Brayton Cycle (Gas turbine power cycle)

# Objective

The objective of this lab exercise is to gain practical knowledge of the Brayton cycle. The Brayton cycle illustrates the cold-air-standard assumption (constant specific heats at room temperature) model of a gas turbine power cycle. A portable propulsion laboratory[[1]](#footnote-1) containing a Model SR-30 turbojet is used in this exercise. The student shall apply the basic equations for Brayton cycle analysis by using empirical measurements at different points in the Brayton cycle.

## Image1

**Figure 1:** TTL Mini-Lab manufactured by Turbine Technologies Ltd. (TTL)

## Background

A simple gas turbine engine has three main components: a **compressor** section, **a combustion chamber** and a **turbine** section. Basic operation entails drawing atmospheric air into the compressor where it is heated through compression. The compressed and heated air is mixed with fuel in the combustion chamber. The air/fuel mixture burns at constant pressure in the combustion chamber. The resulting hot gas is directed to the turbine section where it expands. As the gas expands it produces a thrust reaction and performs work by turning the turbine. The turbine is connected to the compressor by a shaft. The resulting shaft work is used to drive the compressor and auxiliary power supplies.

The gas turbine has wide spread application. Most notably, it is used to power and propel aircraft and large ships. In some cases only the thrust resulting from the expanding gas exiting the turbine is used for propulsion and the shaft work is used to drive the compressor and power electrical systems. In turbo-fan engines some of the shaft work is used to drive a large fan that aids in propulsion. In other applications, such as helicopters and ships, propulsion is achieved through the shaft work, which is used to drive transmission/gear boxes that are connected to the rotor blades or propeller, respectively. Gas turbines are also commonly used to drive large electrical generators in power plant applications.

## Theory

The Brayton cycle consists of four basic processes (see Figure3 & 4). Low-pressure air is drawn into the compressor section and undergoes **isentropic compression**. Next, the heated and compressed air is combined with fuel in the combustion chamber. The air/fuel mixture **experiences reversible constant pressure heat addition**. The resulting hot gas enters the turbine section where it **undergoes isentropic expansion**. To complete the cycle (the exhaust and intake in the open cycle) the gas experiences **reversible constant pressure** heat rejection.

Thermodynamics and the First Law of Thermodynamics determine the overall energy transfer. The following assumptions are used when analyzing the gas turbine cycles:

1. The working fluid (air) is an ideal gas throughout the cycle.
2. The combustion process is constant-pressure heat addition.
3. The exhaust process is constant-pressure heat rejection.
4. The specific heat is constant at the lowest temperature in the cycle.

To perform the thermodynamic analysis on the cycle each component is modeled as a control volume. All processes are executed in steady-flow sections and can be analyzed as a steady-flow process, expressed on a basis of unit mass as *q – w = hexit – hinlet*.

The thermal efficiency of the ideal Brayton cycle is:



Processes 1 2 and 3 4 are isentropic, and P2 = P3 and P1 = P4 therefore:



Using these relationships the thermal efficiency simplifies to:

*th,Brayton = 1 – 1 .*

*rP(k-1)/k*

Where *rP*is the pressure ratio = *P2/P1* and *k* is specific heat ratio, which is 1.4 for air at room temperature.

The back work ratio is defined as the ratio of compressor work to turbine work and is given as:

*rbw* = *wCOMP,in/wTURB,out*

## Image2

Figure 2: SR-30 Engine.



Figure 3: Basic Brayton cycle.



Figure 4: *T – s* and *P  v* diagrams for the ideal Brayton cycle.

## a) Compressor Section

Ideally there is no heat transfer from the control volume to the surroundings. Under steady-state conditions (and neglecting potential and kinetic energy effects) the First Law for the control volume is:



Figure 5: Compressor, control volume model.

This can be rewritten in a more specific form of the First Law considering there is one flow into and one flow out of the control volume:



The terms are rearranged and the enthalpy is rewritten using the equation of state: *dh* = *cpd*T, which assumes the working fluid is an ideal gas and constant specific heat.



For accurate analysis of the compressor the specific heat of the fluid should be evaluated at the linear average between the inlet temperature and the outlet temperature: (T*in* -T*out*)/2.

The irreversibility present in the real process can be modeled by calculating the efficiency (*η*) of the compressor:

*ηC* = *wc,s* = *hout,s – hin* = T*out,s –* T*in*

*wc,a* *hout,as – hin* T*out,a –* T*in*

Where the subscript “*s*” refers to the ideal or isentropic process and the subscript “*a*” refers to the real or actual process. For a perfect gas the above equation is reduced to:

*ηC* = T*out,s –* T*in*

T*out,a –* T*in*

**b) Combustion Section**

In the ideal combustion section no work is transferred to the surroundings from the control volume. Under steady-state conditions, and neglecting kinetic and potential energy effects, the first law application is:





Figure 6: Combustion chamber, constant pressure model.

Considering that we have one flow in and one flow out of the control volume, we can use a more specific form of the first law.



Or, rearrange by grouping the terms associated with each stream: *qB = hout – hin.* Assuming ideal gasses and constant specific heats, enthalpy differences are readily expressed as the temperature differences as:

*qB = Cp,B (TB,out – TB,in)*

Again, to be more accurate, the specific heat of each fluid should be evaluated at the linear average between its inlet and outlet temperature.

**C) Turbine Section**

No heat is transferred to the surroundings in the ideal conditions for a control volume turbine section. Under steady-state conditions, and neglecting kinetic energy and potential energy effects, the first law for this control volume is then written:





Figure 7: Turbine, control volume model

Rearranging the terms associated with each stream gives *wT*= *hout – hin.* Assuming ideal gasses and constant specific heats, enthalpy differences are readily expressed as the temperature differences as:

 *wT = Cp,T (TT,out – TT,in)*

To be more accurate, the specific heat of each fluid should be evaluated at the linear average between its inlet and outlet temperature.

The irreversibility present in the real process can be modeled by calculating the efficiency (*η*) of the compressor:

*ηT* = *wc,a* = *hout,a – hin* = T*out,a –* T*in*

*wc,s* *hout,s – hin* T*out,s –* T*in*

Where the subscript “*s*” refers to the ideal or isentropic process and the subscript “*a*” refers to the real or actual process. For a perfect gas the above equation is reduced to:

*ηT* = T*out,a –* T*in*

T*out,s –* T*in*

**EXPERIMENT PROCEDURES**

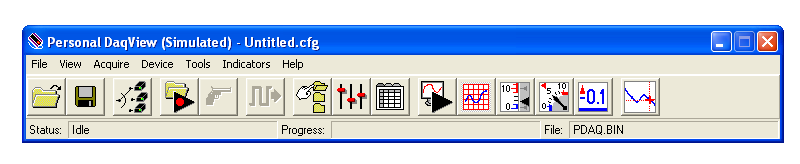
**WARNING**

Before starting the experiment, make sure you read the following.

1. Make sure that neither you nor any of your belongings are placed in front of the intake or the exhaust sections of the SR-30 engine while it is operating.
2. Ear protection must be worn while the SR-30 engine is operating.
3. The SR-30 engine rotates at very fast speeds. Therefore, stay far away from the test bench to avoid injury if the engine malfunctions.
4. Make sure the engine low-oil-pressure light extinguishes immediately after engine start-up. If the light stays illuminated or lights at any time during engine operation turn off the fuel flow to the SR-30 engine immediately.
5. If at any time you suspect the SR-30 engine is not operating properly immediately turn off the fuel flow and shut down the engine.

**Experiment Procedures**

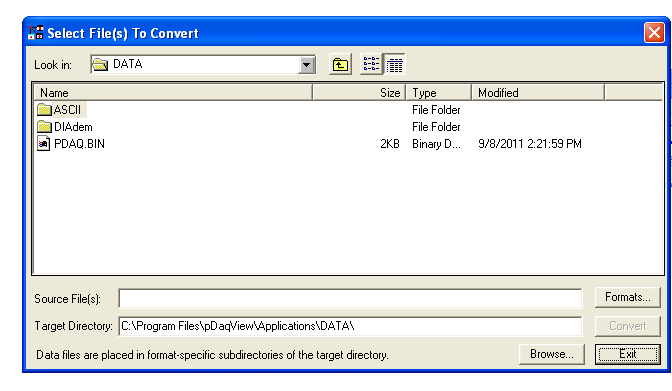
1. The Professor will walk you through the inspection procedure.
2. Inspect for free rotation of the compressor/turbine.
3. Ensure there are no obstructions in front of the intake or exhaust of the SR-30 engine.
4. Check fuel and oil levels.
5. Connect the air hose from the portable compressor or compressed air supply from Facilities to the TTL Mini-Lab.
6. Turn on compressed air to build-up pressure.
7. Turn on power to the computer and launch **pDAQVIEW** program using the icon on the desktop.
8. Prior to operating the engine ensure you know how to read and retrieve data from the pDAQVIEW program.
9. On the Main Control Window (data acquisition tool bar), select **File – Open.**
10. Double Click on **#0431 Factory Congfig.CFG**
11. On the data acquisition tool bar **click** on the **Bar Graph icon.**



1. **Click Screen shot 2011-09-09 at 12.37.07 AM.png** on the menu bar to update all the meter and channel configuration charts. Use to check for correct data reading before starting the operational run (meter will display values during the run but the data is not logged in to a file).
2. **Click Screen shot 2011-09-09 at 12.33.57 AM.png on** menu bar to begin logging data to a file. A **File Overwrite** window will appear.
3. **Click: YES to ALL.**

**CONVERTING BINARY DATA:** Data will be stored in binary format; it must be converted into text file so that it can be read by Excel as spreadsheet.

1. **Click: Tools** in Menu Bar
2. **Click: Convert Binary Data.**



1. In the **Select Files to convert** window, select file name with **.BIN** extension.
2. **Click: Format** button in the above window.
3. **Select ASCII TEXT SPREADSHEET**. A Red check mark should appear left of it, **Click OK.**
4. Then **Select Files to convert** window and **Click: Convert**.
5. A window with **Conform File Overwrite** appears, **Click: Yes to ALL** (your data is now being converted so that it can be imported to excel spreadsheet).
6. In order to convert the file into Excel Spreadsheet: **Click Open > My Computer > Local Disk (C:)> Program Files > pDAQVIEW > Application > Data > ASCII > PDAQ > Click “NEXT” 3 times and the data will be in spreadsheet form.**
7. You are now ready to start the SR-30 engine. MAKE SURE EVERY ONE IN THE AREA IS WEARING EAR PROTECTION.
8. Follow the following procedure to start the engine:
9. Turn the Master Key ON.
10. Turn the El. Master Key ON.
11. Turn the Ignition and Air Start. These events start the engine where the compressed air turns the turbine.
12. After the engine is started, slowly push the throttle handle.
13. Continue to slowly push the throttle handle until the engine speed indicator on the Virtual Bench (the indicator on the test bench panel is not calibrated) reads your target engine speed.
14. Allow the engine to reach steady state then record the data from all of the pressure and temperature sensors. Monitor engine temperature. The temperature should NOT exceed 500 Degree Celsius. The emergency shutdown is to switch off the fuel pump.
15. Repeat steps 23 and 24 until the data for all three-target engine speeds are recorded. At restart, make sure that the temperature of the engine (EGT) falls below 100 Degree Celsius.
16. Have the Professor shut down the SR-30 engine.
17. Turn the power off to the computer, portable compressor and TTL Mini-Lab.
18. Stow the equipment to its rightful location and cover it.

**Data Reduction:**

1. Provide a *T – s* diagram and a *P – v* diagram for the ideal and actual Brayton cycle for each test speed.
2. Calculate the thermal efficiency for the Brayton cycle for each engine speed.
3. Perform a first law analysis of each section of the SR-30 engine at each engine speed.
4. Calculate the efficiency of the compressor section and turbine section for each engine speed.
5. Calculate the back work ratio for each engine speed.

**Questions:**

1. What can be observed about the turbine engine’s efficiency in relation to its RPM?
2. What type of relationship (constant, linear, exponential, etc.) exists between RPM and thrust?

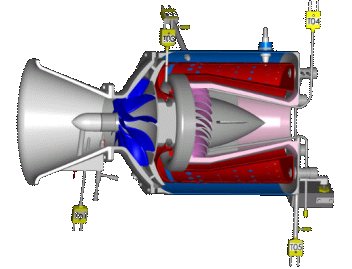


Figure 8: Cut-away of the SR-30 engine

**Sensor Identification**

P01 – Compressor stage static pressure. T01 – Compressor inlet static temperature.

P02 – Compressor stage stagnation pressure. T02 – Compressor stage exit stagnation temperature.

P03 – Combustion chamber pressure. T03 – Turbine stage inlet stagnation temperature.

P04 – Turbine exit stagnation pressure. T04 – Turbine stage exit stagnation temperature.

P05  Thrust nozzle exit stagnation pressure. T05  Thrust nozzle exit stagnation temperature.

1. Manufactured by Turbine Technologies Ltd. Called TTL Mini-Lab [↑](#footnote-ref-1)