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# HIRATA METHOD APPROACH TO THE PERFORMANCE ANALYSIS OF THE GAMMA TYPE STIRLING PISTON

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**Abstract**

The Stirling engine consists of two isothermal cycles and two constant volume cycles. The working principle of the Stirling Engine is to take advantage of changes in the pressure and volume of the gas in a closed system. The Schmidt method is an isothermal calculation method for the Stirling engine based on an ideal gas's isothermal expansion and compression. The method used is analytical and experimental, varying the rotation, compression, and cylinder temperature with the Hirata method. This study aimed to see the effect of air temperature expansion, compression, and temperature changes (∆T). After doing it, it can be concluded that the maximum rotation of P1 = 390 rpm, P2 = 387 rpm, and P3 = 399 rpm. The maximum torque of P1 = 0.967 N.m with a maximum power of 39.5 watts. P2 = 0.96 N.m with a maximum power of 38.9 Watts, and P3 = 0.99 N.m with a maximum power of 41.3 Watts. Calculations using the Hirata method show that the maximum temperature value in the compression cylinder (Tc) P1 = 49.7 ˚C, P2 = 51 ˚C, and P3 = 50 ˚C. Expansion cylinder (Te) P1 = 172.3 ˚C, P2 = 189.6 ˚C and P3 = 198.9 ˚C. Heater temperature (Th) P1= 576 °C, P2= 678.1°C and P3= 769.4 °C. Temperature change (∆T) P1= 126.1 °C, P2= 142.9 °C, and P3= 151 °C. The maximum pressure of the first experiment is 1.2504 Bar. In the second experiment, the maximum pressure reached 1.265 Bar. And in the third experiment, the maximum pressure is 1.2525 Bar

**Keywords:** Stirling gamma engine, hirata method, Piston performance

## INTRODUCTION

Hirata method approach to the performance analysis of the gamma-type stirling piston (Siregar, Jufrizal, & Putra, 2022), according to the Presidential Regulation of the Republic of Indonesia Number 22 of 2017 concerning the National Energy General Plan (RUEN) prioritizing the use of renewable energy with a target of at least 23% by 2025 and at least 31% by 2017. 2050 (Taufiqurrahman & Windarta, 2020). This condition is also exacerbated by the depletion of fossil energy, which is predicted that 2080 oil will run out, followed by natural gas in 2047 (Satria et al., 2020) (Wibowo et al., 2019). This requires a paradigm shift where it is hoped that there will be technological changes that utilize energy not only limited to internal combustion but external and internal combustion as well as air and gas sources (Afin & Kiono, 2021) (Arza & Murtala, 2021); this was adopted by the Stirling engine (Siregar, Jufrizal, Hasanah, et al., 2022). The

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Stirling engine can function with solar, chemical, or nuclear heat sources. The Stirling engine is a heat engine that has a working method of compressing and expanding fluids at different temperatures, which generally causes a change in heat energy into mechanical energy (Rahmalina et al., 2021); according to (Kristiani et al., 2020) the Stirling engine is a technology that utilizes temperature differences as a driver for continuous motion (Katooli et al., 2021), Stirling engine is a technology that can be used to convert alternative energy into mechanical energy (Duzgun & Karabulut, 2021) when compared to the internal combustion engine the Stirling engine is more efficient, has a smoother sound and is not difficult to maintain (Rahmat, 2019). The Stirling engine is generally classified into two according to the kinematic displacement method and the dynamic engine (Raja et al., 2021). In the kinematic Stirling engine, there is a synchronized motion carried out by the drive mechanism system between the displacer and the power piston (Getie et al., 2021). The displacement and the action of the power piston depend on the variation of the crank angle. (Ipci, 2020). This machine has two isothermal and constant volume cycles (Azhar & Nurhalim, 2013). The working principle of the Stirling Engine is to take advantage of the pressure and volume changes in the gas in a closed system (Huang & Chen, 2020) (N & Widyartono, 2020). In principle, there are three types of Stirling engines: Alpha, Beta, and Gamma (Evalina et al., 2020). In addition, another alternative solution is solar energy, where light energy is converted into electricity (Purwoto et al., 2018) depending on the wavelength of the light particles, but this requires a hefty fee for the solar panels. Hirata's method is developed from Schmidt's theory by adding dead volume values in the compression volume calculation. Koichi Hirata, a scientist from Japan. The Schmidt method is an isothermal calculation method for the Stirling engine based on an ideal gas's isothermal expansion and compression. (Satria et al., 2020). The purpose of this study is inseparable from this background which analyzes the performance of the piston with the Hirata method approach on the Gamma-type Stirling engine. (Chen et al., 2022)

## RESEARCH METHOD

This study employs the experimental application method in which a gamma-type striling machine workpiece was prepared and tested and data collected. This study's data collection was conducted indoors by observing temperature variations in heated and frigid chambers, as indicated by thermocouples, and flywheel rotational speed, as indicated by tachometers. There is such a process

1. Prepare a gas stove fire source that will be used for testing the Stirling engine, then place it at the end of the hot cylinder.
2. Install the measuring instrument, the Applan AT4208 thermocouple temperature meter is placed in the cold room and hot room
3. The tachometer is placed next to the flywheel to measure the resulting rpm
4. Retrieval of testing data for hot room temperature, cold room temperature, and rotation is carried out simultaneously. Readings are made starting from the heat source is turned on at 5-minute intervals

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5. Record parameters, namely: hot and cold temperatures and rotation.

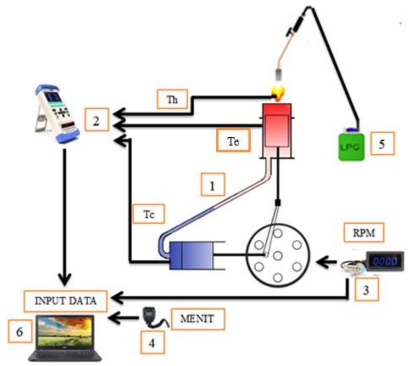


**Figure 1: Schematic Of The Use Of The Stirling Engine Testing Measuring Tool For The Gamma Type**

Gamma-type Stirling engine components and testing tools

1. Stirling engine
2. Thermocouple
3. Tachometer
4. Stopwatch
5. Gas LPG
6. Laptop

Th: Temperatur Heater

Te : Temperatur Ekspansi

Tc : Temperatur Kompresi

Change variables observed in this study

**Table 1: Variable Changes Observed In Research**

| Variable | Indikator | Deskriptor | Instrumen |
|---|---|---|---|
| **temperature** | Hot and cold | K | Thermometer |
| **Stirling engine speed** | Rotation | Rpm | Tachometer |
| **times** | time | Minute | Stopwatch |

## RESULTS AND DISCUSSIONS

### Air Temperature

Three tests were carried out to determine the air temperature profile during the expansion, compression, and temperature change (ΔT) processes; each test was carried out for 390 minutes (6.5 hours) with an interval of 5 minutes for measuring and recording data.

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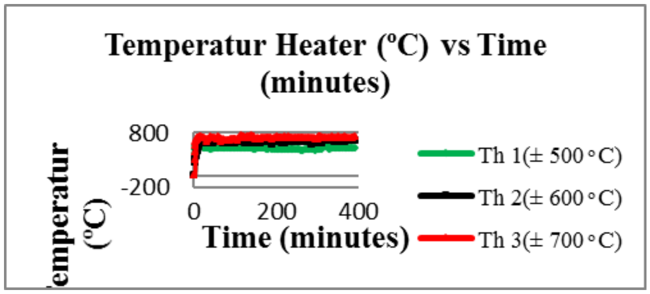


**Figure 2: Graph of the relationship between time (minutes) vs temperature Te (◦C)**

Graph of the relationship between time vs. temperature of the expansion chamber (Te), carried out for 390 minutes with measurement time intervals and data recording every 5 minutes. Where the initial temperature Te of the first experiment = 27°C in the first minute, the temperature reached 45.4°C, and the highest Te temperature reached 172.3°C occurred in the 190th minute. The average temperature Te = 141.2°C, at temperature initial Te second experiment = 28°C in the fifth minute, the temperature reached 34°C. The highest Te temperature reached 189.6°C occurred in the 355th minute, and the average temperature Te = 144.8°C, and at the initial temperature Te experiment third = 27°C in the fifth minute, the temperature reached 64.7°C. The highest Te temperature reached 198.9°C in the 285th minute and the average temperature of Te = 159.1°C. From the graph of the relationship between time and expansion temperature (Te) above, the preheating process still occurs from the first minute to the fifth minute.

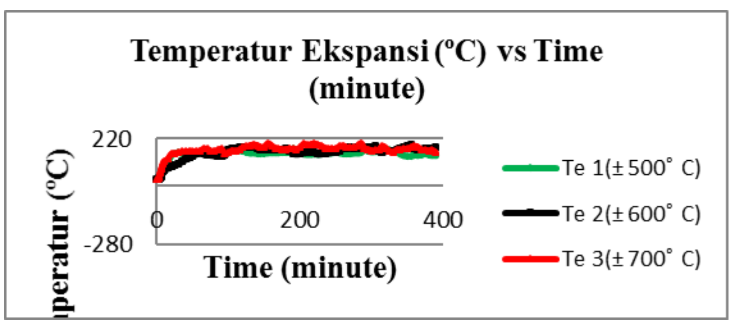


**Figure 3: Grafik Hubungan Waktu (menit) vs Temperatur Tc (◦C)**

The graph of the relationship between time and temperature of the compression chamber (Tc) was carried out for 390 minutes with measurement time intervals and data recording every 5 minutes. Where the initial temperature Tc in the first experiment was = 27 °C in the fifth minute, the temperature reached 32.6 °C, and the highest Tc temperature reached 49.7 °C occurred in the 105th minute, and the average temperature Tc = 43.77 °C. At the initial temperature in the second experiment, Tc was = 26 °C; in the fifth minute, the temperature reached 27°C, the highest Tc temperature reached 51°C occurred in the 305th minute, and the average temperature Tc = 42.93 °C. At the initial temperature, The third experiment's Tc was = 27 °C; in the fifth minute, the temperature reached 34.8°C. The highest Tc temperature reached 50 °C in the 195th minute, and the average temperature Tc = 44.85 °C. From the graph of the

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relationship between time and temperature (Tc) above, it can be seen that in the first minute to the fifth minute, the preheating process still occurs

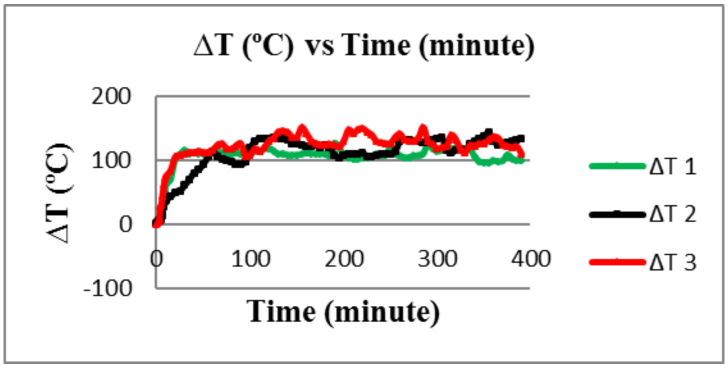


**Figure 4: Graph of Relationship Time (minutes) vs. Temperature ΔT (∘C)**

Graph of the relationship between time and temperature changes (ΔT), carried out for 390 minutes with measurement time intervals and data recording every 5 minutes. At the initial temperature ΔT, the first experiment = 0°C. In the fifth minute, the temperature reached 12.8°C. The highest ΔT temperature reached 126.1°C occurred in the 190th minute, and the average temperature ΔT = 97.43° C; at the initial temperature ΔT in the second experiment = 2°C in the fifth minute, the temperature reached seven °C, and the highest ΔT temperature went 142.9 °C occurred in the 355th minute and the average temperature ΔT = 101.9°C. At the initial temperature ΔT of the third experiment = 0°C in the fifth minute, the temperature reached 34°C, and the highest ΔT temperature reached 151 °C occurred in the 285th minute, and the average temperature ΔT = 114.3°C. From the graph of the relationship between time and ΔT above, it can be seen that the preheating process is still going on from the first minute to the fifth minute.

**Gamma Type Stirling Engine Flywheel Rotation**

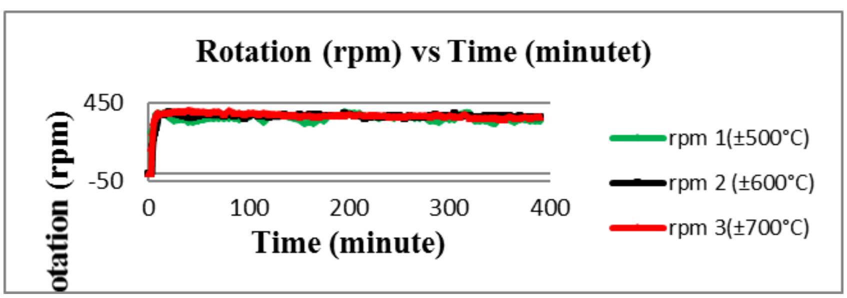


**Figure 5: Time (Minute) and Round (Rpm) Relationship Graph**

Graph of the relationship between time and rounds of the first trial (round 1), the second experiment (round 2), and the third experiment (round 3). In each experiment, the test was carried out for 390 minutes with intervals of measuring time and data recording every 5 minutes. Where the initial rotation of the first trial = 0 rpm in the fifth minute of rotation = 309 rpm and the highest rotation reached = 390 rpm occurred in the 195th minute. The average first trial rotation = was 336.1 rpm, in the second initial trial rotation = 0 rpm in minutes, the fifth round = 230 rpm, and in the second trial round, the highest

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reached = 387 rpm occurred in the 20th minute, and the average second trial spin = 342.2 rpm, in the third trial initial round = 0 rpm in the fifth minute round = 325 rpm and trial round the third highest = 399 rpm occurred in the 40th minute and the average of the third trial round = 350.667 rpm. From the graph of the relationship between time and spin above, the preheating process still occurs from the first minute to the fifth minute.

**Gamma Type Stirling Engine Pressure With Hirata Method**

**Hot Side And Cold Side Temperatures**

$\Delta T$ = T hot side-T cold side

$\Delta T$ = 318,4-305,6

= 12,8 °K

**Pressure As A Function Of Crank Angle**

Hargreaves calculations

$$X_{DE} = \frac{V_{DE}}{V_{SE}}$$

$$= \frac{1{,}59 \times 10^{-5}}{7{,}2 \times 10^{-5}}$$

$$= 0.022 \text{ m}^3$$

the dead volume of space compression ratio can be calculated as follows:

$$X_{DC} = \frac{V_{DC}}{V_{SE}}$$

$$= \frac{1.819 \times 10^{-5}}{7{,}2 \times 10^{-5}}$$

$$= 0.253 \text{ m}^3$$

The regeneration volume ratio can be calculated as follows:

$$X_R = \frac{V_R}{V_{SE}}$$

$$= \frac{2.1 \times 10^{-3}}{7{,}2 \times 10^{-5}}$$

$$= 29.17 \text{ m}^3$$

Temperature ratio:

$$t = \frac{T_C}{T_E}$$

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$$= \frac{305{,}6\ °\mathrm{K}}{318{,}4\ °\mathrm{K}}$$

$$= 0.959\ °\mathrm{K}$$

Variable substitution

$$\mathrm{B} = \mathrm{t} + 2 \cdot \mathrm{X_{DE}} \cdot \mathrm{t} + \frac{4 \cdot \mathrm{t} \cdot \mathrm{X_R}}{1 + \mathrm{t}} + 1 + \mathrm{v} + 2 \cdot \mathrm{X_{DC}}$$

$$= 0.959 + 2 \times 0.02 \times 0.959 + \frac{4 \times 0.959 \times 0.208}{1 + 0.959} + 1 + 1.263 + 2 \times 2.7 \times 10^{-2}$$

$$= 3.721\ \mathrm{m^3}$$

The angle δ is defined by

$$\delta = arctan\left(\frac{v \cdot \sin\varphi}{t - 1 + v \cdot \cos\varphi}\right) + (\pi)$$

$$= arctan\left(\frac{1.263 \times \sin 90^{\circ}}{0.959 - 1 + 1.263 \times \cos 90^{\circ}}\right) + \frac{22}{7}$$

$$= 2.06$$

$$A = \sqrt{t^2 \ - 2 \cdot t + 1 + 2 \cdot (t - 1) \cdot v \cdot \cos\varphi + v^2}$$

$$= \sqrt{0.959^2 \ - 2 \times 0.959 + 1 + 2 \times (0.959 - 1) \times 1.263 \times \cos 90 + 1.263^2}$$

$$= 1.263$$

$$c = \frac{A}{B}$$

$$= \frac{1.595}{3.723}$$

$$= 0.429$$

To find out the average value of pressure can be calculated

$$P_m = \frac{2 \cdot m \cdot R \cdot T_C}{V_{SE} \cdot B \cdot \sqrt{1 - c^2}}$$

$$= \frac{2 \times 0.2130\ \mathrm{kg} \times 0.287 \frac{\mathrm{J}}{\mathrm{kg.K}} \times 305{,}6\mathrm{K}}{7.5 \times 10^{-5}\mathrm{m^3} \times 3.723 \times \sqrt{1 - 0.429^2}}$$

$$= 1.543\ \mathrm{Bar}$$

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For the calculation of the average pressure (P_m)

$$P = \frac{P_m \cdot \sqrt{1-c^2}}{1 - c \cdot \cos(\alpha - \delta)}$$

$$= \frac{1.543 \text{ Bar} \cdot \sqrt{1 - 0.429^2}}{1 - 0.429 \cdot \cos(0 - 2.065)}$$

$= 1.543$ Bar

To get the maximum and minimum pressure values

$$P_{max} = P_m \cdot \frac{\sqrt{1+c}}{\sqrt{1-c}}$$

$$= 1.543 \cdot \frac{\sqrt{1+0.429}}{\sqrt{1-0.429}}$$

$= 2.439$ Bar

$$P_{min} = \mathrm{P_m} \cdot \frac{\sqrt{1-\mathrm{c}}}{\sqrt{1+\mathrm{c}}}$$

$$= 1.543 \cdot \frac{\sqrt{1-0.429}}{\sqrt{1+0.429}}$$

$= 0.$ 975 Bar

**Torsi dan Daya Yang Di Hasilkan Mesin Stirling Tipe Gamma**

Before determining the value of torque, it must first determine the value of the moment of inertia (I) and the value of the mass of the flywheel (r) as follows:

$$\mathrm{I} = 0.5\,.\ \mathrm{m}\,.\,\mathrm{r}^2$$

$$= \ 0.5 \times 2{,}6 \times \ 0.135^2$$

$$= 0.023692\ \mathrm{kg.m^2}$$

$$\omega = \frac{2 \times \pi \times \mathrm{n}}{60}$$

$$= \frac{2 \times 3.14 \times 258}{60}$$

$$= 27.004\ \mathrm{rad/s^2}$$

After the value of the moment of inertia and the mass value of the flywheel have been determined, the torque can be determined by

$$\mathrm{T} = \mathrm{I} \times \omega$$

$$= 0.023692\ kg \cdot m^2 \times 27.004\ \mathrm{rad/s^2}$$

$$= 0.64\ \mathrm{N.m}$$

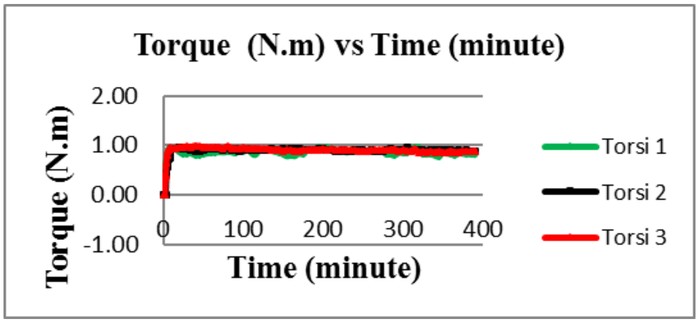


**Figure 6: Time (minutes) vs. Torque (N.m) relationship graph**

The graph of the relationship between time (minutes) and torque (N.m) for the first trial (torque 1), second experiment (2 torque), and third experiment (3 torque) in each experiment were tested for 390 minutes with measurement time intervals and data recording every 5 minutes. Where the initial torque of the first trial = 0.00 N.m in the fifth minute reached = 0.77 N.m and the highest first trial torque reached = 0.97 N.m occurred in the 53rd minute, and the average torque of the first trial = 0.8334 N.m, at torque initial second trial = 0 N.m in the fifth minute the torque reached = 0.57 N.m and the second highest experimental torque reached = 0.95 N.m occurred in the 305th minute and the average torque of the second experiment = 0.8486 N.m, in the third initial trial torque = 0 N.m in the fifth minute the torque reached = 0.81 N.m and the third highest experimental torque reached = 0.99 N.m occurred in the 40th minute and the average torque of the third experiment = 0.8696 N.m. From the graph of the relationship between time and torque above, the preheating process still occurs from the first minute to the fifth minute. To determine the power value of the Stirling engine can be calculated using

$$\mathrm{P} = \frac{2 \cdot \pi \cdot n \cdot T}{60}$$

$$= \frac{2\ \times 3.14\ \times 0.64}{60}$$

$$= 17.3\ \mathrm{watt}$$

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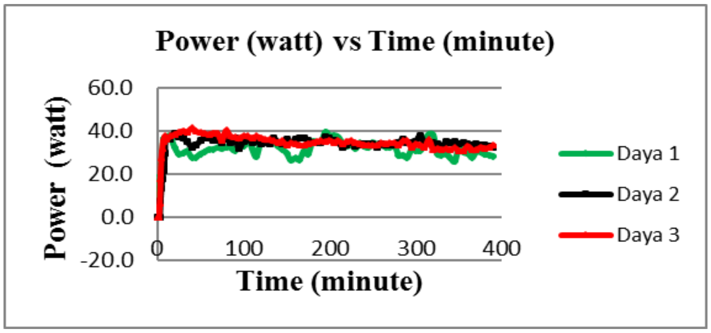


**Figure 7: Time (minutes) and Power (watts) relationship graph**

The graph of the relationship between time (minutes) and Power (watts) for the first experiment (Power 1), the second experiment (Power 2), and the third experiment (Power 3) in each experiment was tested for 390 minutes with measurement time intervals and data recording every 5 minutes. Where the initial Power of the first experiment = 0 watts in the fifth minute, the Power reached = 24.8 watts, and the highest first trial power reached = 39.5 watts occurred in the 195th minute. The average Power of the first experiment was 30.483 watts, the initial Power of the second experiment = was 0 watts in the fifth minute, the Power reached = 13.7 Watts, and the second highest experimental Power reached = 38.9 Watts occurred in the 20th minute. The average Power of the second experiment = was 32.087 Watts, the initial Power of the third experiment was 0 Watts in minutes fifth Power reached = 0.81 watts, the third highest experimental Power reached = 41.3 watts occurred in the 40th minute, and the average Power of the third experiment = 33.26 Watts. From the time and power relationship graph above, it can be seen in the first minute. Until the fifth minute, the preheating process is still going on.

## CONCLUSION

1. From the tests carried out for 390 minutes with three trials, it is concluded that the compressor piston can be a gamma-type Stirling engine power piston because of its heat resistance and good compression. From the analysis and calculations, it can be concluded that the maximum speed of P1 = 390 rpm, P2 = 387 rpm, and P3 = 399 rpm. The maximum torque of P1 = 0.967 N.m with a maximum power of 39.5 watts. P2 = 0.96 N.m with a maximum power of 38.9 Watts, and P3 = 0.99 N.m with a maximum capacity of 41.3 Watts.
2. From the results of calculations using the Hirata method, it can be concluded that the maximum temperature value in the compression cylinder (Tc) P1 = 49.7 ˚C, P2 = 51 ˚C, and P3 = 50 ˚C. Expansion cylinder (Te) P1 = 172.3 ˚C, P2 = 189.6 ˚C and P3 = 198.9 ˚C. Heater temperature (Th) P1= 576 °C, P2= 678.1°C and P3= 769.4 °C. Temperature change ($\Delta T$) P1= 126.1 °C, P2= 142.9 °C and P3= 151 °C
3. The analysis and calculations using the Hirata method show that the maximum pressure in the first experiment is 1.2504 Bar. In the second experiment, the

maximum pressure reached 1.265 Bar. Moreover, in the third experiment, the maximum pressure is 1.2525 Bar.

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