Otto Cycle Lab

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Introduction

To illustrate the cycle of a real piston engine, pressure measurements were conducted in a single cylinder flat head gasoline engine (3.5 HP Briggs and Stratton Engine, Model # 093332, Type 0535 B1). These are compared to pressures in an ideal Otto cycle for the compression ratio of the engine (r = 5.468) referenced to the exhaust temperature and to room conditions.

Measurements

Pressure vs time was measured using a sensor mounted in the head of the engine, and simultaneously a tachometer time series was obtained by light reflection from markers on the flywheel, corresponding to top dead center and bottom dead center. Exhaust temperature was provided based on an earlier measurement. Test conditions included light load, and moderate load, imposed by resistance heaters powered by an alternator driven by the motor. Analysis was conducted on the no-load cycle.

Compression Ratio

The ratio of Bottom Dead Center (BDC) to Top Dead Center is called the Compression Ratio (CR). We can calculate the compression ratio using the following equation:

$$\mathrm{V}_{\mathrm{BDC}} = \pi r^2 h = \pi \left(\frac{2.563}{2}\right)^2 (0.875 \times 2)\,\mathrm{in}^3 + 33.13\,\mathrm{cm}^3 = 11.05\,\mathrm{in}^3 = 181.1\,\mathrm{cm}^3$$

$$\mathrm{CR} = \frac{V_{\mathrm{BDC}}\ (\mathrm{cm}^3)}{V_{\mathrm{TDC}}\ (\mathrm{cm}^3)} = \frac{181.1\ \mathrm{cm}^3}{33.13\ \mathrm{cm}^3} = 5.476$$

Temperatures and Pressures

Using the data from the no-load Otto Cycle, the pressures at each state (P1–P4) were calculated with Python (code in **Appendix B**) using both experimental data and ideal Otto cycle assumptions. The highest pressure during the cycle, corresponding to the end of the combustion process (state 3), was identified by finding the max pressure within the data. The pressure at the end of the compression stroke, P2, was assumed to be 82 psi. From there, the remaining pressures were derived using isentropic relationships:

$$P_1 = \frac{P_2}{r^k} \qquad\qquad P_4 = P_1\left(\frac{T_4}{T_1}\right)$$

where r is the compression ratio and k is the specific heat ratio (1.4 for air).

T3, the temperature at the end of combustion, was given as 481˚C which is 754.15 K. Using the ideal gas law for constant volume processes, T2 was computed using:

$$T_2 = \frac{T_3 * P_2}{P_3}$$

Then, T1 and T4 were determined using isentropic temperature-volume relationships:

$$T_1 = \frac{T_2}{r^{k-1}} \qquad\qquad T_4 = T_3 * r^{1-k}$$

State	Temperature (K)	Pressure (PSI)
1	304.6	7.6
2	601.0	82.0
3	754.1	102.9
4	382.2	9.5

Table 1: Experimental Temperature and Pressure Values

The experimental pressure was first plotted against time as shown below in figure 1:

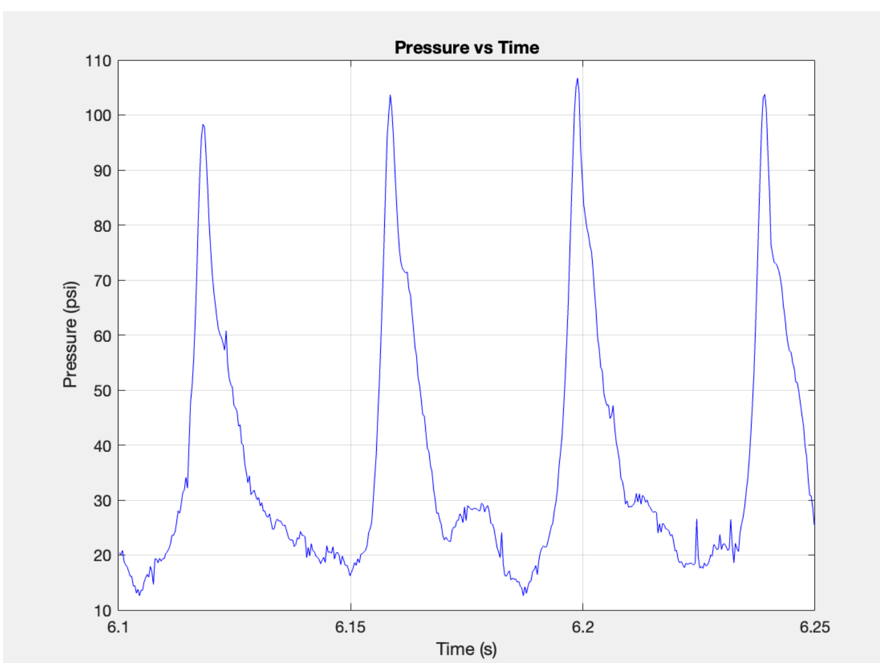

Figure 1: Experimental Pressure (psi) v Time (s)

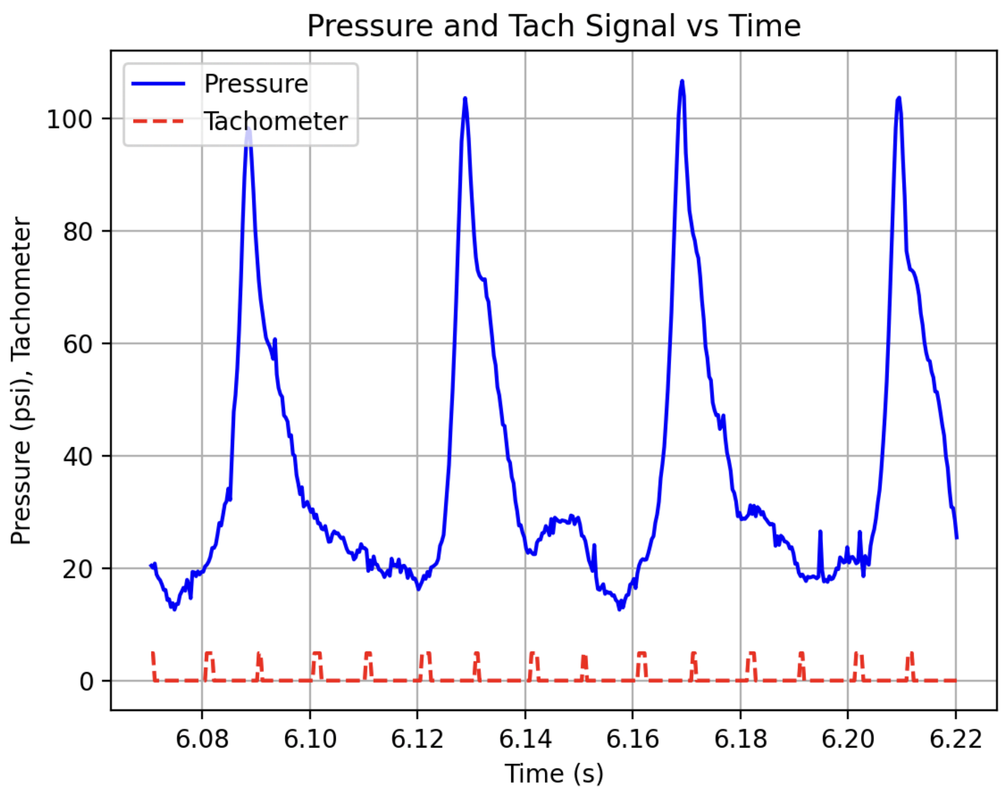

Figure 2: Pressure and Tach Signal (psi) v Time (s)

Volume and Crank Angle

The period of the cycle can be found by subtracting the times of two different adjacent peaks:

$$T = 6.1288 - 6.0885 = 0.0403\text{s}$$

With this, we are able to solve for omega given:

$$\omega = \frac{4\pi}{T} = \frac{4\pi}{0.0403\ \mathrm{s}} \approx 311.82\ \mathrm{rad/s}$$

Pressure vs volume for the cycle was calculated by assuming constant rotational speed between TDC and BDC positions for the compression stroke and independently for the power stroke, using the tachometer data to eliminate time as a parameter. We then find a relationship between the crank angle and the displacement of the cylinder head, with the assumption that θ=ωt.

$$
\begin{aligned}
&\mathrm{x}(\omega t) = R\big(1 - \cos(\omega t)\big) + \tfrac{R^2}{L}\ \sin^2(\omega t) \\
&x\big(311.2\,t\big) = 0.875\big(1 - \cos(311.2\,t)\big) + \tfrac{0.875^2}{2.845}\ \sin^2(311.2\,t) \\
&V(t) = \pi\, r^2\, x(\omega t) + V_d \\
&V(t) = \pi\,(1.2815)^2\, x\big(311.2\,t\big) + 2.02
\end{aligned}
$$

We use the measurements provided in the diagram below (Figure 3) to calculate the displacement of the piston head with respect to time, using the second equation listed above. We then find the instantaneous volume inside the cylinder head using the third and fourth equations listed above and plot it against time (**Figure 4**).

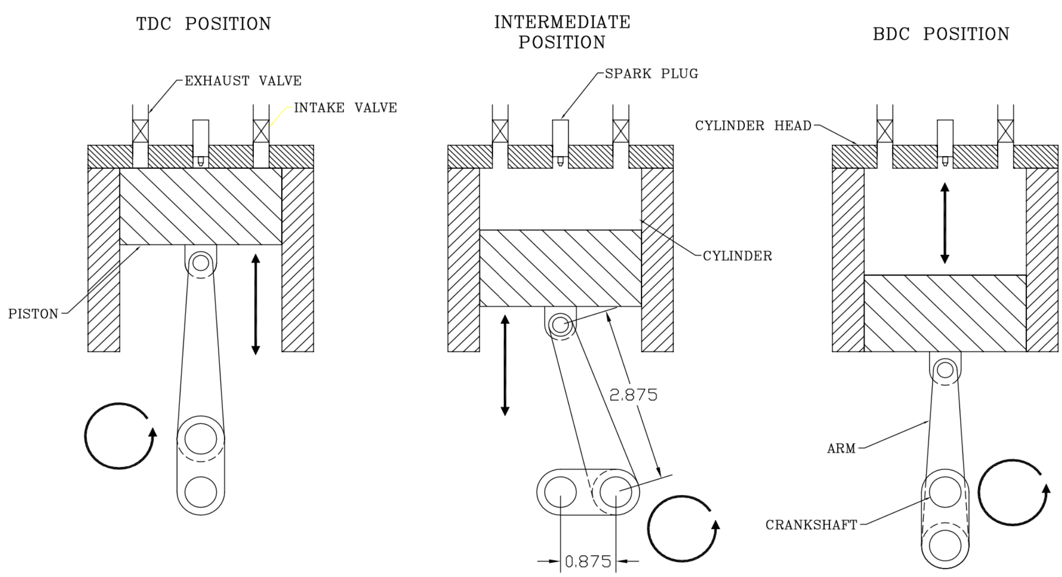

Figure 3: Piston Head Diagram

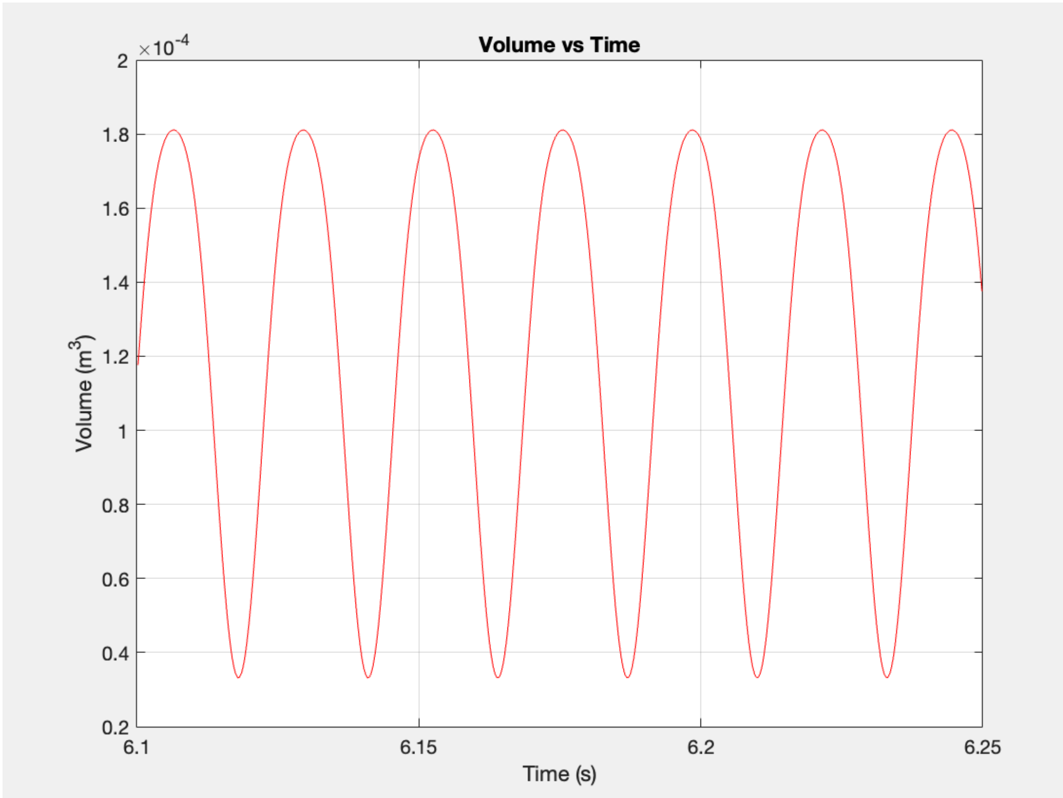

Figure 4: Calculated Volume vs Time Graph

P-V Diagram

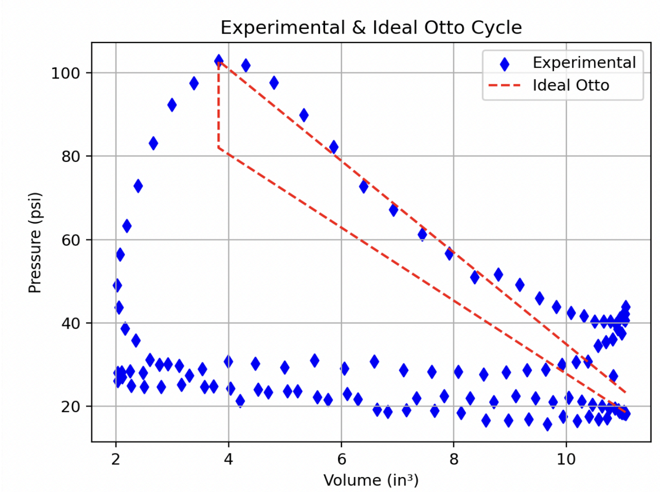

Figure 5a: P-V Diagram

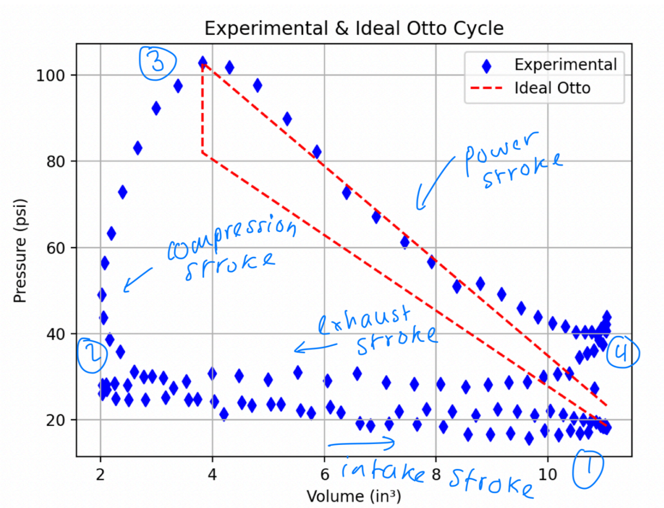

Figure 5b: Annotated P-V Diagram

Isentropic compression and expansion curves were fitted to the P-V data using room conditions as initial state for the compression and exhaust condition as end state for the power stroke. The result is shown above, with annotations of each stroke drawn on to the graph.

Discussion

The results from the experimental Otto cycle highlight key differences between the behavior of an ideal thermodynamic model and a real-world four-stroke spark-ignited reciprocating piston engine. While the ideal Otto cycle assumes instantaneous combustion, perfect gas (cold-air standard), perfectly isentropic compression and expansion, and no heat transfer with the environment, the experimental data revealed deviations due to physical limitations such as heat loss, friction, valve timing, and incomplete combustion. For instance, pressure peaks in the real engine occurred slightly after top dead center, a delay not present in the idealized model, due to the finite duration of the combustion process. Distorted specific heats and real gas composition causes variation in the polytopic exponent n, differing from the ideal isentropic exponent k. Additionally, the actual compression and expansion strokes were not perfectly isentropic, as evidenced by the rounded corners and pressure losses in the P-V diagram. These discrepancies are consistent with real engine inefficiencies that include mechanical losses and heat dissipation through the cylinder walls. Nevertheless, the general shape of the experimental cycle aligns with the ideal Otto cycle, reinforcing the theoretical model's utility while emphasizing the need to account for real-world effects in engine analysis.

Conclusion

This lab successfully modeled an experimental Otto cycle and compared it to the theoretical ideal using measured pressure and tachometer data. The experimental pressure vs. volume data reflected the expected trends of the Otto cycle, and thermodynamic principles were applied to estimate state point temperatures and pressures. Despite some real-world deviations from the idealized model which include: friction, non-isentropic compression/expansion, and heat transfer, the analysis showed that the experimental Otto Cycle still followed the same trends as the ideal Otto Cycle. Future improvements could include using temperature sensors to directly verify T1–T4 or applying correction factors to better account for real engine inefficiencies.

Appendix

Appendix A: Time Series for Data Plotted

Time (s)	Pressure (volts)	Tach (Low-high)	Pressure (PSI)
6.075181	0.581	0.001	44.294
6.075515	0.6	0.001	49.079
6.075848	0.623	0.001	54.726
6.076181	0.658	0.001	63.355
6.076515	0.693	0.001	71.826
6.076848	0.727	0.001	80.376
6.077181	0.768	0	90.338
6.077515	0.798	0.001	97.79
6.077848	0.818	0.001	102.653
6.078181	0.83	0.001	105.634
6.078515	0.825	0.001	104.301
6.078848	0.818	0	102.653
6.079181	0.817	0	102.34
6.079515	0.824	0	104.065
6.079848	0.824	4.882	104.144
6.080181	0.81	4.881	100.771
6.080515	0.799	4.883	98.025
6.080848	0.79	0.001	95.829
6.081181	0.763	0.001	89.24
6.081515	0.744	0.001	84.534
6.081848	0.715	0	77.317
6.082181	0.707	0.001	75.278
6.082515	0.687	0.001	70.493
6.082848	0.668	0.001	65.63
6.083181	0.647	0.001	60.688
6.083515	0.635	0	57.629
6.083848	0.622	0.001	54.491
6.084181	0.615	0	52.609
6.084515	0.602	0.001	49.471
6.084848	0.592	0	47.118
6.085181	0.583	0.001	44.843
6.085515	0.576	0.001	43.196
6.085848	0.565	0.001	40.45
6.086181	0.559	0.001	38.881
6.086514	0.543	0.001	34.959
6.086848	0.533	0	32.528
6.087181	0.527	0.001	30.959
6.087514	0.519	0.001	28.92
6.087848	0.505	0	25.547
6.088181	0.507	0.001	26.096
6.088514	0.503	0	25.154
6.088848	0.503	0.001	25.076
6.089181	0.506	0.001	25.782
6.089514	0.497	0	23.586
6.089848	0.509	0.001	26.566
6.090181	0.502	4.879	24.919
6.090514	0.51	4.885	26.802
6.090848	0.514	4.879	27.743
6.091181	0.515	4.886	28.057
6.091514	0.5	0.481	24.449
6.091848	0.515	0.001	27.978
6.092181	0.513	0.001	27.665
6.092514	0.515	0.001	28.135
6.092848	0.512	0	27.429
6.093181	0.516	0.001	28.292
6.093514	0.518	0.001	28.763
6.093848	0.517	0.001	28.527
6.094181	0.52	0.001	29.233
6.094514	0.524	0.001	30.175
6.094848	0.528	0.001	31.273
6.095181	0.527	0	31.116
6.095514	0.526	0.001	30.881
6.095848	0.528	0.001	31.351
6.096181	0.53	0.001	31.665
6.096514	0.525	0.001	30.41
6.096848	0.517	0.001	28.449
6.097181	0.52	0.001	29.312
6.097514	0.514	0.001	27.743
6.097848	0.512	0.001	27.272
6.098181	0.508	0.001	26.41
6.098514	0.505	0.001	25.704
6.098848	0.507	0.001	26.174
6.099181	0.501	0	24.684
6.099514	0.486	0.001	20.919
6.099848	0.487	0.001	21.154
6.100181	0.484	4.883	20.448
6.100514	0.483	4.88	20.056
6.100847	0.486	0.002	20.84
6.101181	0.478	0.001	18.879
6.101514	0.475	0.001	18.252
6.101847	0.474	0.001	17.86
6.102181	0.47	0.001	17.075
6.102514	0.467	0.001	16.134

Appendix B: Source Code for All Plots

```
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt

df = pd.read_csv('305_noload.csv')
timeD     = df['Time (s)'].values
pressureD = df['Pressure (PSI)'].values
tachD     = df['Tach (Low-high)'].values

start_time = 0.029666
mask0 = timeD >= start_time
time     = timeD[mask0]    - start_time
pressure = pressureD[mask0]
tach     = tachD[mask0]

diamIn = 2.563
radIn  = diamIn / 2
VdIn   = 33.13 * 0.0610
RIn    = 0.875
LIn    = 2.845

stroke_in = 2 * RIn
Vswept_in3 = np.pi * radIn**2 * stroke_in
CR_geom = (VdIn + Vswept_in3) / VdIn
print(f"Geometric compression ratio = {CR_geom:.3f}")

zoom_lo, zoom_hi = 6.1 - start_time, 6.25 - start_time
mask1 = (time >= zoom_lo) & (time <= zoom_hi)
t1, p1, tach1 = time[mask1], pressure[mask1], tach[mask1]

plt.figure()
plt.plot(t1, p1, 'b-')
plt.xlabel('Time (s)')
plt.ylabel('Pressure (psi)')
plt.title('Pressure vs Time (zoomed)')
plt.grid(True)
plt.show()

tPeriod = 0.0403
omega   = 4*np.pi / tPeriod
```

```python
print(f"Period = {tPeriod:.4f} s → ω = {omega:.2f} rad/s")

theta  = omega * time
x      = RIn*(1 - np.cos(theta)) + (RIn**2 / LIn)*np.sin(theta)**2
volume = np.pi * radIn**2 * x + VdIn

plt.figure()
plt.plot(time, pressure, 'b-')
plt.xlabel('Time (s)')
plt.ylabel('Pressure (psi)')
plt.title('Pressure vs Time')
plt.grid(True)

plt.figure()
plt.plot(time[mask1], volume[mask1], 'r-')
plt.xlabel('Time (s)')
plt.ylabel('Volume (in³)')
plt.title('Volume vs Time')
plt.grid(True)

plt.figure()
plt.plot(time[mask1], p1, 'b-', label='Pressure')
plt.plot(time[mask1], tach1, 'r--', label='Tachometer')
plt.xlabel('Time (s)')
plt.ylabel('Pressure (psi), Tachometer')
plt.title('Pressure and Tach Signal vs Time')
plt.legend()
plt.grid(True)

mask_period = (time >= 0) & (time < tPeriod)
idx_bdc     = np.argmax(volume[mask_period])
t_bdc       = time[mask_period][idx_bdc]
print(f"Detected BDC at t = {t_bdc:.4f} s")

mask_cycle  = (time >= t_bdc) & (time < t_bdc + tPeriod)
t_cycle     = time[mask_cycle]
p_cycle     = pressure[mask_cycle]
v_cycle     = volume[mask_cycle]

plt.figure()
plt.plot(v_cycle, p_cycle, 'b-', linewidth=1.2)
plt.scatter(v_cycle, p_cycle, marker='d', color='b')
```

```python
plt.xlabel('Volume (in³)')
plt.ylabel('Pressure (psi)')
plt.title('Experimental Pressure vs Volume')
plt.grid(True)

P3  = p_cycle.max()
V3  = v_cycle[np.argmax(p_cycle)]

V1, V2, V4 = v_cycle.max(), V3, v_cycle.max()

P2  = 82.0
r   = CR_geom
k   = 1.4
T3  = 481 + 273.15

T4  = T3 * r**(1-k)
T2  = (T3 * P2) / P3
T1  = T2 / (r**(k-1))
P1  = P2 / (r**k)
P4  = P1 * (T4 / T1)

ideal_V = [V1, V2, V3, V4]
ideal_P = [P1, P2, P3, P4]

plt.figure()
plt.plot(v_cycle, p_cycle, 'b-', linewidth=1.2, label='Experimental')
plt.scatter(v_cycle, p_cycle, marker='d', color='b')
plt.plot(ideal_V, ideal_P, '--r', linewidth=1.5, label='Ideal Otto')
plt.xlabel('Volume (in³)')
plt.ylabel('Pressure (psi)')
plt.title('Experimental & Ideal Otto Cycle')
plt.legend()
plt.grid(True)

print(f"Compression ratio r = {r:.4f}")
print("State Points (P [psi], T [K]):")
print(f"P1={P1:.1f}, T1={T1:.1f}")
print(f"P2={P2:.1f}, T2={T2:.1f}")
print(f"P3={P3:.1f}, T3={T3:.1f}")
print(f"P4={P4:.1f}, T4={T4:.1f}")

plt.show()
```

```python
P3  = p_cycle.max()
V3  = v_cycle[np.argmax(p_cycle)]

V1, V2, V4 = v_cycle.max(), V3, v_cycle.max()

P2  = 82.0
r   = V1 / V2
k   = 1.4
T3  = 481 + 273.15

T4  = T3 * r**(1-k)
T2  = (T3 * P2) / P3
T1  = T2 / (r**(k-1))
P1  = P2 / (r**k)
P4  = P1 * (T4 / T1)

ideal_V = [V1, V2, V3, V4]
ideal_P = [P1, P2, P3, P4]

plt.figure()
plt.plot(v_cycle, p_cycle, 'b-', linewidth=1.2, label='Experimental')
plt.scatter(v_cycle, p_cycle, marker='d', color='b')
plt.plot(ideal_V, ideal_P, '--r', linewidth=1.5, label='Ideal Otto')
plt.xlabel('Volume (in³)')
plt.ylabel('Pressure (psi)')
plt.title('Experimental & Ideal Otto Cycle')
plt.legend()
plt.grid(True)

print(f"Compression ratio r = {r:.4f}")
print("State Points (P [psi], T [K]):")
print(f"P1={P1:.1f}, T1={T1:.1f}")
print(f"P2={P2:.1f}, T2={T2:.1f}")
print(f"P3={P3:.1f}, T3={T3:.1f}")
print(f"P4={P4:.1f}, T4={T4:.1f}")

plt.show()
```