an alternative engine in the future [4].

However, the creation of a Stirling engine intended for mass production was extremely rare. This is because Otto and Diesel engines can provide many times greater output power than Stirling engine. Additionally, since this engine uses an external combustion system, requires longer time to heating it up to its initial operating temperature [5].

Aside from that, because the Stirling engine has such great potential for the future, until now much further research and development is still being carried out even though its use is more for environmentally friendly power generators such as solar dish stirling engines to radioisotope generators for electricity supply on space satellites [6, 8].

This serves as the background for this research, which aims to design a Stirling engine and then testing and analysis its performance by using power indicators and thermal efficiency indicators. The Alpha type of Stirling engine was created and tested for this study because of its straightforward design and accessible parts. Additionally, using Schmidt's theory, the performance of the Stirling engine was analyzed. This theory was chosen because according to Walker, Schmidt's theory provides a more accurate estimate of an engine performance than ideal cycle analysis [7].

2 Method

2.1 Determine engine design stirling type - α (alpha)

The basic specifications of the Stirling engine to be made for the experimental test in this study can be seen in **Table 1** as follows.

Table 1. Stirling engine specifications to be made

Specifications		**Description**
Engine Configurations	:	Type - α (Alpha)
Drive Mechanism	:	Crank Shaft
Piston Configurations	:	Two Cylinder, V-90^{o}
Engine Capacity	:	228 cc
Diameter and Stroke	:	55 mm x 48 mm
Working Fluids	:	Air
Displacer Material	:	Steel Wool
Displacer Dimension	:	54 mm x 147 mm

2.2 Stirling engine fabrication

Following the creation of the design, the materials that have been gathered are then divided into various components (see **Fig. 1**). The parts are as follows, as shown in **Fig.2.**a to 2.f.

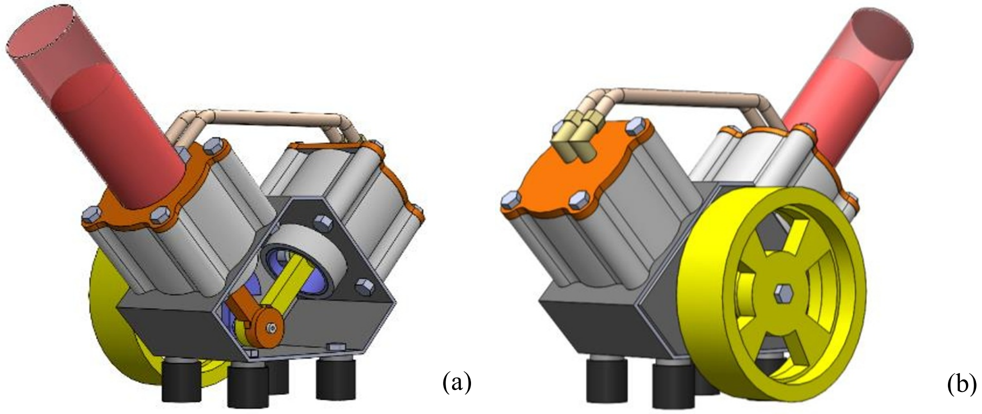

Fig. 1. Stirling engine type-α (alpha) that will be designed: (a) View-A; (b) View-B

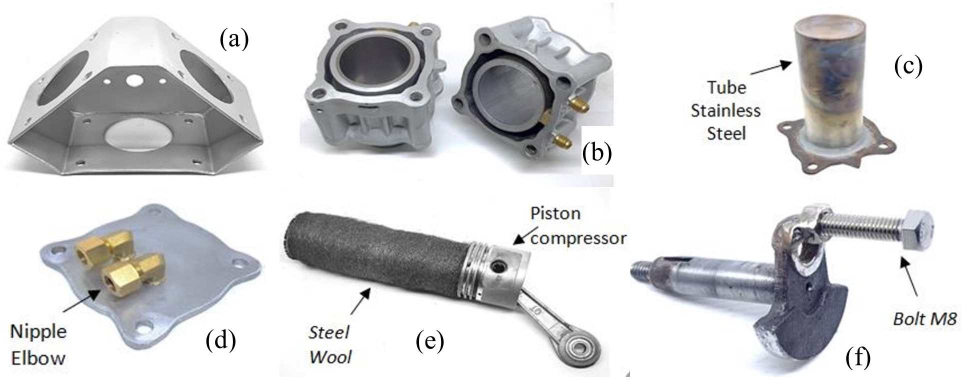

Fig. 2. Stirling engine fabrications: (a) Crankcase; (b) Cylinder block; (c) Cylinder cover hot; (d) Cylinder cover cold; (e) Piston displacer; (f) Crank shaft

When constructing the crankcase, the iron plates are bent, welded and drilled according to a pre-designed template. The size of the crankcase must be very precise so that every component placed can be properly connected to each other as shown in **Fig. 2**.a. The material for the engine block using a Yamaha Jupiter MX 135 cc motorbike is then changed in shape and size according to the finished design, such as removing the timing chain guard and enlarging the cylinder diameter (hole). Previously 54mm in diameter, changed to 55mm as shown in **Fig. 2**.b. The hot cylinder cover is made of stainless-steel tube and is welded to an iron plate which has previously been formed and perforated in such a way according to the design that has been made. Make sure there are no leaks in the weld joint area as shown in **Fig. 2**.c. The cold cylinder cover is made of aluminum plate which is formed in such a way and then elbow elbows are attached based on the design made. Make sure there are no leaks in the area as shown in **Fig. 2**.d. Expansion pistons, or displacer pistons as they are commonly called, are made from a compressor piston, and then treated with steel wool which has been shaped in the same way as the previous design as shown in **Fig. 2**.e. The crankshaft is made from one side of the lawnmower crankshaft, which has a main shaft with a diameter of 15 mm. At the top, an M8 bolt is attached as the connecting rod shaft is 24 mm from the center shaft according to the piston stroke length of 48 mm as shown in **Fig. 2**.f.

 https://doi.org/10.1051/e3sconf/202450003018

2.3 Stirling engine type - *α* (alpha) assembly

The components that have been completed are then assembled into a complete Stirling engine according to a predetermined design, taking into account the suitability of the size and layout of the components.

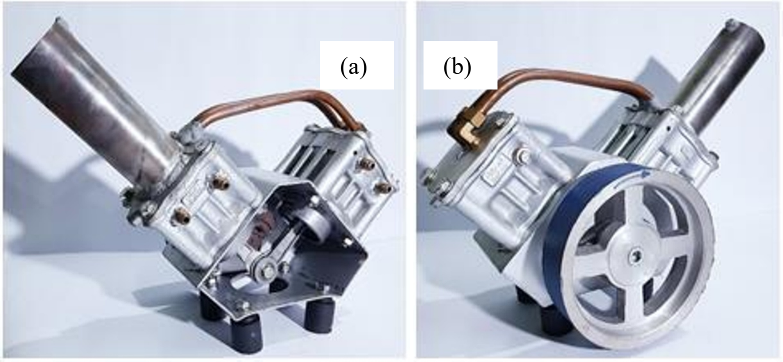

Fig. 3. Stirling engine type-*α* (alpha) assembly: (a) View-A; (b) View-B

2.4 Trial and error

In this trial and error test, there are several parameters that the author uses as a reference for determining the success of the test. The parameters are as follows: the machine is able to work stable; there are no pressure leaks on components that can affect engine performance; as long as the machine is running, the components are not damaged such as jammed, broken, position changes, or abnormal sounds.

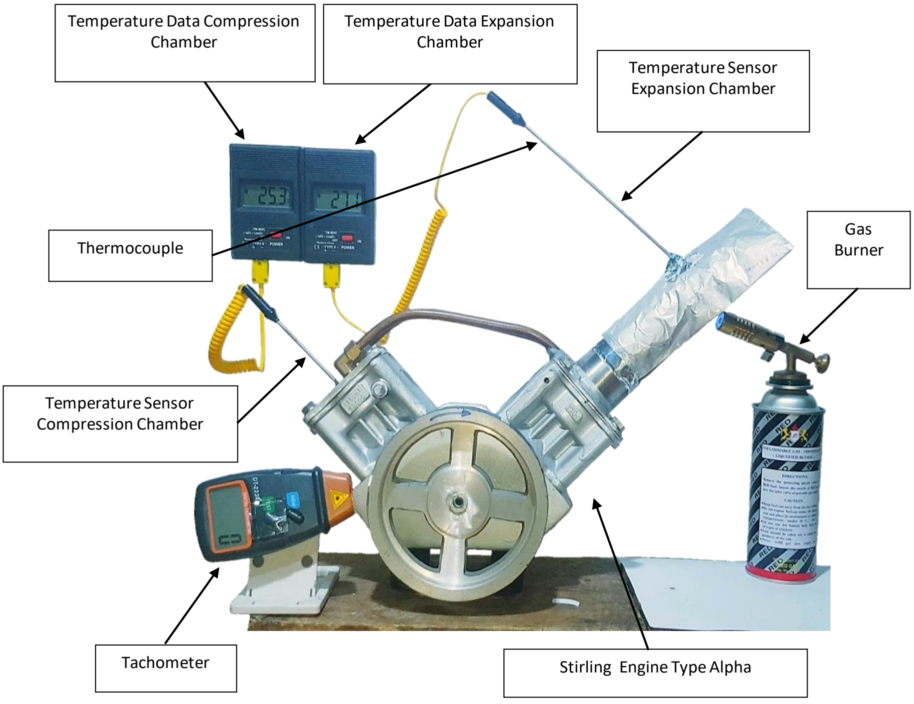

Fig. 4. Test schematic stirling engine performance

3 Results and discussion

3.1 Design results

The Stirling engine that has been designed and tested through trial and error is then tested for its performance, in order to obtain some of the data needed to analyze the performance of the Stirling engine. The resulting Stirling engine and its test scheme are shown in **Fig. 4**.

3.2 Test results

Data acquisition on the Stirling engine performance test was carried out in accordance with the data acquisition steps. The test results data are presented in the **Table 2**.

Table 2. Stirling engine performance test results

Time (Second)	Compression Chamber Temperature Tc (°C)	Expansion Chamber Temperature T_E (°C)	Temperature Difference ΔT (°C)	Engine Speed (rpm)
0	29.9	31.1	1.2	0
209	31.9	482.2	450.3	215
215	32	492.1	460.1	360.1
221	32.2	502	469.8	341.5
227	32.5	512.1	479.6	388
233	32.7	522.1	489.4	388.5
240	32.9	532.2	499.3	387.7
247	33.1	542.1	509	431.1
255	33.4	552.1	518.7	406.6
272	33.7	562	528.3	419.9
273	34.1	572	537.9	398.9
286	34.6	582.1	547.5	418.3
299	35.2	592.4	557.2	425.7
317	35.9	602.2	566.3	445.8
339	36.7	612	575.3	463.2
368	37.8	622.1	584.3	515.3
410	40	632.3	592.3	579.3
487	41.9	642.5	600.6	590.6
517	42.7	652.2	609.5	592.5
596	45.5	662.4	616.9	598

Based on the data from the test results that presented in **Table 2**, it can be seen several things as follows: the initial temperature in the expansion chamber (T_E) = 31.1 °C and in the compression chamber (T_C) = 29.9 °C. Initial temperature is the temperature of the engine room before being heated; the engine starts working when it reaches the expansion chamber temperature (T_E) = 482.2 °C and compression chamber temperature (T_C) = 31.9 °C, with the resulting engine rotation speed of 215 rpm. The temperature is reached after heating the hot cylinder for 209 seconds; the highest achievement was obtained at the expansion chamber temperature (T_E) = 662.4 °C and compression chamber temperature (T_C) = 45.5 °C, with the resulting engine rotation speed of 598 rpm. Under these circumstances, the temperature of the expansion chamber and the engine speed tended to be stable, however, because the burner cans also heated up and there was fear of an explosion, the test was terminated for safety reasons; an increase in the temperature difference between the expansion chamber and the compression chamber affects the increase in engine rotation speed as shown in **Fig. 5**.

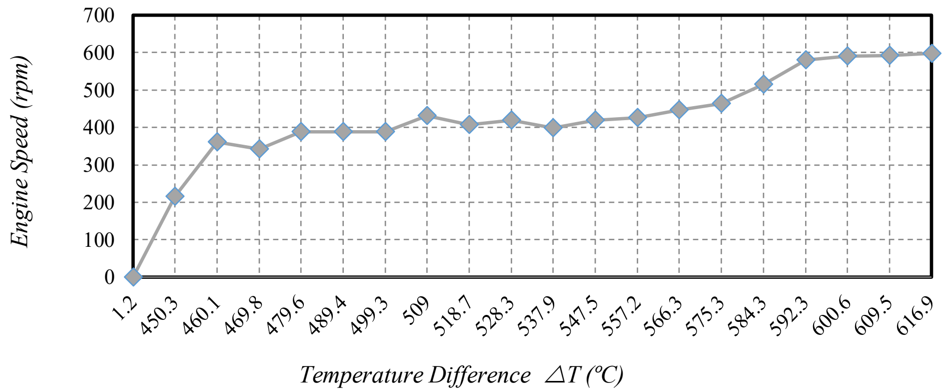

Fig. 5. Effect of increasing ΔT on rpm

3.3 Engine volume analysis

Based on the basic engine specification data that has been shown in **Table 3**, several parameters can be determined that will be used in the volume analysis on the engine. The parameters are as follows.

Table 3. Engine volume analysis parameters

Parameters	Unit	Formula
Piston stroke volume of compression (V_{SC}) and expansion (V_{SE})	m^3	$V_{SC} = V_{SE} = \frac{1}{4} . \pi . D^2 . L$
Piston stroke volume ratio (v)	m^3	$v = \frac{V_{SC}}{V_{SE}}$
Remaining volume of compression chamber (V_{DC})	m^3	$V_{DC} = \frac{1}{4} . \pi . D^2 . S_{CE}$
Remaining volume of expansion chamber (V_{DE})	m^3	$V_{DE} = \left(\frac{1}{4} . \pi . {D_H}^2 . S_E\right) - \left(\frac{1}{4} . \pi . {D_D}^2 . S_D\right)$
Displacer residual volume (V_D)	m^3	$V_D = \left(\left(\frac{1}{4} . \pi . {D_H}^2 . L_D\right) - \left(\frac{1}{4} . \pi . d^2 . L_D\right)\right)$
Volume regenerator (V_R)	m^3	$V_R = V_D + 2 . \left(\frac{1}{4} . \pi . {D_R}^2 . L_R\right)$
Expansion chamber remaining volume ratio (X_{DE})	m^3	$X_{DE} = \frac{V_{DE}}{V_{SE}}$
Compression chamber remaining volume ratio (X_{DC})	m^3	$X_{DC} = \frac{V_{DC}}{V_{SE}}$
Regenerator residual volume ratio (X_R)		$X_R = \frac{V_R}{V_{SE}}$
Regenerator temperature (T_R)	K	$T_R = \frac{T_E + T_C}{2}$
Temperature ratio (t)	K	$t = \frac{T_C}{T_E}$

Parameters	Unit	Formula
Instantaneous volume of expansion chamber (V_E)	m^3	$V_E = \frac{V_{SE}}{2}(1-\cos(x)) + V_{DE}$
Instantaneous volume of compression chamber (V_C)	m^3	$V_C = \frac{V_{SC}}{2}\{1-\cos(x-dx)\} + V_{DC}$
Total instantaneous volume (V)	m^3	$V = V_E + V_C + V_R$

3.4 Total mass working gas analysis

The working gas mass is the total mass of air included in the expansion chamber, compression chamber and regenerator chamber. In accordance with its working principle, the Stirling engine is a closed cycle engine, so that the calculation of the working gas mass is carried out at the initial operating conditions or before the engine is warmed up, and the engine volume is at its maximum (when the crank angle is 225 degrees). Based on the test results data, some of the known parameters are as follows (**Table 4**).

Table 4. Total mass gas analysis parameters

Parameters	Unit	Formula
Total mass working gas	*kg*	$m = \frac{P \,.\, V_E}{R \,.\, T_E} + \frac{P \,.\, V_R}{R \,.\, T_R} + \frac{P \,.\, V_C}{R \,.\, T_C}$

3.5 Engine pressure analysis

After the volume value is known, then it is necessary to know the pressure values of this Stirling engine during its work process. The pressure value can be classified as follows (**Table 5**).

Table 5. Engine pressure analysis parameters

Parameters	Unit	Formula
Engine pressure based on crank angle (P)	*Pa*	$P = \frac{2 \,.\, m \,.\, R \,.\, T_C}{V_{SE} \,.\, \{S - B \,.\, \cos(\theta - a)\}}$
Average pressure (P_{mean})	*Pa*	$P_{mean} = \frac{2 \,.\, m \,.\, R \,.\, T_C}{V_{SE} \,.\, \sqrt{S^2 - B^2}}$
Maximum pressure (P_{max}) and minimum pressure (P_{min})	*Pa*	$P_{max} = \sqrt{\frac{1+c}{1-c}} \,.\, P_{mean}$, $P_{min} = \sqrt{\frac{1-c}{1+c}} \,.\, P_{mean}$

According to **Table 6**, the minimum pressure (Pmin) and maximum pressure (Pmax), respectively, are produced when the crank angle is 251.19 degrees and 71.19 degrees, respectively.

It should be noted that the calculation of the average pressure value as well as the minimum and maximum pressures above is a calculation of the pressure that occurs when the engine is at a compression chamber temperature (TC) of 45.5 °C and an expansion chamber temperature (TE) of 662.4 °C, which is the highest value in the results of this Stirling engine performance test (for more information on the test results, see **Table 2**). Consequently, the pressure value will alter as the temperature does.

In the following **Table 6** and **Fig. 6**, the engine's pressure and volume values can be seen along with the P-V diagram.

 https://doi.org/10.1051/e3sconf/202450003018

Table 6. P-V Table based on crank angle

X (Degree)	V_R (m³)	V_C (m³)	V_E (m³)	V (m³)	P (Pa)
0	0.0000484492	0.0000641149	0.0000071239	0.0001196880	300,092.19
10	0.0000484492	0.0000542185	0.0000079897	0.0001106574	335,420.60
20	0.0000484492	0.0000446228	0.0000105609	0.0001036329	375,575.88
30	0.0000484492	0.0000356194	0.0000147592	0.0000988278	419,158.30
40	0.0000484492	0.0000274818	0.0000204572	0.0000963882	463,132.28
50	0.0000484492	0.0000204572	0.0000274818	0.0000963882	502,540.08
60	0.0000484492	0.0000147592	0.0000356194	0.0000988278	531,089.92
70	0.0000484492	0.0000105609	0.0000446228	0.0001036329	543,021.27
80	0.0000484492	0.0000079897	0.0000542185	0.0001106574	535,609.31
90	0.0000484492	0.0000071239	0.0000641149	0.0001196880	510,569.25
100	0.0000484492	0.0000079897	0.0000740113	0.0001304502	473,157.04
110	0.0000484492	0.0000105609	0.0000836069	0.0001426170	429,752.23
120	0.0000484492	0.0000147592	0.0000926104	0.0001558188	385,729.67
130	0.0000484492	0.0000204572	0.0001007480	0.0001696545	344,578.63
140	0.0000484492	0.0000274818	0.0001077725	0.0001837035	308,039.88
150	0.0000484492	0.0000356194	0.0001134705	0.0001975391	276,644.85
160	0.0000484492	0.0000446228	0.0001176689	0.0002107409	250,242.04
170	0.0000484492	0.0000542185	0.0001202401	0.0002229078	228,367.37
180	0.0000484492	0.0000641149	0.0001211059	0.0002336700	210,462.20
190	0.0000484492	0.0000740113	0.0001202401	0.0002427005	195,985.25
200	0.0000484492	0.0000836069	0.0001176689	0.0002497251	184,461.73
210	0.0000484492	0.0000926104	0.0001134705	0.0002545301	175,499.47
220	0.0000484492	0.0001007480	0.0001077725	0.0002569697	168,789.30
230	0.0000484492	0.0001077725	0.0001007480	0.0002569697	164,099.46
240	0.0000484492	0.0001134705	0.0000926104	0.0002545301	161,268.58
250	0.0000484492	0.0001176689	0.0000836069	0.0002497251	160,199.73
260	0.0000484492	0.0001202401	0.0000740113	0.0002427005	160,856.43
270	0.0000484492	0.0001211059	0.0000641149	0.0002336700	163,261.09
280	0.0000484492	0.0001202401	0.0000542185	0.0002229078	167,495.96
290	0.0000484492	0.0001176689	0.0000446228	0.0002107409	173,706.58
300	0.0000484492	0.0001134705	0.0000356194	0.0001975391	182,107.33
310	0.0000484492	0.0001077725	0.0000274818	0.0001837035	192,988.30
320	0.0000484492	0.0001007480	0.0000204572	0.0001696545	206,721.62
330	0.0000484492	0.0000926104	0.0000147592	0.0001558188	223,763.03
340	0.0000484492	0.0000836069	0.0000105609	0.0001426170	244,640.82
350	0.0000484492	0.0000740113	0.0000079897	0.0001304502	269,916.68
360	0.0000484492	0.0000641149	0.0000071239	0.0001196880	300,092.19

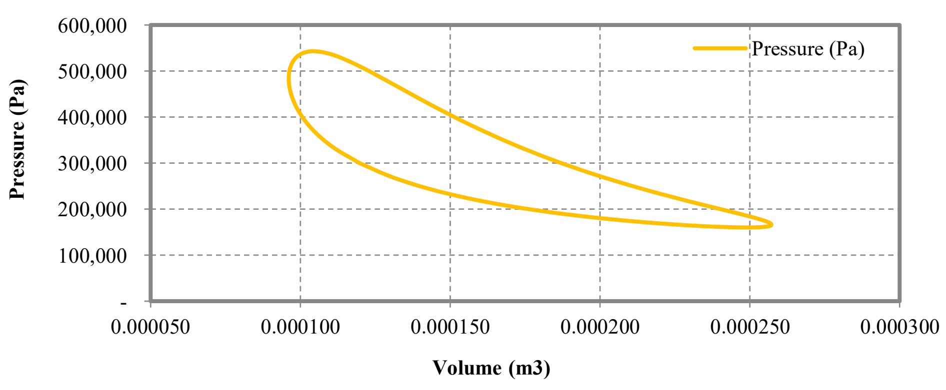

Fig. 6. P-V diagram

4 Conclusion

The designed Stirling engine type alpha can work properly and start working when the compression chamber temperature (TC) = 31.9 °C and expansion chamber temperature (TE) = 482.2 °C. While the highest engine speed obtained was 598 rpm at the compression chamber temperature (TC) = 45.4 °C and expansion chamber temperature (TE) = 662.4 °C. The power indicator produced by this engine is 194.6 watt at 598 rpm with a thermal efficiency indicator reaching 65.94%. An increase in the temperature difference between the temperature of the expansion chamber and the temperature of the compression chamber causes an increase in the rotational speed of the engine.

The authors are thankful to management of Mechanical Engineering, Engineering Faculty of Universitas Islam 45 Bekasi for their motivation and encouragement toward the publication of this research.

References

1. Bauer. Reinhold, "The Stirling Engine : The 'Cyclical Life' Of An Old Technology", History of Science & Technology Journal, 2009, 15.108-118.
2. Egas. Jose, Clucas, and Don.M, "Stirling Engine Configuration Selection", Energy, 2017, 11(3). 584.
3. Wagner. Andreas, "Calculations And Experiments On Γ-Type Stirling Engines", Thesis, University of Wales, 2008.
4. Chmielewski. Adrian, et.al., "Experimental research and application possibilities of microcogeneration system with Stirling engine", Journal of Power Technologies, 2015, 95. 14-22.
5. H. Karabulut, C. Çınar, E. Oztürk, and H. S. Yücesu, "Torque and Power Characteristics of a Helium Charged Stirling Engine With a Lever Controlled Displacer Driving Mechanism", Renewable Energy, 2010, vol. 35. pp. 138-143.
6. H. Karabulut, "Dynamic Analysis of a Free Piston Stirling Engine Working With Closed and Open Thermodynamic Cycles", Renewable Energy, 2011, vol. 36. pp. 1704-1709.
7. Walker. Graham, "Stirling Engines", New York : Oxford University Press, 1980.