California State University, Long Beach

College of Engineering
Department of Mechanical Engineering

EXPERIMENT 4: The Analysis of a Gas Turbine Engine

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Course: MAE 337-Thermal Engineering Lab

Section 9

Group 5
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Abstract:

In this experiment, the MiniLab SR30 Turbojet engine was utilized to study the behaviors and characteristics of the Brayton cycle. Furthermore, the thermodynamic characteristics of the gas cycle are also obtained and analyzed. By calculating the overall, we can conclude which Temperature and engine speed will give the best performance. Moreover, the variety of temperature and engine speed will also improve the efficiency of the turbine. Therefore, the students will have the understanding of which speed and temperature combination will have the prominent results. A gas turbine engine consists of a rotary engine that extracts energy from a flow of combustion gas and upstream compressor coupled to a downstream turbine. The temperature, the pressure and the fuel consumption were obtained through software and displaced through a LCD screen. After that, the instructor will send the data to the student in order to determine the other thermodynamic characteristics (heat, specific enthalpy) of the cycle. Therefore in the end, one will determine which option would be the most efficient.

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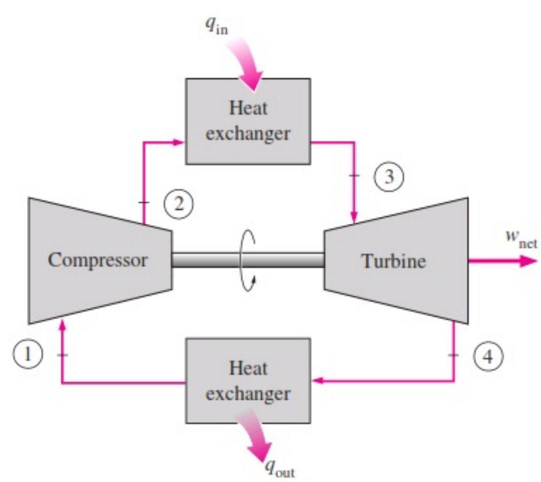
Objective

The main objective of this experiment is to determine the characteristics of a simple gas turbine jet engine. The thermodynamic properties at each point of the Brayton cycle are calculated to permit complete analysis of the cycle.

Introduction

This experiment utilizes a gas turbine engine, which is a rotary engine that extracts energy from a flow of combustion gas. The components in order include a compressor, combustion chamber, turbine, and heat exchanger. The combustion chamber mixes air and fuel then ignites it, adding energy to the gas stream. This increase in energy causes an increase in temperature, velocity, and volume which is then directed at the turbine's blades, spinning a shaft and powering the compressor. Energy can be extracted in the form of shaft power, thrust, and compressed air.

Closed Cycle Gas Turbine Engine:



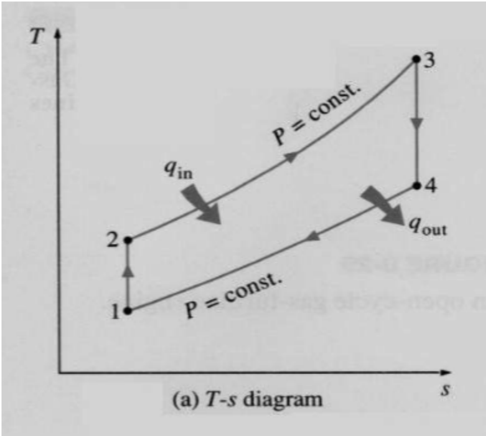
The Brayton cycle is made up of four internally reversible processes:

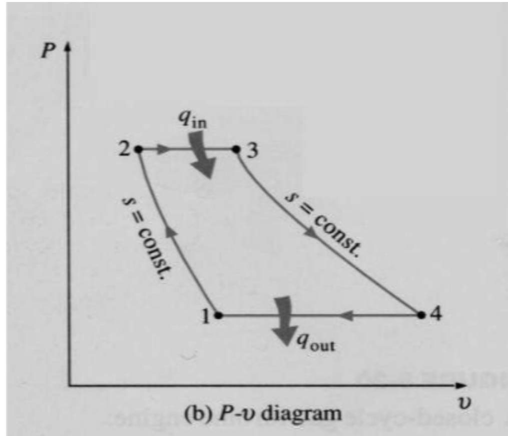
1-2 Isentropic compression

2-3 Constant pressure heat addition

3-4 Isentropic expansion

4-1 Constant pressure heat rejection





The four processes may be analyzed as steady-flow processes since they are executed in steady flow devices.

Energy Balance (neglecting KE and PE changes):

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_{exit} - h_{inlet}$$

Heat transfer to and from the working fluid:

$$q_{in} = h_3 - h_2 = C_p(T_3 - T_2)$$

$$q_{out} = h_4 - h_1 = C_p(T_4 - T_1)$$

Using the cold-air standard assumption, thermal efficiency of the ideal Brayton cycle:

$$\zeta = \frac{W_{net}}{q_{in}} = \frac{q_{in} - q_{out}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{C_p(T_4 - T_1)}{C_p(T_3 - T_2)}$$

Since processes 1-2 and 3-4 are isentropic:

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{(k-1)}{k}} = \left(\frac{P_3}{P_4}\right)^{\frac{(k-1)}{k}} = \frac{T_3}{T_4}$$

Substituting into the thermal efficiency equation:

$$\zeta_{th,\, Brayton} = 1 - \frac{1}{(r_p)^{\frac{(k-1)}{k}}}$$

Where:

$$r_p = \frac{P_2}{P_1}$$

List of Apparatus

Figure 1: MiniLab Gas Turbine Engine

Procedure

The turbine engine was started by the lab instructor and before that several safety precautions were enforced. First of all, each student was equipped with ear protection. The engine turbine was placed in a designated area in the lab and kept clear from the other objects(equipment, belongings,..). The lab instructor also conducts inspection on the engine prior to the experiment. The lab participants were also required to keep a certain distance from the gas turbine when the experiment occurred. The engine was started by igniting the fuel(kerosene) in the combustion chamber and at the same time, monitoring the engine performance to ensure the system will have the desired temperature and engine speed. The experiment was conducted in 3 runs with the relative engine speed of 55000, 65000, and 75000. After each run , the acquisition of the data was performed using the MiniLab software and the data was displayed through a LCD screen. In the end, all data is recorded, converted, and sent out to the students by the instructor.

Table of Data and Results

Data Table

Run 1	T(R)	h(btu/lbm)
1	544.75	130.13
2	712.06	170.43
2s	649.89	155.48
3	1627.30	403.06
4	1516.27	373.48
4s	649.89	257.97

Run 2	T(R)	h(btu/lbm)
1	544.82	130.34
2	772.10	185.22
2s	671.193	160.76
3	1687.72	419.75
4	1511.71	372.78
4s	1121.634	271.89

Run 3	T(R)	h(btu/lbm)

1	549.66	131.50
2	860.60	206.82
2s	687.17	164.63
3	1821.71	456.13
4	1572.08	388.72
4s	1219.31	296.59

	Unit	Run 1	Run 2	Run 3
$W_{compressor}$	(Btu/lbm)	40.29	54.88	75.32
q_{in}	(Btu/lbm)	232.63	234.53	249.31
$W_{turbine}$	(Btu/lbm)	29.57	46.97	67.31
W_{cycle}	(Btu/lbm)	10.71	7.91	8.01
$\eta_{th}(basic\ cycle)$	%	4.61	3.37	3.22
$\eta_{th}\ (jet\ engine)$	%	17.3	23.4	20.2
rp		72.96	70.81	70.35
$\eta_{th,\ Brayton}$	%	29.4	29.6	29.7
$\eta_{compressor}$	%	63	55.4	44.0
$\eta_{turbine}$	%	20.4	31.8	26
Air Density	(lbm/ft^3)	0.0315	0.0319	0.0315
Air Velocity	(ft/s)	393.69	492.5	643.31
Air volumetric flow rate	(ft^3/s)	10.59	13.25	17.31
Air mass flow rate	(lbm/s)	0.334	0.423	0.55

Fuel mass flow rate	(lbm/hr)	19.73	27.89	36
Fuel mass flow rate	(lbm/s)	0.00548	0.00775	0.01
air/fuel ratio		60.92	54.58	54.97
Thrust	(lbf)	4.09	6.47	10.90
TSFC	bm/lbf.hr	4.44	4.31	3.31
Mach number		0.22	0.28	0.35

Sample Calculations

Part I-Thermodynamic analysis for run 1

a) Specific enthalpy at each point of the thermodynamic cycle using Table A-17

$$h_1 = \frac{T_{m,1}-T_{table,1}}{T_{table,2}-T_{table,1}}(h_{table,2} - h_{table,1}) + h_{table,1} = \frac{302.49K-300K}{305K-300K}(305.22\frac{kJ}{kg} - 300.19\frac{kJ}{kg}) + 300.19\frac{kJ}{kg} = 302.70\frac{kJ}{kg}$$

$$h_2 = \frac{T_{m,2}-T_{table,1}}{T_{table,2}-T_{table,1}}(h_{table,2} - h_{table,1}) + h_{table,1} = \frac{395.49K-390K}{400K-390K}(400.98\frac{kJ}{kg} - 390.88\frac{kJ}{kg}) + 390.88\frac{kJ}{kg} = 396.42\frac{kJ}{kg}$$

$$h_3 = \frac{T_{m,3}-T_{table,1}}{T_{table,2}-T_{table,1}}(h_{table,2} - h_{table,1}) + h_{table,1} = \frac{904.06K-900K}{920K-900K}(955.38\frac{kJ}{kg} - 932.98\frac{kJ}{kg}) + 932.98\frac{kJ}{kg} = 937.52\frac{kJ}{kg}$$

$$h_4 = \frac{T_{m,4}-T_{table,1}}{T_{table,2}-T_{table,1}}(h_{table,2} - h_{table,1}) + h_{table,1} = \frac{842.38K-840K}{860K-840K}(888.27\frac{kJ}{kg} - 866.08\frac{kJ}{kg}) + 866.08\frac{kJ}{kg} = 868.72\frac{kJ}{kg}$$

b) Specific work consumed by the compressor (1-2)

$$w_{compressor} = h_2 - h_1 = 396.42\frac{kJ}{kg} - 302.70\frac{kJ}{kg} = 93.72\frac{kJ}{kg}$$

c) Specific energy added by the fuel (2-3)

$$q_{in} = h_3 - h_2 = 937.52\frac{kJ}{kg} - 396.42\frac{kJ}{kg} = 541.10\frac{kJ}{kg}$$

d) Specific work of the turbine (3-4)

$$w_{turbine} = h_3 - h_4 = 937.52\frac{kJ}{kg} - 868.72\frac{kJ}{kg} = 68.80\frac{kJ}{kg}$$

e) Specific work done by the cycle

$$w_{cycle} = w_{turbine} - w_{compressor} = 68.80\frac{kJ}{kg} - 93.72\frac{kJ}{kg} =- 24.92\frac{kJ}{kg}$$

f) Thermal efficiency for gas turbine cycle and gas turbine jet engine

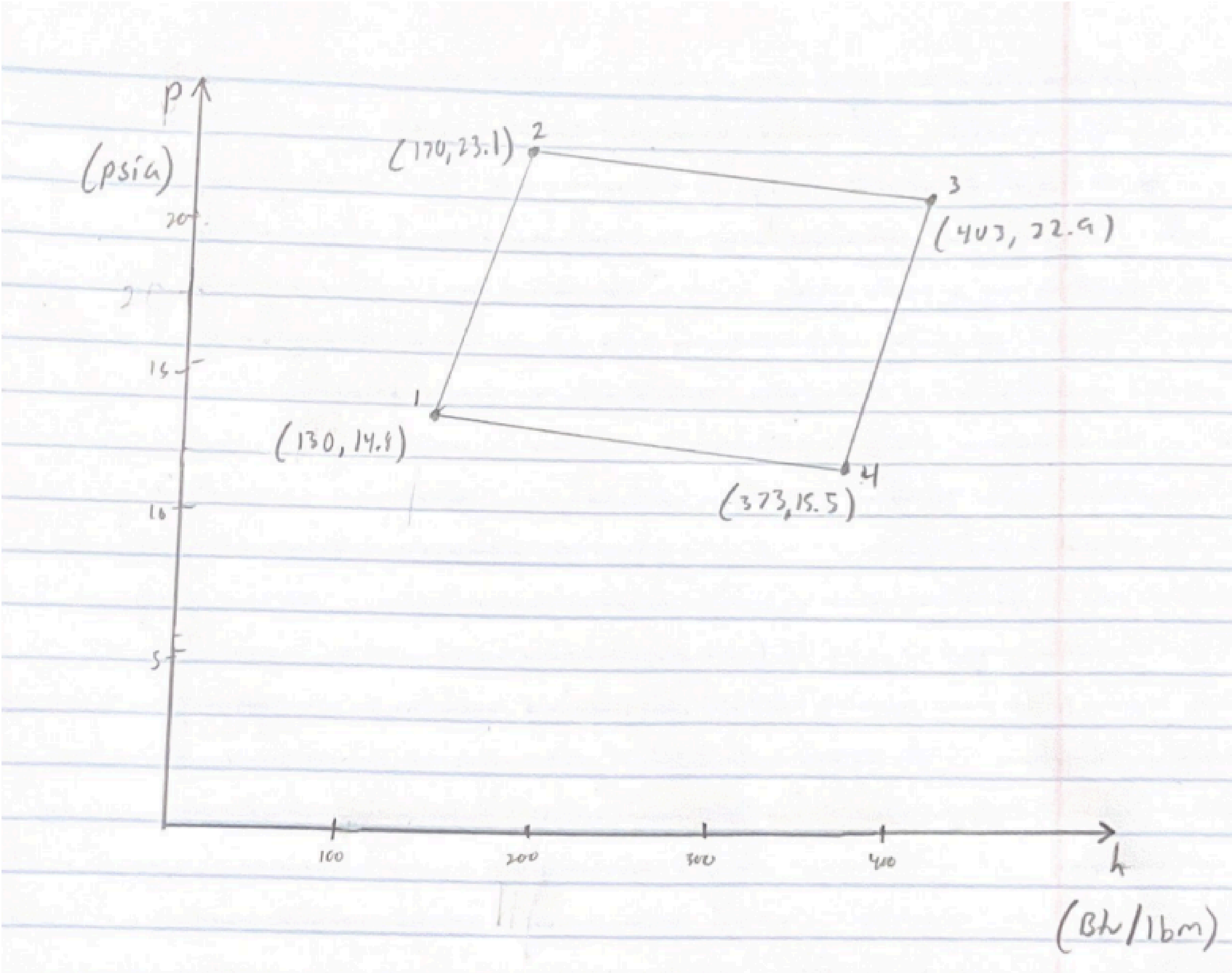
For the basic gas turbine cycle $\eta_{th} = \frac{w_{cycle}}{q_{in}} = \frac{-24.92\frac{kJ}{kg}}{540.1\frac{kJ}{kg}} = 0.0461 = 4.61\%$

For the gas turbine jet engine $\eta_{th} = \frac{Kinetic\ energy\ added}{q_{in}} = \frac{93.72\frac{kJ}{kg}}{541.10\frac{kJ}{kg}} = 0.173 = 17.3\%$

g) The pressure ratio and the ideal efficiency of the Brayton cycle

$r_p = \frac{P_2}{P_1} = \frac{57.87429kPa}{0.793286kPa} = 72.96$ $\eta_{th,Brayton} = \frac{1}{r_p^{\frac{r-1}{r}}} = \frac{1}{72.96^{\frac{1.4-1}{1.4}}} = 0.294 = 29.4\%$

h) P-h diagram for the actual gas turbine cycle



i) Compressor and turbine isentropic efficiencies under Cold air-standard assumptions (constant specific heats)

$$T_{2s} = T_1\left(\frac{P_2}{P_1}\right)^{\frac{r-1}{r}} = 29.49^{\circ}C\left(\frac{57.87kPa}{0.79kPa}\right)^{\frac{1.4-1}{1.4}} = 87.9^{\circ}C$$

$$T_{4s} = T_3\left(\frac{P_4}{P_3}\right)^{\frac{r-1}{r}} = 630.9^{\circ}C\left(\frac{5.475kPa}{58.789kPa}\right)^{\frac{1.4-1}{1.4}} = 320.19^{\circ}C$$

$$h_{2s} = \frac{T_{m,2s}-T_{table,1}}{T_{table,2}-T_{table,1}}(h_{table,2} - h_{table,1}) + h_{table,1} = \frac{361.05K-360K}{370K-360K}(370.67\frac{kJ}{kg} - 360.58\frac{kJ}{kg}) + 360.58\frac{kJ}{kg} = 361.64\frac{kJ}{kg}$$

$$h_{4s} = \frac{T_{m,4s}-T_{table,1}}{T_{table,2}-T_{table,1}}(h_{table,2} - h_{table,1}) + h_{table,1} = \frac{593.34K-590K}{600K-590K}(607.02\frac{kJ}{kg} - 596.52\frac{kJ}{kg}) + 596.52\frac{kJ}{kg} = 600.03\frac{kJ}{kg}$$

$$\eta_{compressor} = \frac{h_{2s}-h_1}{h_{2a}-h_1} = \frac{361.64\frac{kJ}{kg}-302.70\frac{kJ}{kg}}{396.42\frac{kJ}{kg}-302.70\frac{kJ}{kg}} = 0.63 = 63\%$$

$$\eta_{turbine} = \frac{h_3 - h_{4a}}{h_3 - h_{4s}} = \frac{937.52\frac{kJ}{kg} - 868.72\frac{kJ}{kg}}{937.52\frac{kJ}{kg} - 600.03\frac{kJ}{kg}} = 0.204 = 20.4\%$$

Part 2- Thrust analysis

j) air density (ρ)

$$\rho_5 = \frac{p_5}{r_{air} T_5} = \frac{2193 psfa}{53.34\frac{ft.lb_f}{lb_m R} 1305.27R} = 0.0315\frac{lb_m}{ft^3}$$

k) Air velocity

$$V = \sqrt{\frac{2P_5 g_c}{\rho_5}} = \sqrt{\frac{2(75.87 psfg)(32.174\frac{ft\cdot lb_m}{lb_f \cdot s^2})}{0.0315\frac{lb_m}{ft^3}}} = 393.69\frac{ft}{s}$$

l) Volumetric flow rate of air

$$V^{\circ} = AV = 0.0269 ft^2 \cdot 393.69\frac{ft}{s} = 10.59\frac{ft^3}{s}$$

m) Mass flow rate of air

$$m^{\circ}_{air} = V^{\circ} \times \rho = 10.59\frac{ft^3}{s} \times 0.0315\frac{lb_m}{ft^3} = 0.334\frac{lb_m}{s}$$

n) Thrust generated

$$thrust = \frac{m^{\circ}_{air} \times V}{g_c} = \frac{0.334\frac{lb_m}{s} \times 393.69\frac{ft}{s}}{32.174\frac{ft\cdot lb_m}{lb_f \cdot s^2}} = 4.09 lb_f$$

o) Mass flow rate of fuel

$$m^{\circ}_{fuel} = V^{\circ}_{fuel} \times \rho_{fuel} = 0.000811\frac{gallon}{s} \times 6.76\frac{lb_m}{gallon} = 0.00548\frac{lb_m}{s}$$

p) Air to fuel ratio

$$Air\ fuel\ ratio = \frac{m^{\circ}_{air}}{m^{\circ}_{fuel}} = \frac{0.334\frac{lb_m}{s}}{0.00548\frac{lb_m}{s}} = 60.92$$

q) Ratio of mass flow rate of fuel in lbm/hr to thrust

$$TSFC = \frac{\dot{m}_{fuel}}{Thrust} = \frac{19.728\frac{lb_m}{hr}}{4.44 lb_f} = 4.44\frac{lb_m \cdot lb_f}{hr}$$

r) Mach number of gasses leaving the nozzle

$$M = \frac{V}{\sqrt{KRg_cT_5}} = \frac{393.69\frac{ft}{s}}{\sqrt{(1.4)(53.34\frac{ft\cdot lb_f}{lb_m R})(32.174\frac{ft\cdot lb_m}{lb_f\cdot s^2})(1305.81R)}} = 0.222$$

Discussion and Analysis of Results

Negative work of the cycle is acceptable since energy is still being conserved. Negative work means that the work is being done on the system and not by the system. The major reasons for finding a negative value would be from loss of energy through friction and inefficiencies in the mechanical components of the system. Gas turbine engines operate most efficiently at constant output speeds and also don’t produce a lot of energy when compared to other engines, yet they do produce a lot of thrust, making them very useful to power aircraft. The thermal efficiencies calculated for the gas turbine jet engine was considerably less than as expected. The calculated thrust using temperature and pressure measured at the exhaust is different from what is captured by the system’s load cell thrust because there is loss of energy to the surrounding environment. The temperature at the exhaust loses heat and pressure to the surrounding, therefore the system’s load cell thrust measurement is most accurate. The calculated compressor efficiency is on the very low end of typical gas turbine engines at 63%. The calculated turbine efficiency is very low at 20.4% when compared to the turbine of typical gas turbine engines. The number one source for the error of data is the heat loss during the duration of the engine running. The engine may not be fully isolated, therefore the heat can escape and also transfer into other types of energy(sound). The accuracy of temperature will be affected which led to error in the enthalpy, entropy, and specific heat. Next to that, the gas/fuel leakage would be another potential since it can highly impact the efficiency of the turbine.Human errors were minimized since the data was obtained electronically and the results had a digital display.

Conclusion and Recommendations

Considering the specific enthalpy of each run, we can recognize the positive correlation between the temperature and the engine speed as well as the correlation between the specific enthalpy with temperature and engine speed. The data was gathered in a time difference of 1 second and peak temperature for all runs is at the 3 second mark. The peak temperature is also correlated with the peak specific enthalpy. For instance, in run one the peak temperature is at 473 R while having the specific enthalpy of 403 Btu/lbm and on run two the peak performance is at 1687 R and 419 Btu/lbm. The best way to get a higher thermal efficiency out of the cycle is to reuse the heat that is lost. This can be done through a regenerative cycle, in which exhaust air is used to heat up the air after being compressed.

References

Çengel, Yunus A. Thermodynamics : an Engineering Approach. Boston :McGraw-Hill Higher Education, 2008.

Member's Contribution

Hung Ngo: Abstract, Procedure, Discussion and analysis of results

Paul Yousefian: Data and results, Sample Calculations

Ricardo Jimenez: Discussion and analysis of results, recommendation, Introduction