

## **AC 2008-2319: IMPROVING THERMODYNAMICS INSTRUCTION: HANDS-ON EXPERIENCE WITH A GAS TURBINE ENGINE**

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# **Improving Thermodynamics Instruction: Hands-On Experience with a Gas Turbine Engine**

## **Abstract**

Thermodynamics offered by the Department of Mechanical Engineering at North Carolina A&T State University covered in two consecutive three-credit-hours courses, the first course covers the fundamental of thermodynamics principles. The topics include: energy, heat and work, thermodynamics properties of substances, real and ideal gases, first and second laws of thermodynamics, the basic Rankine power cycle, and the basic compression refrigeration cycle. The second course involves applications of basic thermodynamics principles to real systems. The topics covered include: gaseous mixtures, psychrometrics, combustion, power cycles and refrigeration cycles.

In an effort to give students a combination of theoretical background and hands-on experience, a new experiment on gas turbine engine was introduced. This paper describes the experiences the students gained in this experiment. During this exercise the students actually learned how to operate a gas turbine engine, collected and analyzed the output data including thrust and efficiency, and related the experimental result to the theory learned in the thermodynamics course. This experiment complemented the thermodynamics course and fully integrated some aspects of thermodynamics and enhanced the student's learning process.

The gas turbine engine used in this exercise was a table top arrangement of a single-stage radial-flow compressor, a single-stage axial-flow turbine, and a reverse-flow annular combustion chamber turbojet engine. The engine is of a single shaft design. Both the compressor and turbine rotate on the same shaft at the same speed. The turbojet engine was equipped with a data acquisition system to monitor engine speed, exhaust gas temperature, fuel flow and thrust.

## **Introduction**

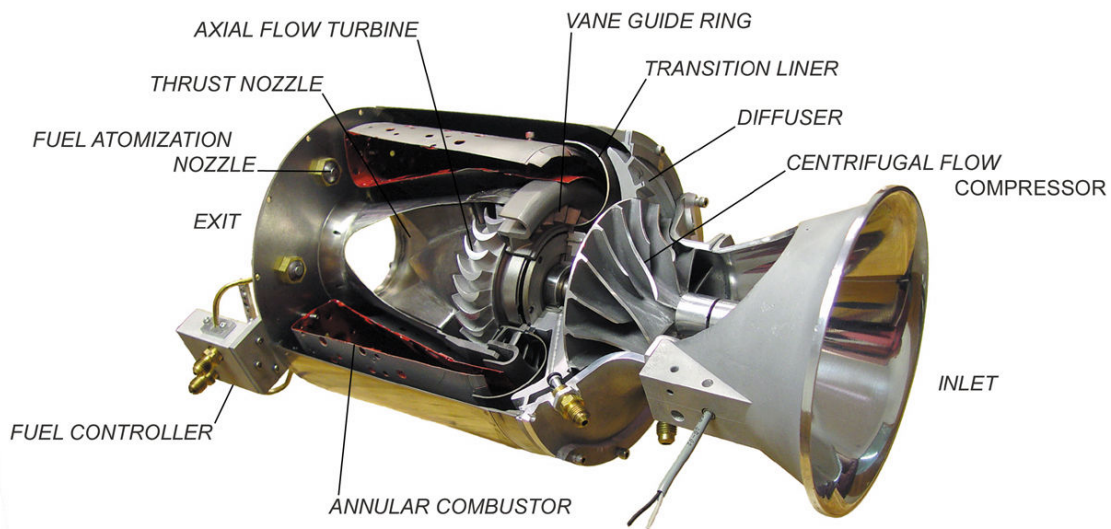
This experiment is designed to give the students a hands-on experience with a gas turbine engine and to directly relate the mechanical device to the theory learned in a typical thermodynamics course. This paper describes the experiences the students gained in the areas of propulsion and gas turbine engines. The experiment introduces the students to the basic principles of the gas turbine engine. During this experiment the students actually learn how to operate a gas turbine engine, collect and analyze the output data and relate the result to the theory learned in the thermodynamics courses. The broader educational objectives are to improve the students' understanding of thermodynamics, to help them integrate this knowledge with other subjects, and to give them a better basic understanding of how a gas turbine engine works.

## Equipment

The gas turbine experiment was conducted using the SR-30 turbojet engine manufactured by “The Turbine Technologies, LTD”; a cut-away view of the SR-30 model gas turbine engine is shown in Figure 1. and its major engine components are shown in Figure 2.

### The SR-30 turbo jet engine is comprised of:

1. A single stage axial flow turbine,
2. Radial flow compressor and
3. Reverse flow annular combustion chamber.
4. The engine is of single shaft design.
5. Both the compressor and turbine rotate on the shaft at the same speed.
6. The engine is fully throttleable from an idle speed of 45,000 rpm to a maximum speed of up to 90,000 rpm.



**Figure 1. Cut-Away View of Turbine Technologies SR-30 Gas Turbine Engine<sup>1</sup>**



**Figure 2. Turbine Technologies SR-30 Major Engine Components<sup>1</sup>**

### **Jet-Propulsion Cycle**

Aircraft gas turbines operate on an open cycle, as shown in Figure 3, called jet-propulsion cycle. The ideal jet-propulsion cycle differs from the simple ideal Brayton cycle in that the gases are not expanded to the ambient pressure in the turbine. Instead, they are expanded to a pressure such that the power produced by the turbine is just sufficient to drive the compressor and the auxiliary equipments. That is, the net work output of the jet propulsion is zero (in the ideal case, the turbine work is assumed to equal the compressor work). The gases that exit the turbine at relatively high temperature and pressure are accelerated in a nozzle to provide the thrust to propel the aircraft. The process can be simplified as follows:

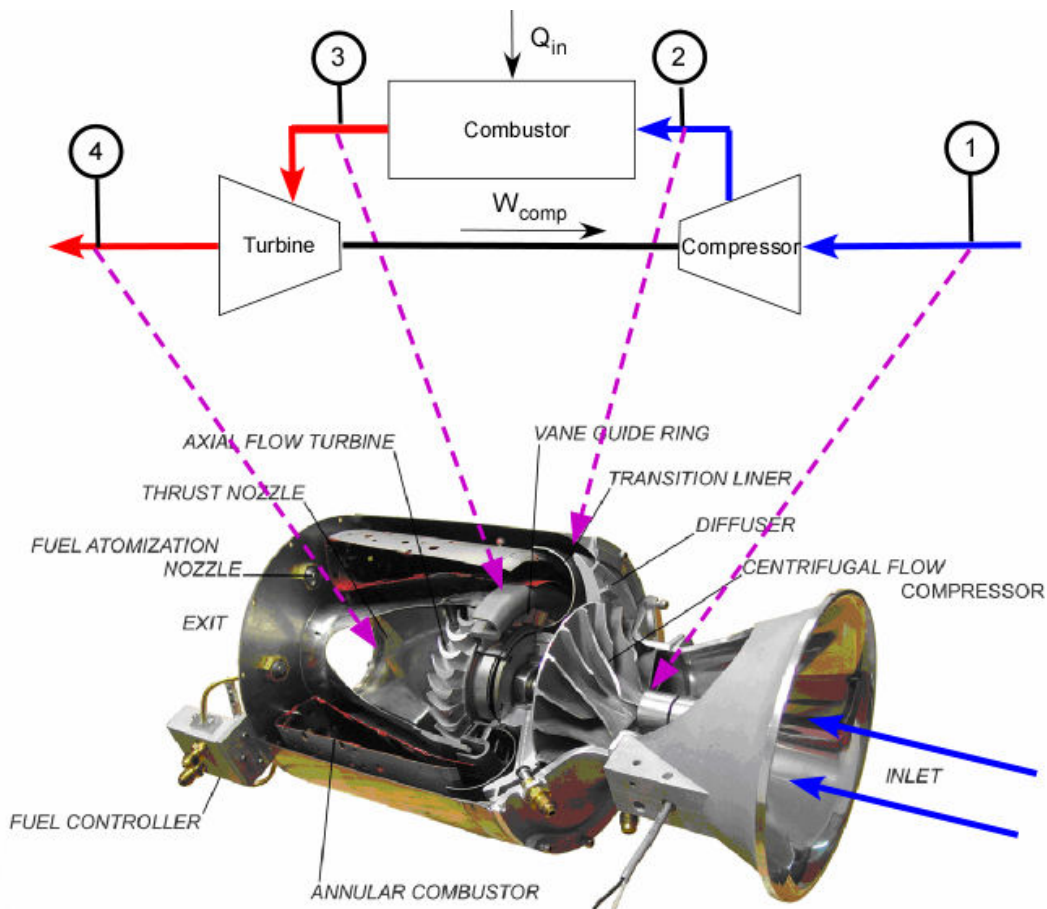
- Fresh air at ambient conditions is drawn into the compressor, where its temperature and pressure are raised.
- The high pressure air proceeds into the combustion chamber, where the fuel is burned at constant pressure.
- The resulting high temperature and pressure gases then enter the turbine while producing power. The power produced by the turbine drives the compressor.

- The high-temperature and high-pressure gases leaving the turbine are accelerated in a nozzle to provide thrust.

### Specifications of the Turbine Technologies SR-30 Turbojet Engine

Diameter: 6.75 inches  
 Length: 10.75  
 Max. RPM: 90,000  
 Max. Exhaust Gas Temperature EGT: 720° C  
 Pressure Ratio: 3.4  
 Specific Fuel Consumption: 1.18  
 Engine Oil: Turbine Oils meeting military specification Mil-L-236993C (Exxon 2380 Turbo oil and Aeroshell 500)

Approved Fuels:  
 Commercial Grades: Jet A, Jet A-1, Jet B, Kerosene, Diesel, Heating fuel oil #1 or #2  
 Military Grades: JP-4, JP-5, JP-8



**Figure 3. Schematic of Jet-Propulsion Cycle and Cut Away of SR-30 Engine**

## Engine Sensor Location and Data Acquisition System

The Turbine Technologies, LTD Gas Turbine engine<sup>1</sup> comes equipped with a turnkey data acquisition system shown in Figure 4. Thirteen data points (pressures, temperatures, thrust, rpm, and fuel flow) are collected via sensors located at each key engine station. Engine sensor locations are shown in Figure 5.

1. Compressor Inlet Pressure,  $P_1$  (Displayed on Data Acquisition Screen)
2. Compressor Inlet Temperature,  $T_1$  (Displayed on Data Acquisition Screen)
3. Compressor Exit Pressure,  $P_2$  (Displayed on Data Acquisition Screen)
4. Compressor Exit Temperature,  $T_2$  (Displayed on Data Acquisition Screen)
5. Turbine Inlet Pressure,  $P_3$  (Displayed on Panel and Data Acquisition Screen)
6. Turbine Inlet Temperature,  $T_3$  (Displayed on Panel as TIT and Data Acquisition Screen)
7. Turbine Exit Pressure,  $P_4$  (Displayed on Data Acquisition Screen)
8. Turbine Exit Temperature,  $T_4$  (Displayed on Data Acquisition Screen)
9. Exhaust Gas Pressure,  $P_5$  (Displayed on Data Acquisition Screen)
10. Exhaust Gas Temperature,  $T_5$  (Displayed on Panel as EGT and Data Acquisition Screen)
11. Fuel Pressure (Displayed on Panel)
12. Engine shaft speed, **RPM**, Tachometer Generator (Displayed on Panel and Data Acquisition Screen)
13. Fuel Flow Sensor



Figure 4. Data Acquisition Screen of the Mini-Lab

## Engine Sensor Locations

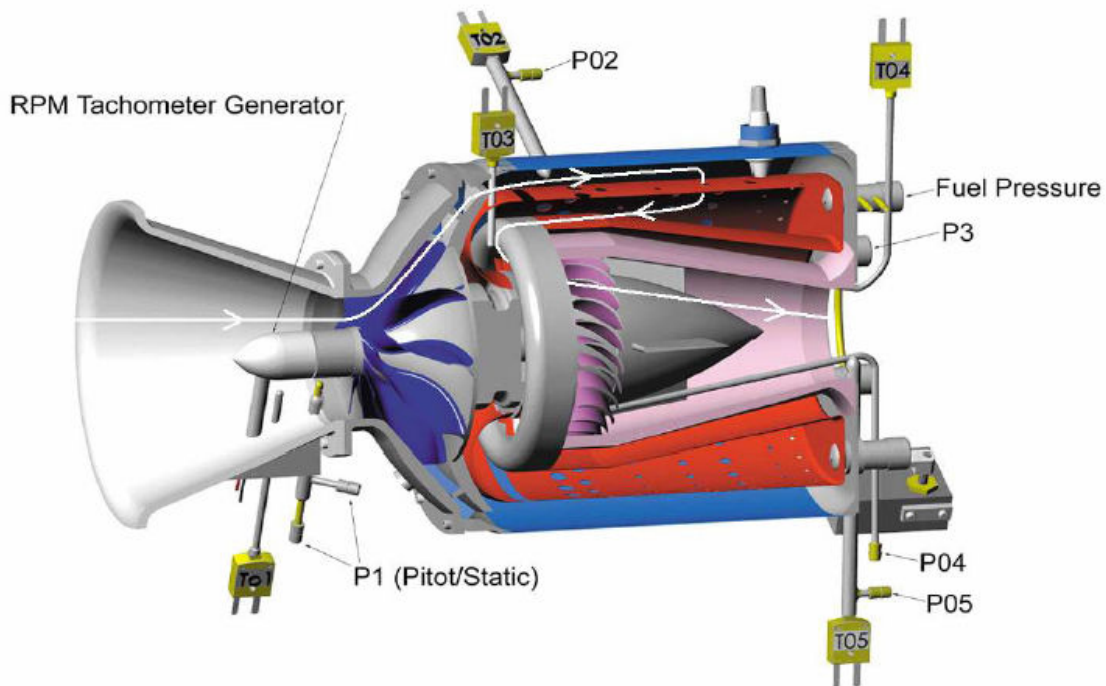


Figure 5. Engine Sensor Locations of SR-30<sup>1</sup>

## Experimental Procedures

The instructions provided to the students for engine operation are given below:

### Before Engine Start

1. Compressor Rotor: Rotate by hand. Check for smooth rotation.
2. Fuel Quantity: Check
3. Oil Quantity: Check
4. Ventilation: Ensure adequate room ventilation
5. Hearing Protection: In Place
6. Eye Protection: In Place
7. Fire Extinguisher: Accessible
8. Starting Air: Connected (100 psi minimum) a compressed air source is required for engine starting (engine starting is accomplished via compressed air impingement)

### Engine Starting

1. Air Pressure: 100-120 psig
2. Master Switch Key: ON
3. Red Low Oil Pressure Light: ON
4. Electronics Master Switch: ON

- |                        |                             |
|------------------------|-----------------------------|
| 5. All LED Instruments | ON                          |
| 6. Throttle            | Engine Start Position       |
| 7. Ignitor Switch      | ON                          |
| 8. Digital EGT Readout | Green Digits (Below 100° C) |
| 9. Air Starter Switch  | ON                          |
| 10. Fuel Switch        | ON at 7,000 RPM             |

**After Start**

- |                           |                                                       |
|---------------------------|-------------------------------------------------------|
| 1. Ignition Switch        | OFF                                                   |
| 2. Air Start Switch       | OFF                                                   |
| 3. Throttle               | Idle (check for normal engine instrument indications) |
| 4. Engine Instrumentation | Monitor Throughout Run                                |

**Normal Shutdown**

- |                |                                                         |
|----------------|---------------------------------------------------------|
| 1. Idle Engine | at 10 psig (combustion chamber pressure) for one minute |
| 2. Fuel Switch | OFF                                                     |

**Emergency Shutdown**

- |                     |                     |
|---------------------|---------------------|
| 1. Fuel Switch      | OFF                 |
| 2. Ignition Switch  | OFF                 |
| 3. Air Start Switch | ON for Cooling      |
| 4. All Switches     | OFF Below 85° C EGT |

**Cycle Analysis and performance**

Refer to the schematic diagram of the jet-propulsion cycle, Figure 3. which is made up of four irreversible processes:

- 1 – 2 Isentropic compression (in a compressor)
- 2 – 3 Constant-pressure heat addition
- 3 – 4 Isentropic expansion (in a turbine)
- 4 – 1 Constant-pressure heat rejection

**Analysis:**

The students were given the following instructions for analysis of their data and prediction of engine performance.

**Thrust**

The thrust developed in a turbojet engine is the unbalanced force that is caused by the difference in the momentum of the low-velocity air entering the engine and the high-velocity exhaust gases leaving the engine, and it is determine from Newton's second law. The pressures at the inlet and exit of a turbojet engine are identical (ambient pressure).



Recall Newton's second law

$$F = ma \quad (1)$$

Where

$$a = \frac{dv}{dt} \quad (2)$$

Therefore,

$$F = \frac{d}{dt}(mv) \quad (3)$$

$$Fdt = d(mv) \quad (4)$$

Integrate

$$\int_{t_1}^{t_2} Fdt = \int_1^2 d(mv) \quad (5)$$

$$F(\Delta t) = (mv)_2 - (mv)_1 \quad (6)$$

$$F = \frac{(mv)_2 - (mv)_1}{\Delta t} \quad (7)$$

$$F = (\dot{m}v)_{exit} - (\dot{m}v)_{inlet} \quad (8)$$

$$F = \dot{m}(v_{exit} - v_{inlet}) \quad (9)$$

Where

$F \equiv$  Thrust Force

$\dot{m} \equiv$  Mass flow rate of air through the engine

$v_{exit} \equiv$  The exit velocity of the exhaust gases

$v_{inlet} \equiv$  The aircraft velocity, assume the aircraft cruising in still air

$(\dot{m}v)_{inlet1} \equiv$  Rate of linear momentum of the inlet flow

$(\dot{m}v)_{exit} \equiv$  Rate of linear momentum of the hot exhaust gases

## Propulsive Power

The power developed from the thrust of the engine is called the propulsive power, which is the thrust times the aircraft velocity.

$$\dot{W}_P = FV_{aircraft} \quad (10)$$

## Propulsive Efficiency

The propulsive efficiency is the ratio of the desired output to the required input. The desired output is the power produced to propel the aircraft and the required input is the heating value of the fuel

$$\eta_P = \frac{\dot{W}_P}{\dot{Q}_{in}} \quad (11)$$

$$\dot{Q}_{in} = \dot{m} HV_{fuel} \quad (12)$$

Where  $HV_{fuel}$  is the heating value of the fuel

## Experimental Results

Figures 6-11 show sample of the output results obtained at various operating conditions by the students.

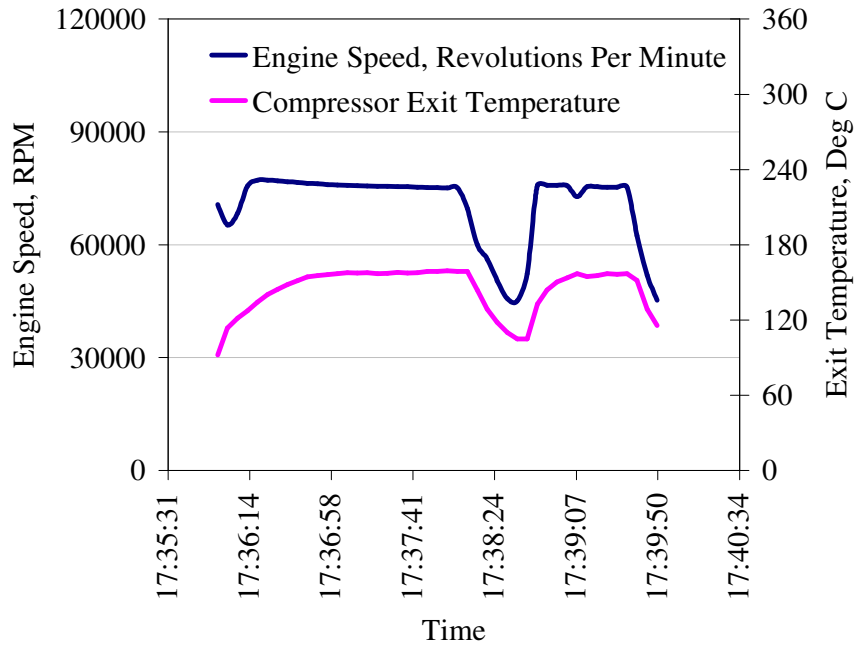
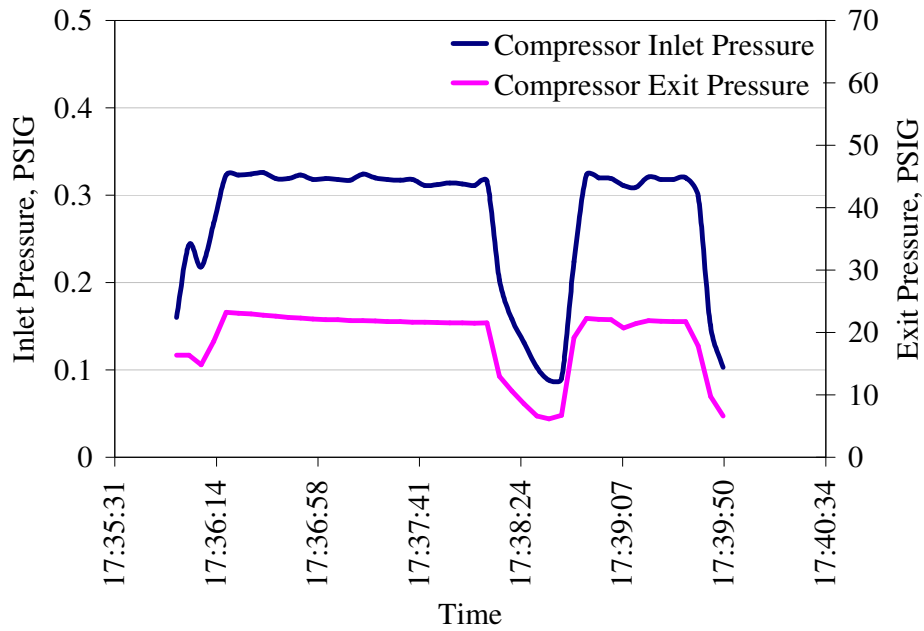
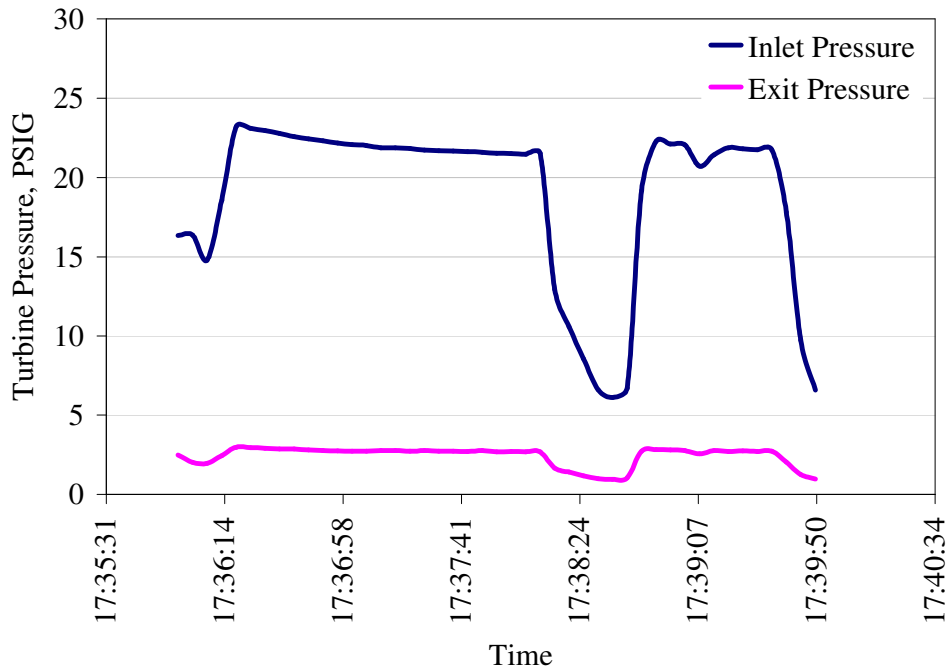


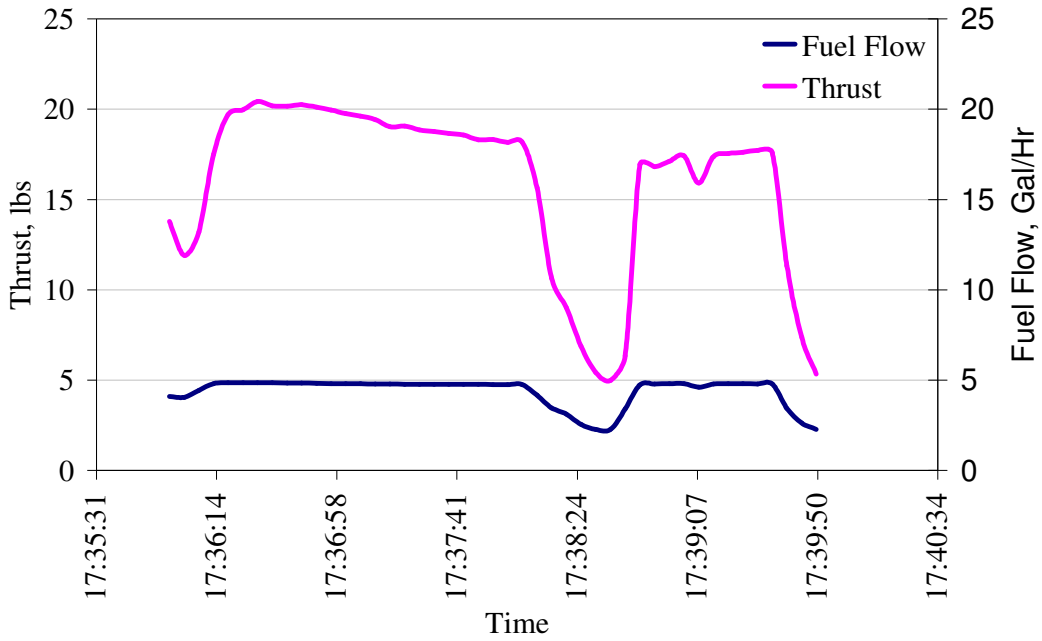
Figure 6. Compressor Exit Temperature and Engine Speed versus Time



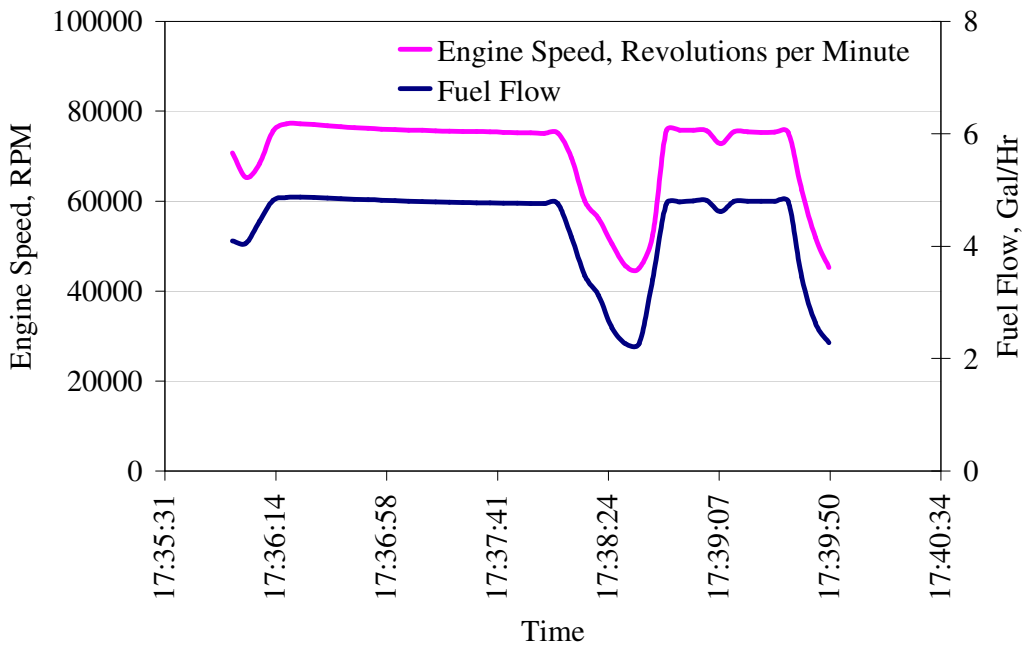
**Figure 7. Compressor Inlet and Exit Pressure versus Time**



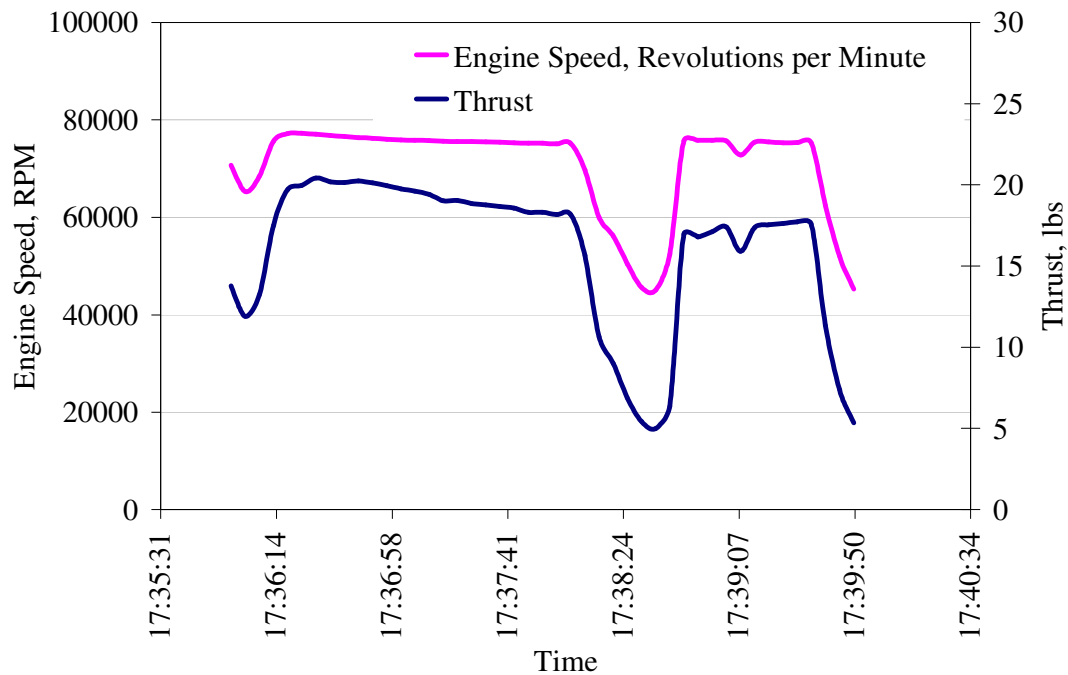
**Figure 8. Turbine Inlet and Exit Pressure versus Time**



**Figure 9. Fuel Flow and Thrust versus Time**



**Figure 10. Engine Speed and Fuel flow versus Time**



**Figure 11. Engine Speed and Thrust versus Time**

In addition to the above information the students were asked to include in their report the description of the main component of the jet engine and the function of each component, as well as the history of the gas turbine engine and the limitation of the early engine. The student' report also included list of the various types and of gas turbine engine and their application.

## Conclusions

The experiment provided the students in the thermodynamics course with a hands-on experience with a real engine. The students were able to operate the small scale turbo jet engine and analyze the out put results under various conditions and relate it to the theory learned in their thermodynamics courses.

## References

1. Mini-Lab Operator's Manual, Turbine Technologies, Ltd, Chetek, WI, USA.
2. Mini-Lab Gas Turbine Power System Sample Lab Experiment Manual, Turbine Technologies, Ltd, Chetek, WI, USA.
3. <http://www.turbine technologies.com>
4. "THERMODYNAMICS AN ENGINEERING APPROACH", Fifth Edition, Yunus A. Cengel & Michael A. Boles, McGraw-Hill, Inc. 2006.