MECH5500-01
MECHANICAL DESIGN PROJECT
Summer 2016

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Professor Duva,

 This report contains the entire structure of our team's process and execution of tasks to conduct "Performance Analysis and Testing on Wentworth Institute of Technology's Mini Jet Turbine" in the thermodynamics laboratory. The report focuses on first upgrading the current instrumentation and data acquisition (DAQ) system. The new DAQ system directly outputs data recorded by the mini turbine into a user-friendly LabVIEW interface. Steps were taken in order to accurately measure the five stages of pressure and temperature of the system, RPM, thrust, and fuel pressure. These values are paralleled by an EES turbine system analysis, which will be used to calculate the compressor, turbine, and overall efficiencies, including the overall work of the system.

The existing laboratory experiment report was modified and a new draft was created for future students to use in their thermodynamics laboratory period. This draft will be under review by department faculty for finalization. This system gives students the ability to further understand the first and second laws of thermodynamics in a practical and industry-like setting. A main focus of this project was to create a friendly user interface for future students running this machine. When the students are conducting the experiment, the LabVIEW program will acquire run data and display real time temperature, pressure, RPM, and thrust outputs. These values will be inputted into the EES program to calculate the actual efficiencies of the system on that given run day.

The tasks that have been completed are as follows: various preparations for DAQ replacement, pressure transducer and thermocouple implementation and calibration, RPM and thrust calibration, mounting of laptop arm, laptop and second monitor, mounting of DAQ bracket and DAQs to the bracket, rewiring of system to new DAQs, a LabVIEW DAQ and technical display program, an EES program with interactive display, a laboratory experiment, detailed engineering notebooks, and this final report.

We look forward to your review of the final report,

Sincerely,
Matthew Dietter, Kyle Lavoie, Jonathan Sewell, and Kurtis Madden

Performance Analysis and Testing of the Mini Gas Turbine
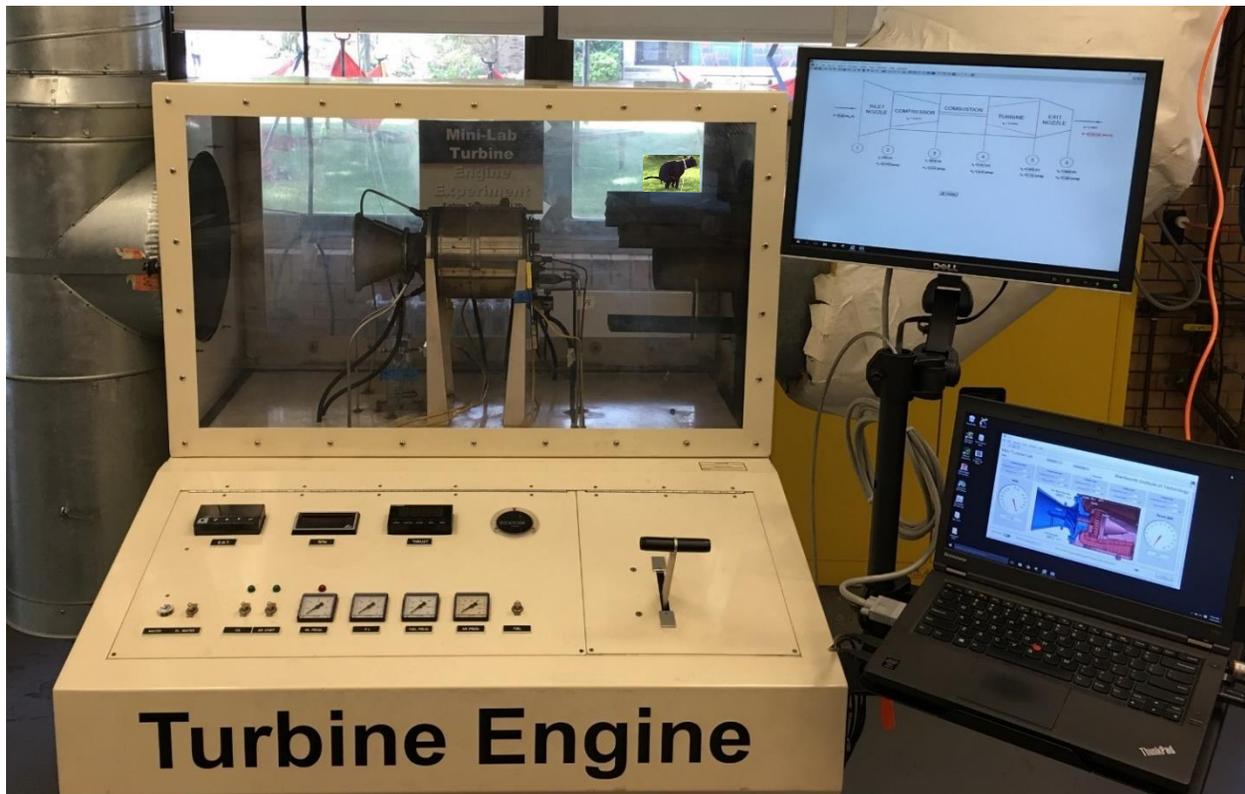
WENTWORTH INSTITUTE OF TECHNOLOGY
MECH5500
Mechanical Capstone Project

Submitted to:
Professor *Anthony W. Duva*
Date: 8/9/2016
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1. **ABSTRACT**

This report defines the Performance Analysis and Testing of the Mini Gas Turbine that our team completed for our mechanical engineering capstone project. The main objective of this project was to restore the capability of the Turbine Engine located in Wentworth Institute of Technology's Thermodynamics Laboratory in order to provide a laboratory experiment for future students. This objective was met through updating the existing data acquisition system, writing a new data acquisition program in LabVIEW, installing new pressure and temperature sensors, and performing a first and second law of thermodynamics analysis on the engine in Engineering Equation Solver. In order to update the existing data acquisition system, new NI SCB-68 connector blocks were implemented along with NI USB-6251 terminals. The new hardware is operated through a LabVIEW program running on a new laptop designated and mounted to the mini jet turbine housing.

Tasks completed in order to finalize this project include formal proposal report, various preparation for DAQ replacement, pressure transducer and thermocouple implementation and calibration, mounting of laptop arm, laptop and second monitor, mounting of the DAQ bracket and DAQs to the bracket, rewiring of system to new DAQs, a LabVIEW DAQ and technical display program, an EES program with interactive display, a laboratory experiment, detailed engineering notebooks from each group member, and this final report.

As a result, the mini jet turbine system is now capable of producing consistent run data in order to be used as an experimental laboratory for future thermodynamic students. Each component of the system is calibrated including all thermocouples and pressure transducers, RPM, and thrust. Students will now utilize run data displayed on the LabVIEW front panel and input it into the EES program to determine various efficiencies and work of the mini turbine system.

Contents

LIST OF FIGURES

LIST OF TABLES

2. PROBLEM DEFINITION

The Turbine Technologies Mini Gas Turbine in the Wentworth Institute of Technology thermodynamics lab is in great need of an instrumentation overhaul. Due to the high cost of replacing the data acquisition system completely, our team will be replacing it ourselves. The current DAQ system is outdated and incompatible with current software on the computer it is paired to. A new set of DAQ hardware will be paired with a new computer running a LabVIEW program to collect the data.

Our team's goals also include calibration of pressure transducers and thermocouples for accurate measurement. Our team will then run a 1st and 2nd law of thermodynamics on the system using Engineering Equation Solver (EES).

The mini gas turbine in the thermodynamics lab is a fantastic resource that is going un-used. Many students can benefit from the mini turbine's technical sophistication. Benefits include but are not limited to technical understanding, conceptual understanding, and practical application. With the recent creation of the Aerospace Engineering Minor at Wentworth, this machine could open the eyes to many young engineers and give them the ability to have a future in the aerospace industry. Turbine propulsion is used on various aircraft, but dominates the commercial jet and military jet industries.

The main problem of this project is to overhaul the instrumentation of the mini gas turbine and have it ready to be run for students in the upcoming fall of 2016 semester. Instrumentation, testing, and calibration are the three main milestones for this project. A technical lab will be produced for thermodynamics students to run.

3. INTRODUCTION

The turbine engine discussed throughout this report is a self-contained turbojet engine that is used as an educational tool for engineering students. This engine operates on a Brayton cycle. The Brayton cycle depicts the air-standard model of a gas turbine power cycle. A simple gas turbine is comprised of three main components: a compressor, a combustor, and a turbine. According to the principle of the Brayton cycle, air is compressed in the compressor. The air is then mixed with fuel, and burned under constant pressure conditions in the combustor. The resulting hot gas is allowed to expand through a turbine to perform work. Most of the work produced in the turbine is used to run the compressor and the rest is available to run auxiliary equipment and produce power.

The gas turbine is used in a wide range of applications. Common uses include stationary power generation plants (electric utilities) and mobile power generation engines (ships and aircraft). In power plant applications, the power output of the turbine is used to provide shaft power to drive a generator, a helicopter rotor, etc. A jet engine powered aircraft is propelled by the reaction thrust of the exiting gas stream. The turbine provides just enough power to drive the compressor and produce the auxiliary power. The gas stream acquires more energy in the cycle than is needed to drive the compressor. The remaining available energy is used to propel the aircraft forward.

Shown below in Figure 1 is a schematic of the Brayton cycle. Low-pressure air is drawn into a compressor (state 1) where it is compressed to a higher pressure (state 2). Fuel is added to the compressed air and the mixture is burnt in a combustion chamber. The resulting hot gases enter the turbine (state 3) and expand to state 4.
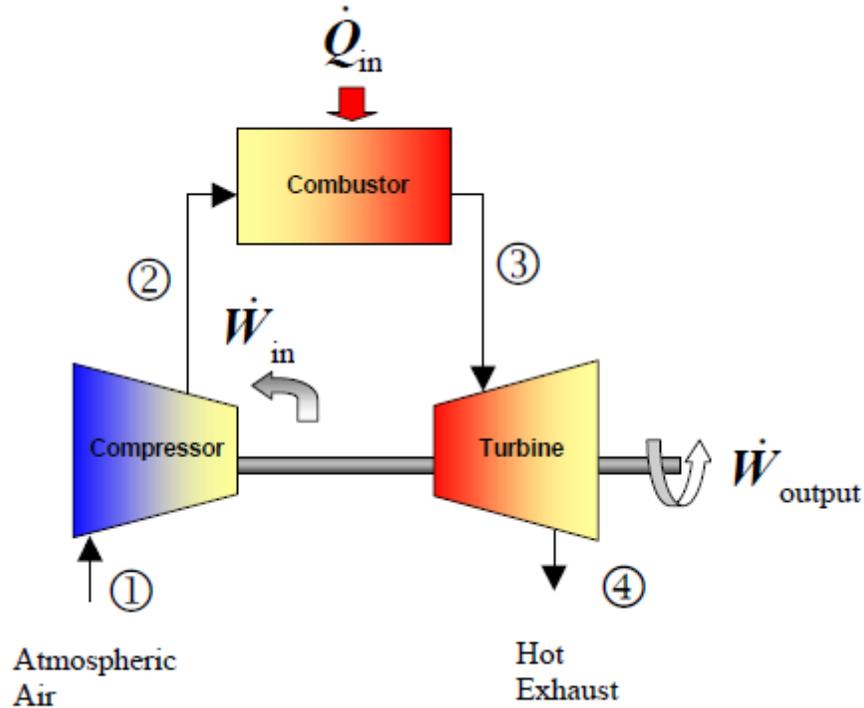
Figure 1. Basic Brayton Cycle

An analysis on this engine provides important performance characteristics such as thrust, compressor performance, turbine performance (work and power, expansion ratio, turbine efficiency), combustion/emission analysis, and overall isentropic efficiency. In order to perform an analysis on this engine, several quantities at specific locations are needed. Sensors are instrumented on this engine at the compressor inlet, compressor outlet, turbine inlet, turbine exit, and exhaust to collect data on the temperature and pressure at each location. This data is then used to perform a performance analysis on the engine. In addition, there are sensors on this engine to monitor thrust, RPM, and fuel flow rate.

Shown below in Figure 2 is a cross section of the engine with main components labeled.
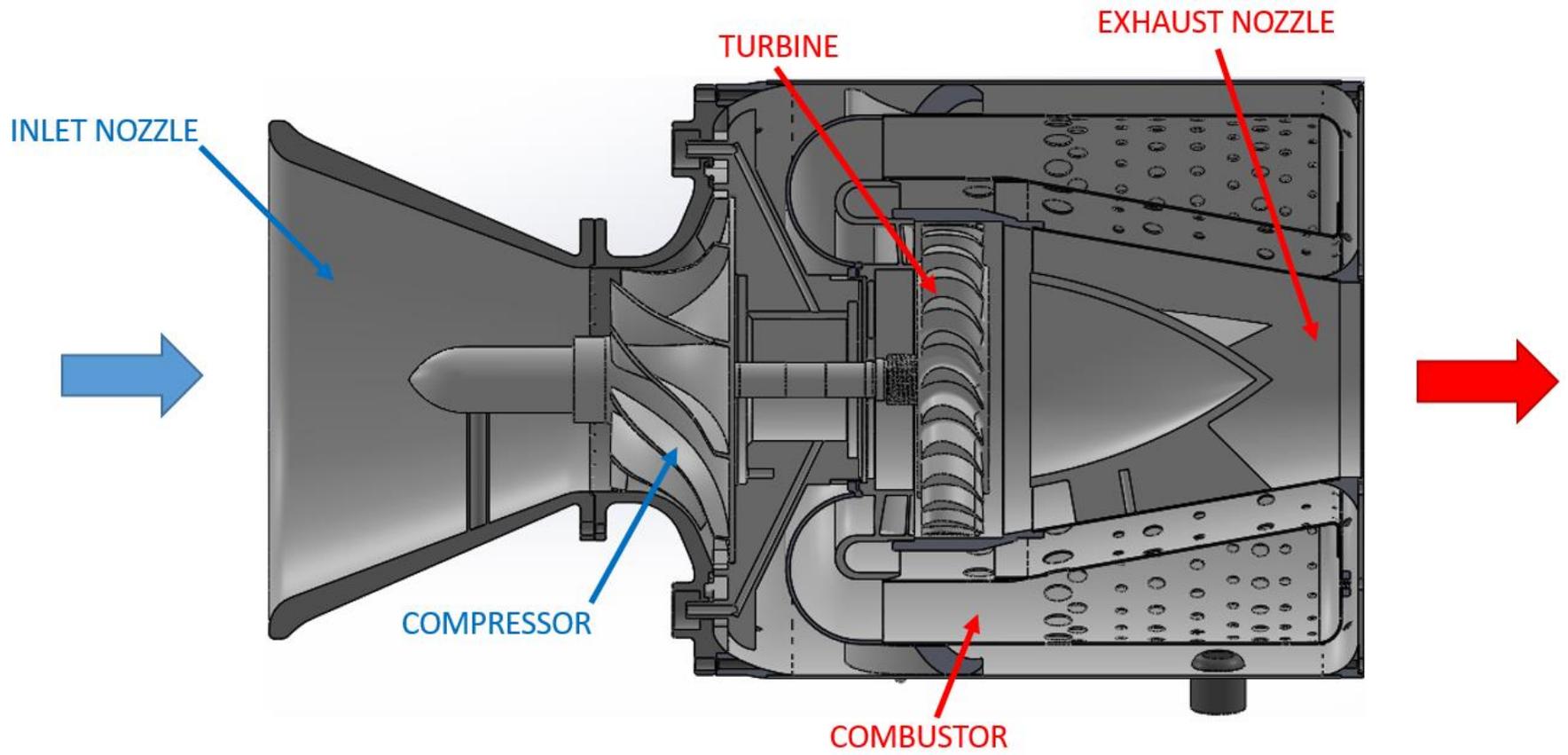
Figure 2. Turbine Engine Layout (Brayton Cycle)

Figure 3 below shows the location of each temperature and pressure being measured on the engine.
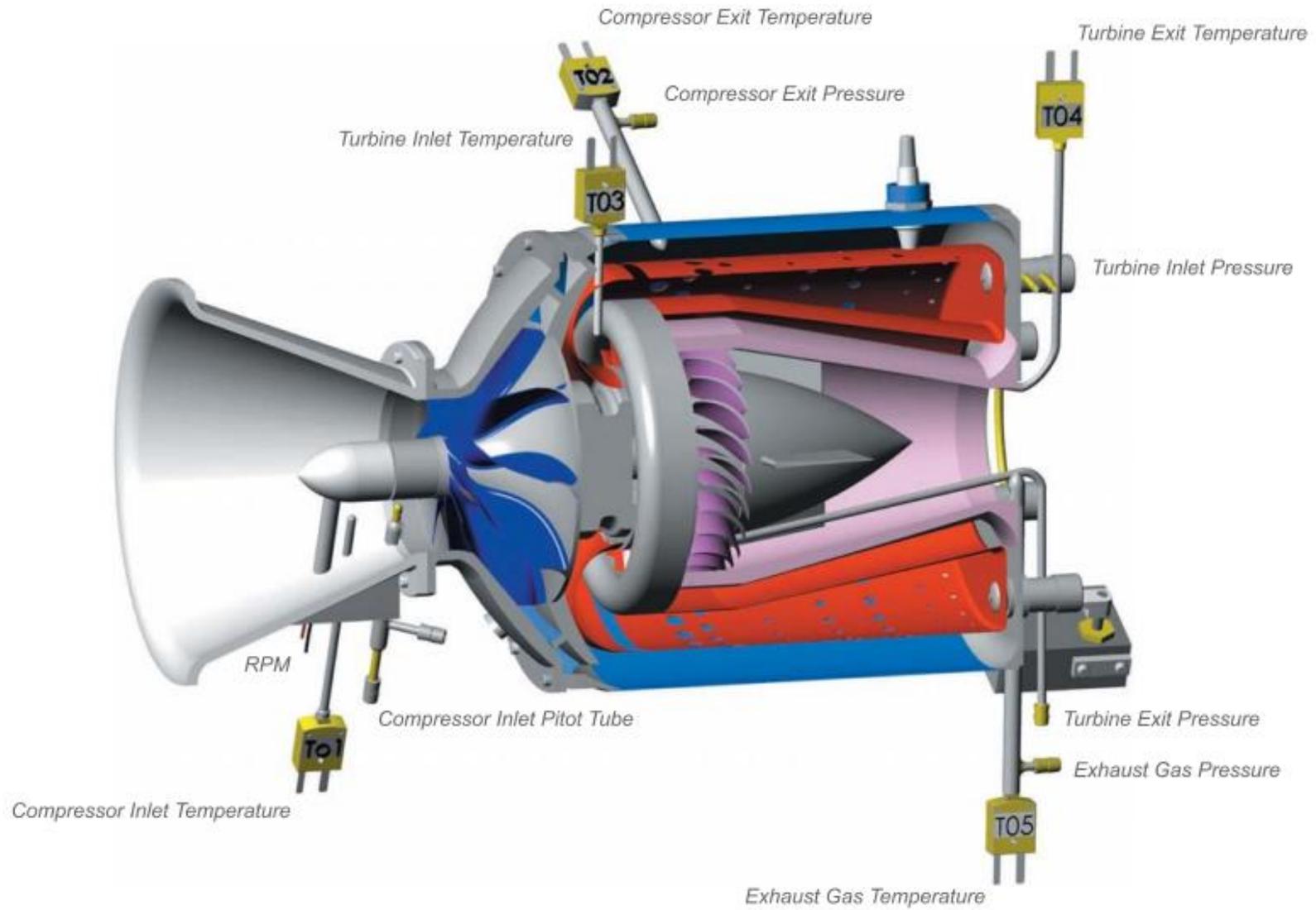
Figure 3. Engine Instrumentation Locations

Shown below in Table 1 are the specifications of the engine.

Table 1. Engine Manufacturer Specifications

Manufacturer	Turbine Technologies, Ltd.
Model Number	2000DX
Max. RPM	90,000
Max. Exhaust Temperature	720 C
Pressure Ratio	3.4:1
Specific Fuel Consumption	1.18 lb./lb.-hr

4. PROJECT OBJECTIVE

The objectives of this capstone project are as follows:

1. Replace existing DAQ components with new NI DAQ
2. Rewire the DAQ components to generate temperature, pressure, RPM, and thrust outputs
3. Create mounting bracket for new DAQ components
4. Generate LabVIEW program to output data from new DAQ
5. Calculate first and second law of thermodynamics analysis on components and the overall system to find overall efficiencies using Engineering Equation Solver
6. Develop a project to be conducted by future thermodynamics students

4.1. Detailed Performance Specification

By utilizing the previously attached instrumentation, the majority of the form, fit, and function of the design has already been established. The main components that will be added are as follows:
- New LabVIEW program with user friendly interface
- New computer and computer mount
- Shelving unit to hold the NI chassis
- Measurement device to read inlet air velocity

Collectively these items will revamp and improve the preexisting DAQ system. The laptop and stand will be placed on the right side of the unit in order for easy access to connect to the NI chassis. Above the laptop there will be a second screen mounted for a user friendly display of the EES program or LabVIEW front panel. The shelving unit will be mounted inside the unit to allow the chassis to be mounted and for the instrumentation to be easily connects. A measurement device for reading inlet air velocity will be added in for proper analysis.

In addition to the instrumentation and components for the DAQ system, an EES program using first and second law analysis will be created. This will allow for comparison between calculated and measured results.

The outcomes for this project will be a laboratory report for student use, our final report, and our final poster presentation. Throughout the semester there will be formal and information PowerPoint presentations, informing the other teams in our course section. This will improve our

presentation skills, our ability to convey technical information and to solve problem and innovate through group discussion.

5. **PROJECT PLAN**

The responsible parties of this senior capstone project are Matthew Dietter, Kyle Lavoie, Jonathan Sewell, and Kurtis Madden. Our mentors throughout the semester will be Professor Anthony Duva and Professor Haifa El-Sadi of the Mechanical Engineering & Technology department at Wentworth.

Our team's qualifications are primarily from major/minor courses along with work experience. Each of the group members is majoring in mechanical engineering and minoring in aerospace engineering which has given a wide range of courses that apply directly to this project. Resumes of each team member are attached in Appendix B.

Due to the location of the mini gas turbine in the thermodynamics lab, the vast majority of our meetings and working sessions will and have occurred there.

This project will be graded on the ability for this system to be used by students as a laboratory experiment. This goal entails that the DAQ system is fully functional and outputting data correctly, the turbine system is calibrated and producing repeatable data, and there is a tangible laboratory experiment ready for student use.

The work plan process we have used has been consistent from the start of this project. Our team created a Microsoft Project file and have been revising it consistently with respect to our current and projected timelines. Professor Duva has been mentored us on how a realistic timeline functions and how to estimate lead times for various tasks.

The Gantt chart for this capstone project has been an ever-changing reference, updated at nearly every meeting to correspond with the current timeline of our capstone project. Below in Figure 4 is our final detailed Gantt chart.

#	Task Name	Duration	Start	Finish	Predecessors
1	System				
2	Evaluate & understand system and hardware	6 days	Tue 5/17/16	Tue 5/24/16	
3	Continuation of task identification	0 days	Thu 5/19/16	Thu 5/19/16	
4	Test all channels/write labview program	3 days	Sun 5/22/16	Tue 5/24/16	
5	Label Everything (DAQ, System)	3 days	Sun 5/22/16	Tue 5/24/16	
6	Instrumentation & Labview programming	22 days	Wed 5/25/16	Thu 6/23/16	
7	Create LabVIEW program to test	16 days	Thu 6/2/16	Thu 6/23/16	
8	Implement new DAQ system	15 days	Tue 6/14/16	Mon 7/4/16	17
9	Connect pressure and temp wiring to new DAQs	14 days	Wed 6/15/16	Mon 7/4/16	10
10	Mount DAQs to Bracket	1 day	Tue 6/14/16	Tue 6/14/16	
11	Formal Proposal Report	3 days	Tue 5/31/16	Thu 6/2/16	
12	Individual portions	3 days	Tue 5/31/16	Thu 6/2/16	
13	Laptop mounting arm	6 days	Wed 6/8/16	Wed 6/15/16	
14	Mounting block print to Jason	1 day	Wed 6/8/16	Wed 6/8/16	
15	Mount laptop arm	1 day	Thu 6/9/16	Thu 6/9/16	14
16	Secure laptop on arm	4 days	Fri 6/10/16	Wed 6/15/16	15
17	Bracket	15 days	Wed 5/25/16	Tue 6/14/16	
18	Measure & Model System	3 days	Wed 5/25/16	Fri 5/27/16	
19	Design Bracket	3 days	Mon 5/30/16	Wed 6/1/16	18
20	Manufacture Bracket	10 days	Wed 6/1/16	Tue 6/14/16	19
21	Raw material	4 days	Thu 6/2/16	Tue 6/7/16	19
22	Labor & mount to system	5 days	Wed 6/8/16	Tue 6/14/16	21
23	Order Hardware (to mount bracket,DAQs)	5 days	Thu 6/2/16	Wed 6/8/16	19
24	EES	36 days	Thu 6/9/16	Thu 7/28/16	
25	Lay groundwork with textbook and EES Turbine model	11 days	Thu 6/9/16	Thu 6/23/16	
26	1st & 2nd Law	28 days	Tue 6/21/16	Thu 7/28/16	
27	Running, Testing & Calibration of System	20 days	Mon 7/4/16	Fri 7/29/16	
28	Preparation to run system - Prof Duva & Lab techs	9 days	Tue 7/12/16	Fri 7/22/16	
29	RPM	14 days	Thu 7/7/16	Tue 7/26/16	
30	Thrust	14 days	Mon 7/11/16	Thu 7/28/16	
31	Testing/Results				
32	New Lab for 1st and 2nd Law	12 days	Mon 7/25/16	Tue 8/9/16	
33	Run system to verify function	6 days	Mon 7/25/16	Mon 8/1/16	
34	Deliverables	0 days			
35	Midterm Report	11 days	Thu 6/9/16	Thu 6/23/16	
36	Poster	3 days	Thu 7/28/16	Mon 8/1/16	
37	Official Presentation	9 days	Mon 7/25/16	Thu 8/4/16	
38	Lab Report	18 days	Fri 7/15/16	Tue 8/9/16	
39	Final Report	37 days	Mon 6/20/16	Tue 8/9/16	
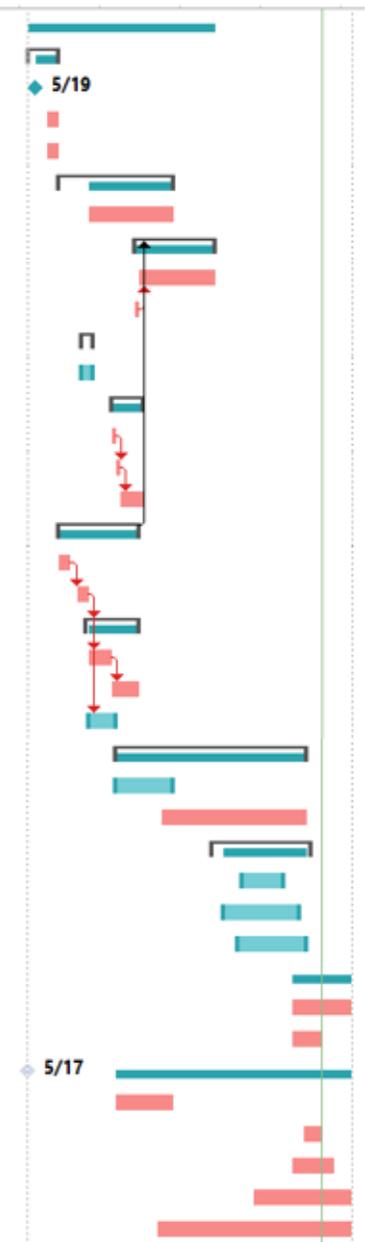
Figure 4. Project Gantt Chart

The following is a description of the budget for this project. Purchased parts for revamping the DAQ system will be the primary cost during this project. The LabVIEW and EES software is provided so there will be no additional cost for software. The budget breakdown is as follows:

- 1 Lenovo T440p computer - $1595
- 1 computer stand - $55
- 2 National Instrument SB-68 - $341 each
- 2 National Instrument USB-6251 - $2,053 each
- 1 12" x 24" steel sheet metal - $30
- Miscellaneous, i.e. wiring, adhesives… - $100

According to the items listed above, the total budget for this project is $6718. Labor will be performed by all group members and Wentworth faculty, therefore there will not be any additional cost for work done. Consultation with Professor Duva and Professor El-Sadi will also not incur any additional cost. Altogether, the budget will be fully funded by the Mechanical Department of Wentworth Institute of Technology.

The future of this project's successful completion includes the use of the fully functional turbine engine as a thermodynamics laboratory experiment for mechanical engineering students. Future students will be able to run the engine and collect data in order to calculate the efficiency of the engine. In addition, the EES program will provide students a secondary tool to perform an analysis on the engine. A goal of this project is to be able to obtain consistent results.

6. RESULTS

This section outlines system updates including a new computer system, new hardware mounting system, new instrumentation, data acquisition hardware, instrumentation calibration, LabVIEW software, engine testing overview and experimental data, and Engineering Equation Solver (EES) analysis.

6.1. System Updates

System updates include a new computer system, new hardware mounting system, select new instrumentation.

6.1.1. Computer System

One of the first updates was mounting the new laptop and monitor securely to the system. It was important that they were mounted rigidly and looked professional since this is a direct user to system interface. A laptop mount was purchased which came with an adjustable arm and mounting bracket. Since the sheet metal housing for the engine is not very rigid, a thicker mounting block was made to strengthen the mount. Figure 5 below shows the design of the mount. Figure 6 below shows the entire system mounted and installed.
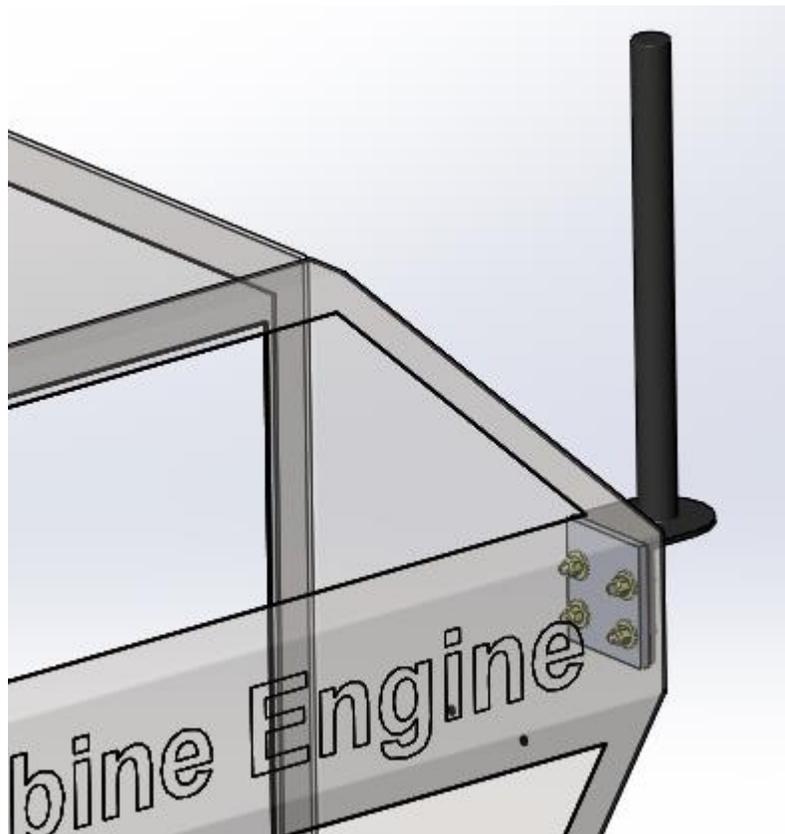
Figure 5. Computer Mount Design

Figure 6 below shows the laptop system mounted and installed.
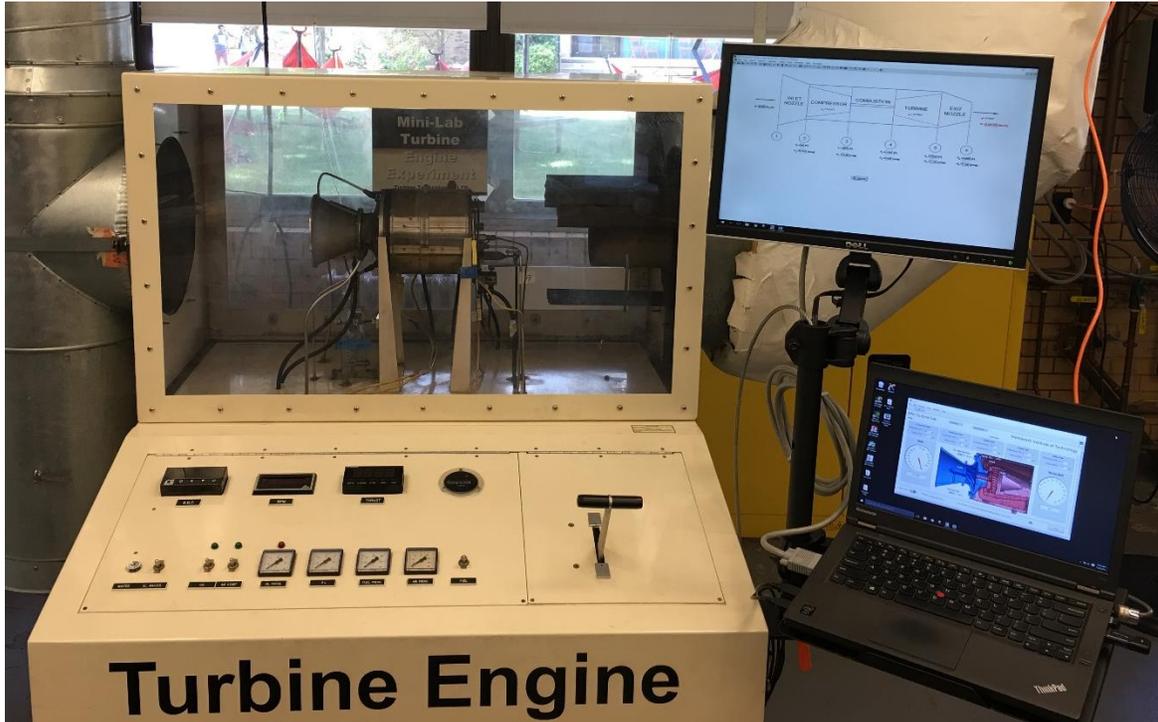
Figure 6. Laptop and Monitor Installed

Lastly, a panel was made to cover the opening where the access to the old DAQ was. This was simply a piece of aluminum sheet metal cut to size and painted to match the rest of the sheet metal housing. Figure 7 below shows the cover panel installed on the system.

Figure 7. Chassis Cover Panel

6.1.2. Hardware Mounting

Removing all of the old DAQ components and mounting the new DAQ was another major task in the system update. Since the new DAQ has several additional components which are much larger than the old system a much larger mounting bracket was necessary. After modeling all of the current system components in SolidWorks, a sheet metal bracket was designed to fit all of the DAQ components without interfering with any of the existing surrounding components. Figure 8 below shows the old DAQ setup.
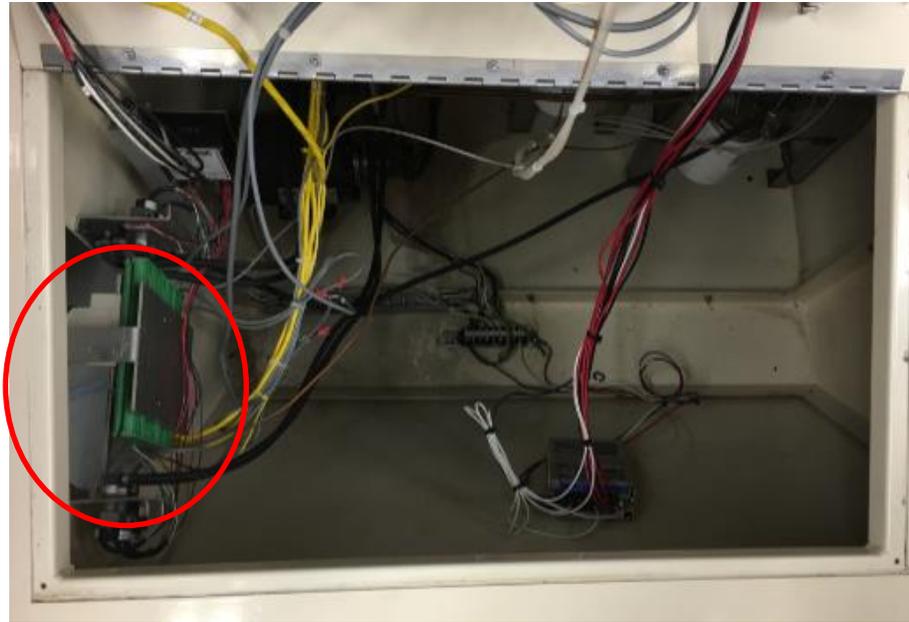
Figure 8. Old DAQ Setup

Figure 9 below shows the design of the new DAQ setup.
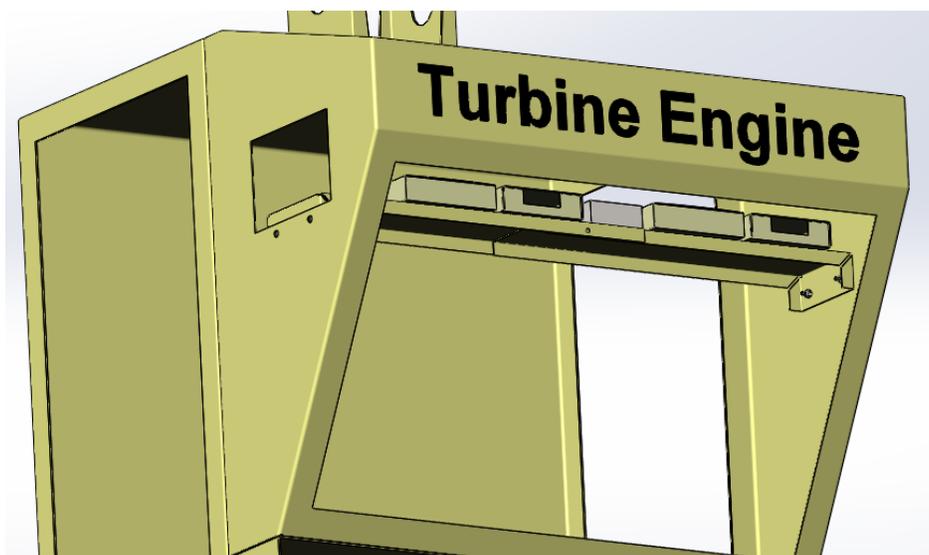
Figure 9. New DAQ Design

Figure 10 below shows the final mounting of the new DAQ system.

Figure 10. DAQ Components Installed

6.1.3. <u>New Instrumentation</u>

During the course of this project, there were many sensors that needed to be changed or added. The preexisting DAQ system was capable of collecting temperature and pressure readings from the various mini-turbine engine stages; however, there was room for improvement. One of the main additions made to the instrumentation was implementing a new pressure transducer to read the static pressure at the inlet of the nozzle. The pitot-static mast style device can be seen below in Figure 11:
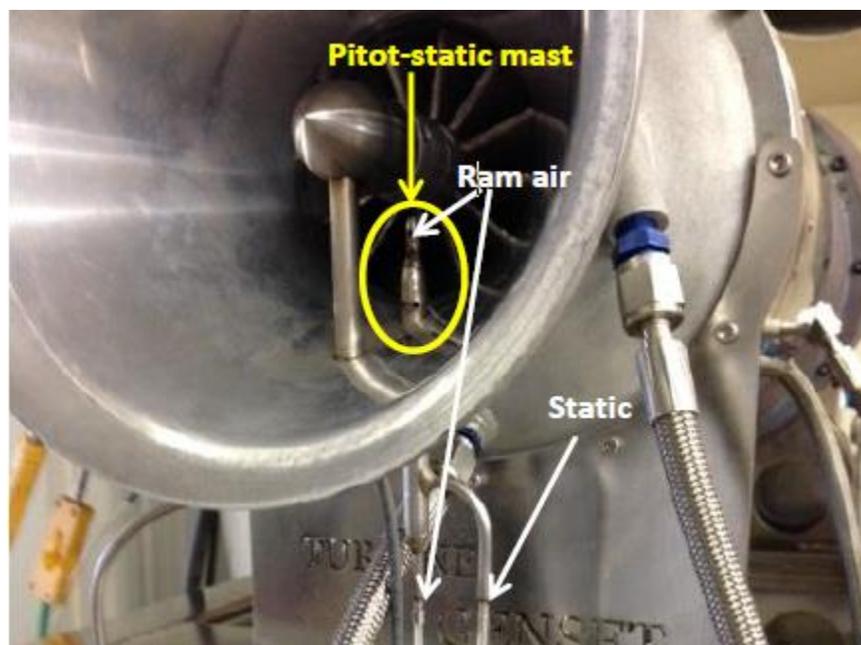
Figure 11. Inlet Pitot Tube Current Set-Up

The preexisting set-up had both the dynamic and static pitot lines attaching to the P1 pressure transducer. This allowed for the correct differential pressure to read; however, velocity could not be calculated due to the unknown density. By being able to read the static pressure, correct velocity

can be calculated using the know density at the static pressure and Bernoulli's equation. In order to get the correct static pressure reading from the preexisting set-up, the static tube was to be teed off and attached to a PX139 pressure transducer. The other port on the PX139 was be left open to the atmospheric air within the housing. Below in Figure 12, the new transducer and set-up can be seen:
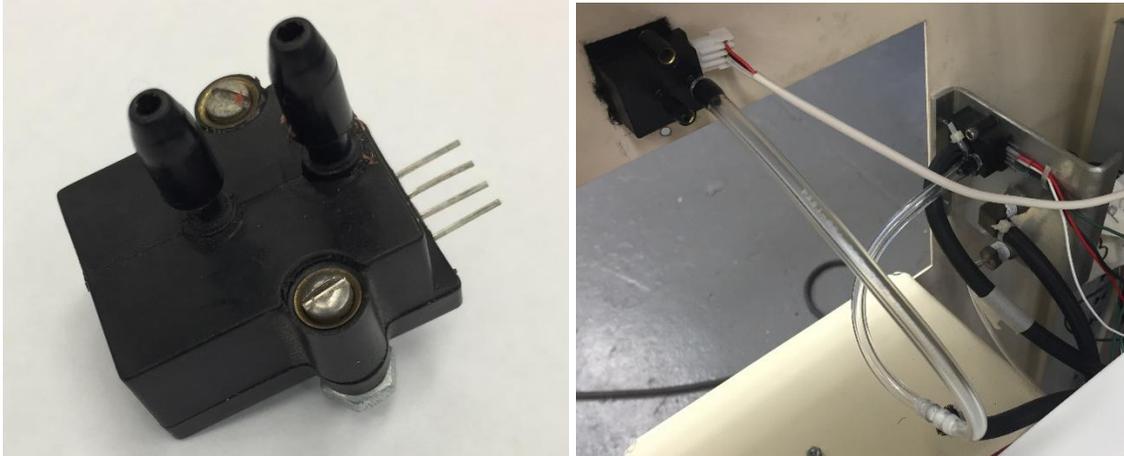
Figure 12: PX139 Pressure Transducer

In addition to a new pressure transducer, three thermocouples had to be replaced. Part of the process of implementing the new DAQ system was to test each instrumentation component individually to ensure they were functioning properly. When testing thermocouples T3 (Turbine Inlet), T4 (Turbine Exit), and T5 (Exhaust Gas) there was significant noise experienced. After isolating each thermocouple from the engine and ruling out broken wires as the cause, it was determined that the noise was a result of ground loops and crosstalk. To relegate this issue, various grounding methods, including sheath grounding, were tested without success. It was ultimately decided that the thermocouples experiencing the issue needed to be replaced completely with a different type. The three main types of thermocouples can be seen below:
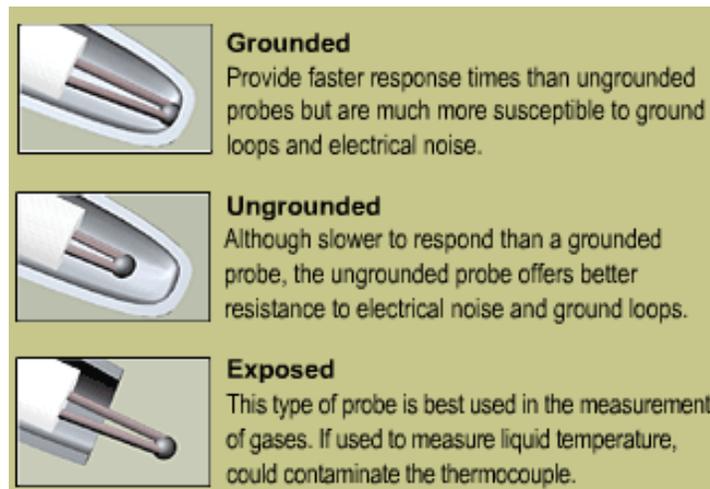
Figure 13. Thermocouple Types

The three thermocouples which had been experiencing the grounding issues were determine to be of the grounded type. The grounded type has its wire touching the sheath which is what resulted in the ground loops and electrical noise. To fix the noise issue, the turbine inlet (T3) thermocouple and the turbine exit (T4) thermocouple were replaced with an ungrounded type of the same size. The exhaust gas temperature thermocouple was also replaced. The thermocouple selected was an exposed type which responds quickly (EGT is a critical temperature) and does not experience electrical noise. The specifications for the new thermocouples are as follows:

Table 2. New System with Signal Conditioning Parameters

Thermocouple Location	Style	Connector	Calibration	Sheath	Length (in)	Diameter (in)	Junction	Omega Model
T3 - Turbine Inlet Temperature	Quick Disconnect	Standard	K	SS	12	0.125	Ungrounded	KQSS-18U-12
T4 - Turbine Exit Temperature	Quick Disconnect	Mini	K	SS	12	0.125	Ungrounded	KMQSS-125U-12
T5 - Exhaust Gas Temperature	Quick Disconnect	Mini	K	SS	6	0.125	Exposed	KMQSS-125E-6

6.2. Data Acquisition

Data acquisition includes DAQ hardware description, instrumentation calibration, and LabVIEW software description.

6.2.1. DAQ Hardware

The basis of this project is to transition from the outdated TBX-68T and old software which is no longer supported, to the new hardware and supported LabVIEW software. The hardware chosen for the task are the NI SCB-68 and NI USB-6251. Two of each have been implemented in the DAQ system.
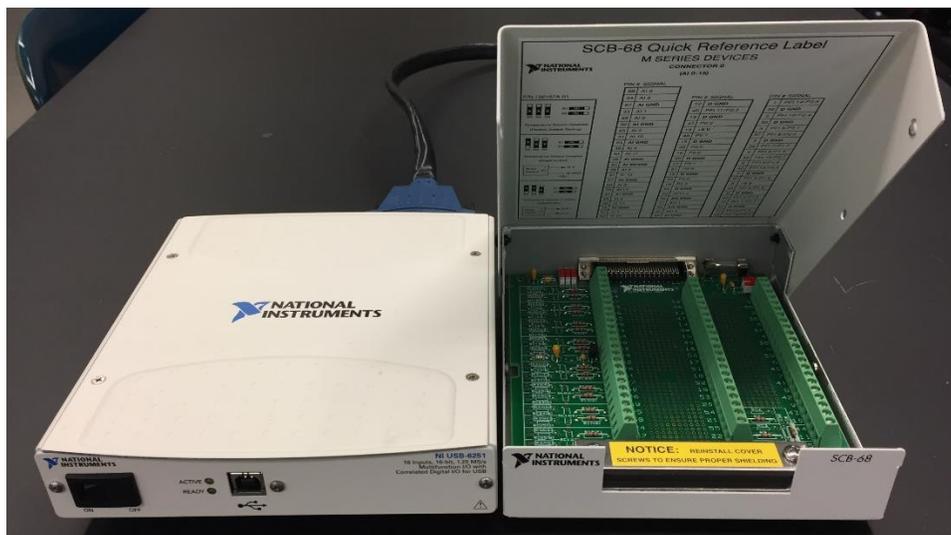
Figure 14: NI USB-6251 (left) and NI SCB-68 (right)

One NI SCB-68 and NI USB-6251 will be dedicated to thermocouple temperature readings, and the other to pressure transducer readings and other voltage readings. The NI SCB-68 allows for single-ended and differential temperature measurements to be made. For the temperature readings to be made, the differential temperature mode will be used as it is more accurate than single-ended. In order to perform this, the SCB-68 needs to be configured for temperature reference to be enabled within LabVIEW. This will allow for the built-in Cold Junction Compensation of the SCB-68 to be utilized. The built-in Cold Junction Compensation temperature sensor can be seen below in as well as AI channels to be utilized can be seen in Figure 15 below.

1	+5 V Power Pads R20 and R21	5	Fuse	9	Analog Output Pads
2	Switches S3, S4, and S5	6	Switches S1 and S2	10	Analog Input Pads
3	68-Pin I/O Connector	7	Screw Terminals	11	Temperature Sensor
4	Breadboard Area	8	PFI 0 Pads		
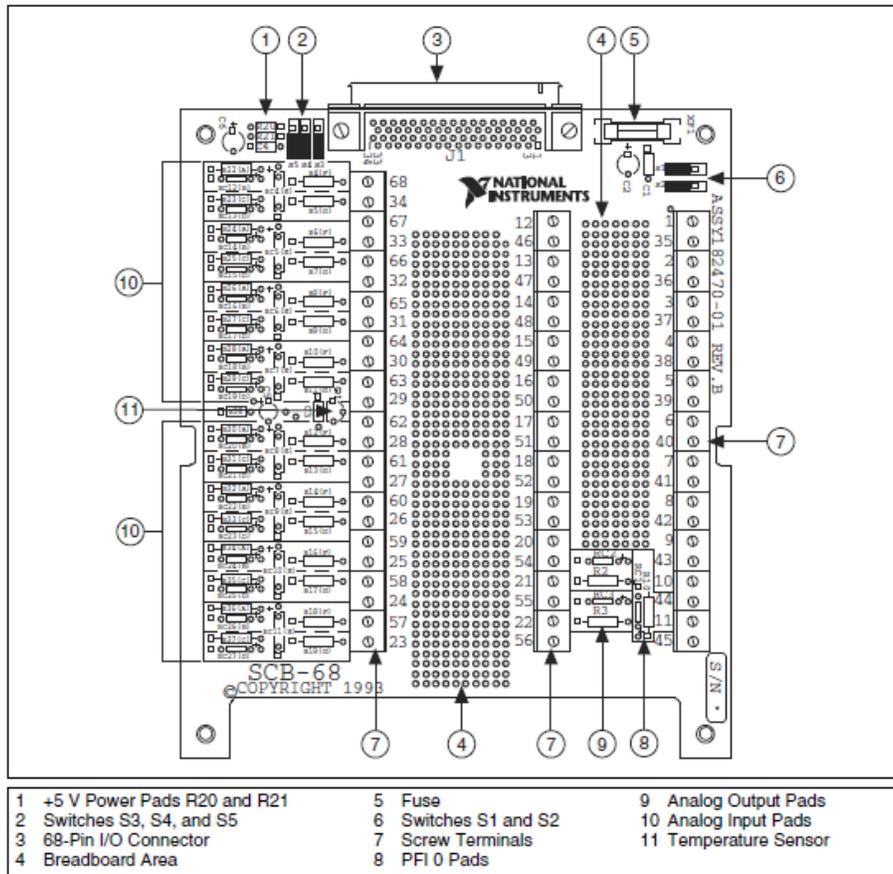
Figure 15: SCB-68 Printed Circuit Board Diagram

 For measurements using pressure transducers and other instrumentation, the SCB-68 will be in the factory default setting for correct voltage readings. The PX139 pressure transducer will be attached to the built-in +5V power supply within the SCB-68. The instrumentation that will also be attached to this chasses consist of the RPM and thrust indicators. Each of the SCB-68 has 8 different AI channels that can be used for instrumentation; between the two a total of 16 devices can be connected.

While attempting to calibrate the thrust strain gauge, significant noise to the NI chassis was experienced. The pre-existing set-up had the wires from the strain gauge splitting between the meter and the NI chassis. While the out-put signal from the strain gage was filtered through the DP25-S, it was not filter through the NI chassis. To remedy the issue, the DP25-S was replaced

20

with a DP25-S-A which had the correct analog signal output. With the new signal analog signal output, there was no noise experienced from the thrust strain gage and meter. Below the new meter can be seen:

Figure 16. New Thrust Display

6.2.2. Instrumentation Calibration

The instrumentation on the turbine engine, including new sensors, are shown below in Table 3. Also listed in Table 3 are the signal conditioning parameters and calibration curves for each sensor. New sensors, or replaced sensors, from the existing instrumentation list contain a new sensor part number in the Measurement Type column.

Table 3. Instrumentation Parameters and Calibration

AI	Name	Measurement Type	Range	Calibration m	Calibration b
NI SCB-68 Module 2					
0	Compressor Inlet Press	VDC	0-1 PSIG	67.183	0
1	Compressor Exit Press	VDC	0-6 PSIG	1016	-0.9964
2	Turbine Inlet Press	VDC	0-6 PSIG	1000	0
3	Turbine Exit Press	VDC	0-5 PSIG	101.4	-0.06873
4	Nozzle Exit Pressure	VDC	0-5 PSIG	101.4	-0.06894
5	Compressor Inlet Static Pressure	VDC (Omega PX139-0.3D4V 2G18-21)	0-0.3 PSIG	0.1504	-0.3515
6	Fuel Flow	VDC	0-5 GAL/Hr	83.33	0
NI SCB-68 Module 1					
1	Compressor Inlet Temp	K type	0-2000 ˚C		
2	Compressor Outlet Temp	K type	0-2000 ˚C		
3	Turbine Inlet Temp	K type (Omega KQSS-18U-12)	0-1000 ˚C		
4	Turbine Exit Temp	K type (Omega KMQSS-125U-12)	0-1000 ˚C		
5	Exhaust Gas Temp	K type (Omega KMQSS-125E-6)	0-1000 ˚C		
6	Thrust	VDC	0-25 Lbs	12.135	-24
7	RPM*	VDC	9.484E4-2.720E-1	258226	38687

* Further scaling performed – see RPM calibration below

Thermocouples

Thermocouples do not have custom scaling curves; they are configured within the data acquisition board (NI SCB-68) as well as within the LabVIEW DAQ Assistant. For correct temperature readings, "Temperature Sensor Enabled" has to be set on the SCB-68 and the Cold Junction

Compensation has to be set to "Built-In" in LabVIEW. In addition, within LabVIEW, the thermocouple setup is set to type K.

RPM

Shown below in Figure 17 is the initial RPM calibration curve. This calibration curve is not necessary, but it was set when further calibration was performed – it does not affect the accuracy in any way, but it must be included in the DAQ Assistant prior to further calibration.
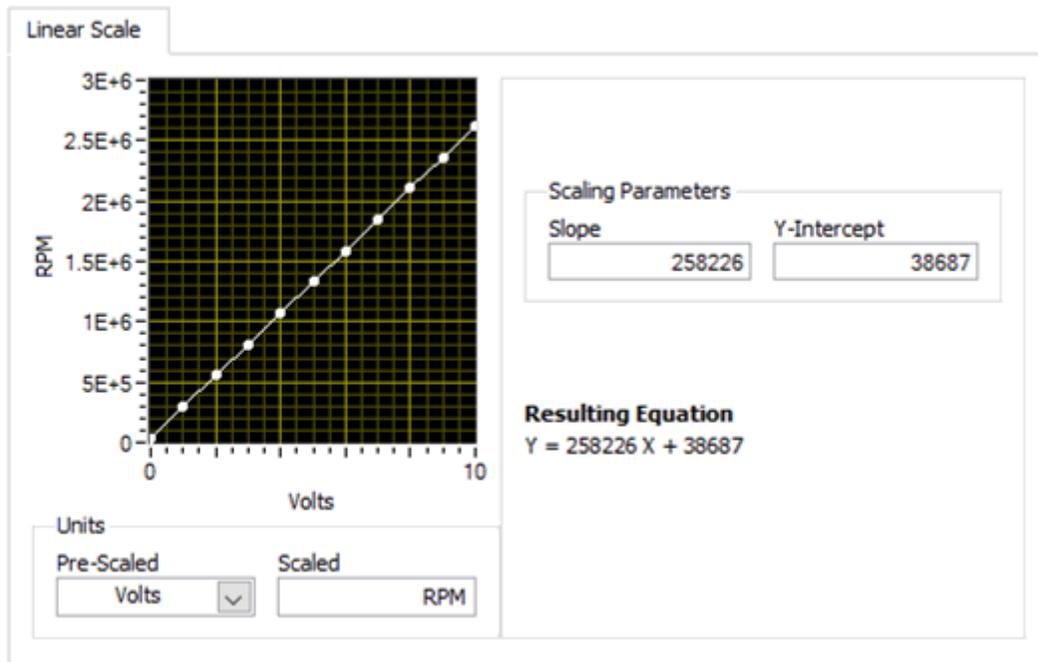
Figure 17. Initial RPM Calibration Curve

The RPM module outputs the RPM on a frequency domain rather than a voltage signal. The frequency of the signal is measured in LabVIEW and is manually scaled to correspond with the actual RPM. This calibration curve consists of a slope (m) of 62.65 and a Y-intercept (b) of negative 671.25.
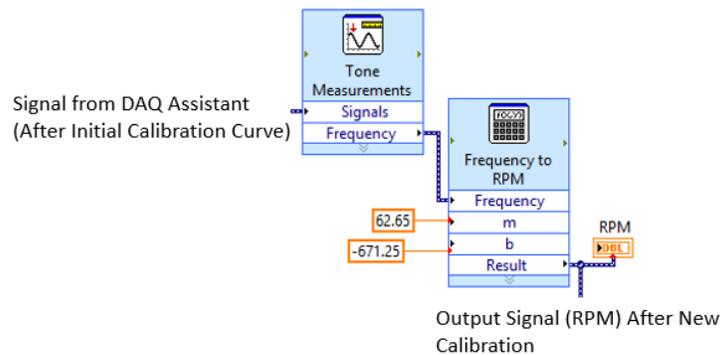
Figure 18. Manual RPM Calibration

Thrust

The calibration curve for the thrust measurement is shown below in Figure 19. This calibration curve was obtained through pull-testing the engine with a scale and determining the corresponding voltage output. The thrust display was calibrated using the device manual which will be contained within a package of this report.
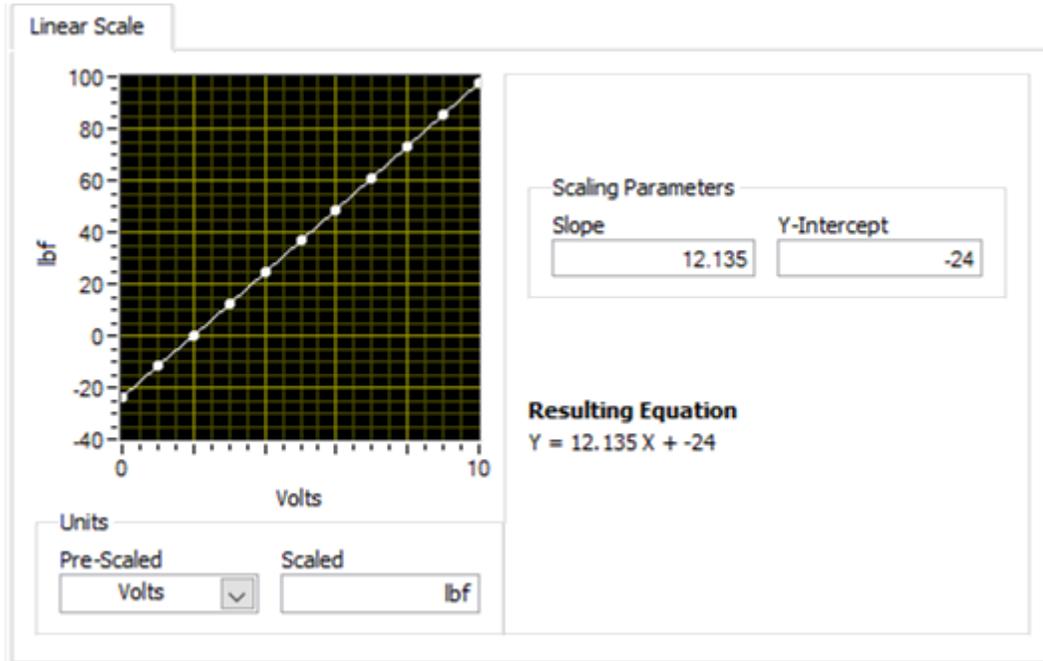
Figure 19. Thrust Calibration Curve

Figure 20. Thrust Calibration Method

Pressure Sensors

All pressure calibration curves remained the same from the existing DAQ system except for the Compressor Inlet Static Pressure and Compressor Inlet Dynamic Pressure sensors. The Compressor Inlet Static Pressure needed calibration because it was a completely new sensor to the

system. In addition, the Compressor Inlet Dynamic Pressure transducer needed calibration because the static pressure was connected into the same hose coming out of the pitot static tube as the Dynamic pressure sensor.

The pressure sensors that were calibrated, were done so using a Pasco Heat Engine. The calibration method includes applying a force on the top of the piston (known weights), calculating the theoretical pressure, and reading the voltage output from the pressure transducer. The relationship between pressure and voltage can then be obtained through a linear trend line. This calibration was verified using a manometer at atmospheric pressure. An example of the Compressor Inlet Static Pressure calibration curve plot is shown below in Figure 21.
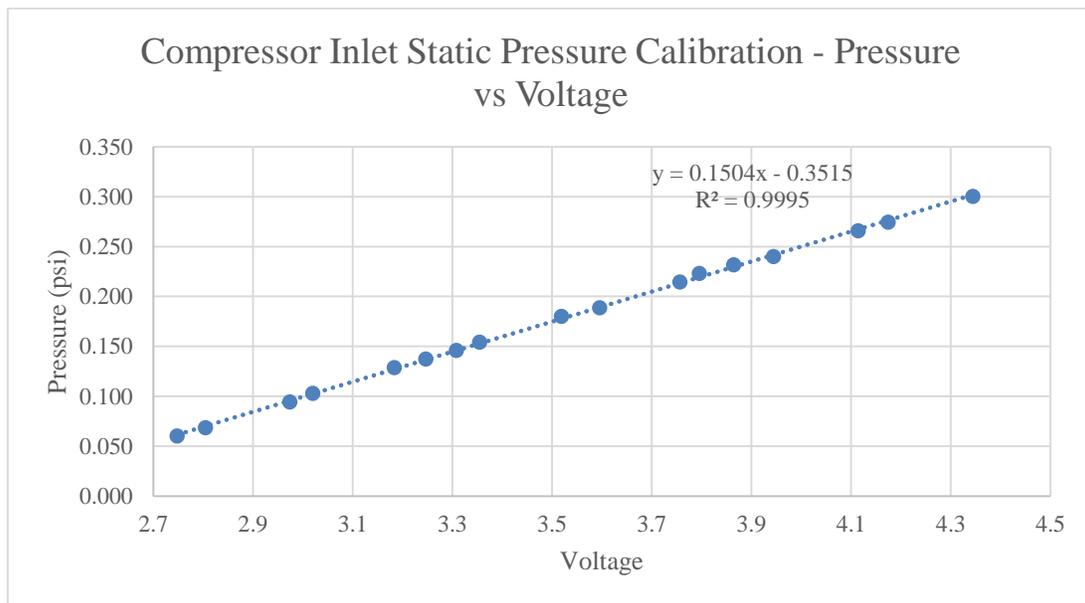
Figure 21. Compressor Inlet Static Pressure Calibration

The Pasco Heat Engine is shown below in Figure 22.

Figure 22. Pressure Sensor Calibration Method

Shown below in Figure 23 through Figure 28 are calibration curves for all main pressure sensors.
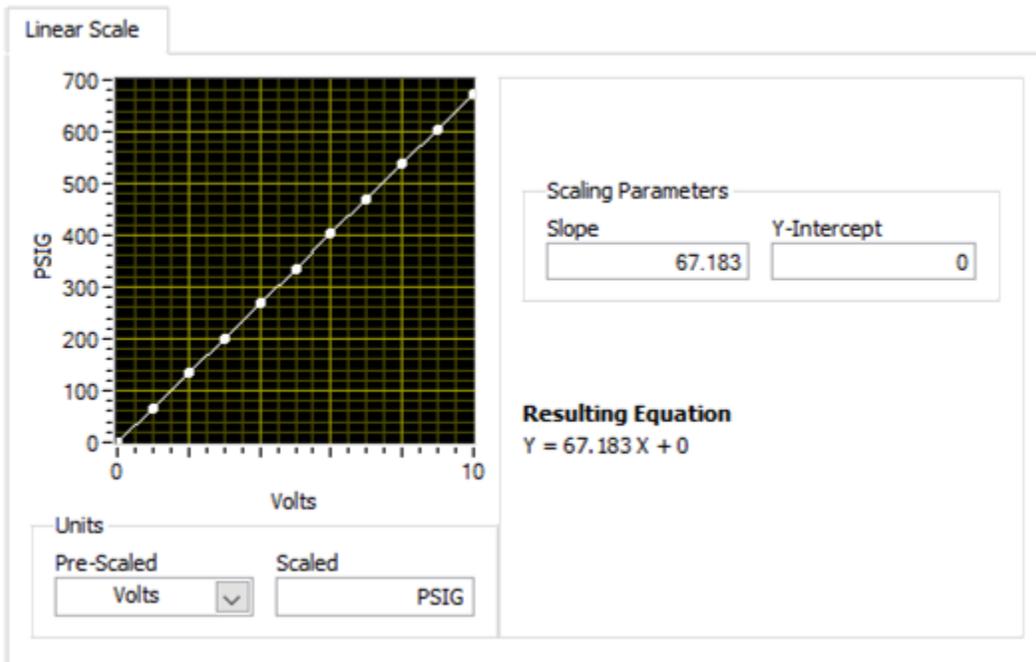
Figure 23. Compressor Inlet Pressure (P1) Calibration Curve
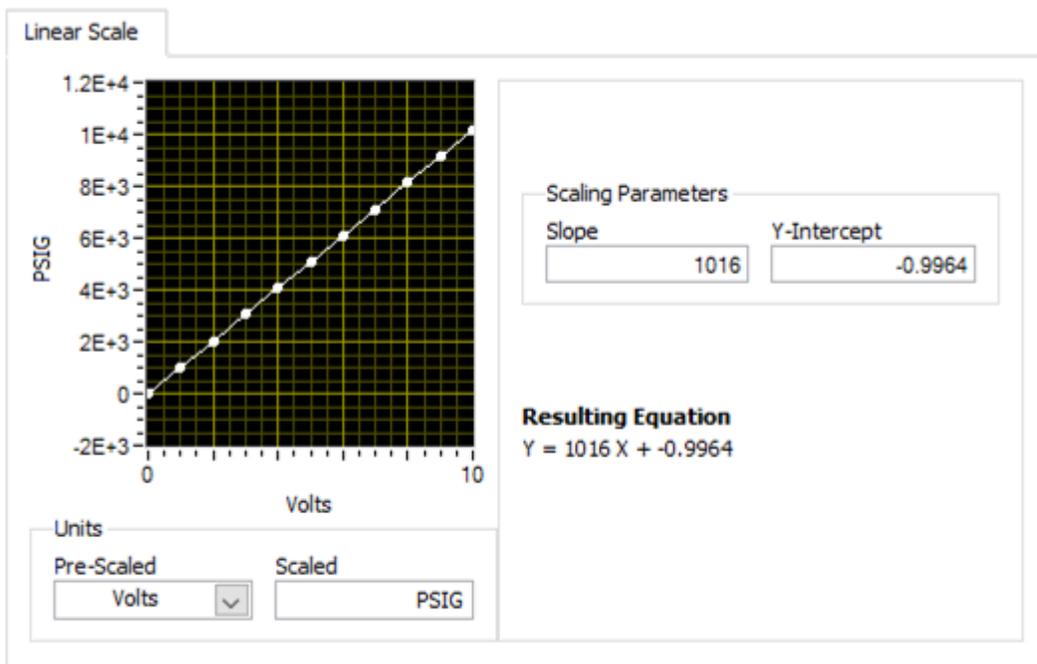
Figure 24. Compressor Exit Pressure (P2) Calibration Curve
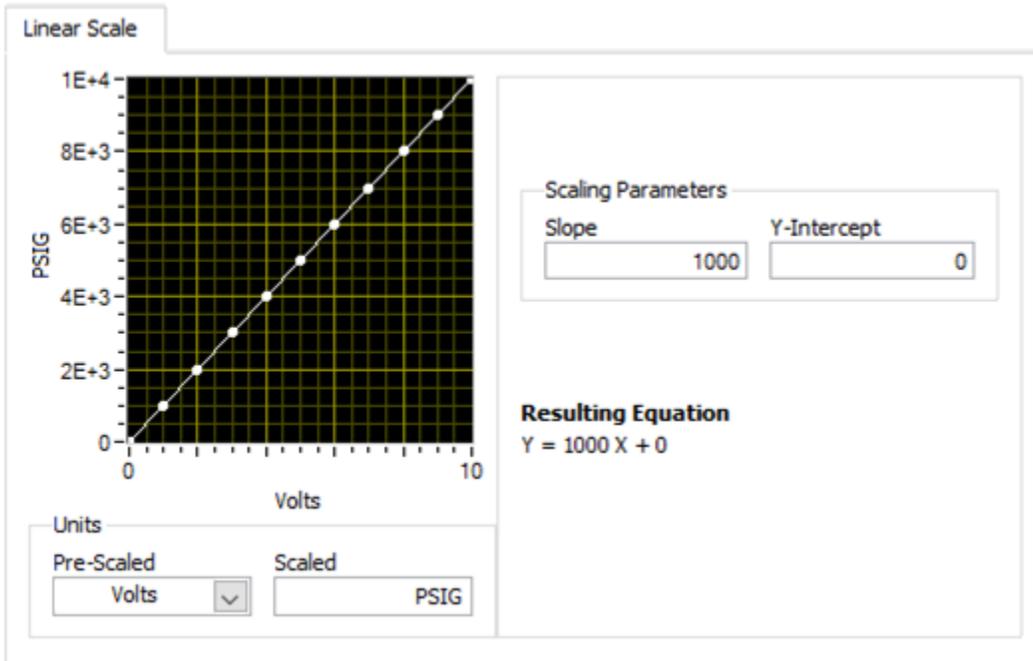
Figure 25. Turbine Inlet Pressure (P3) Calibration Curve
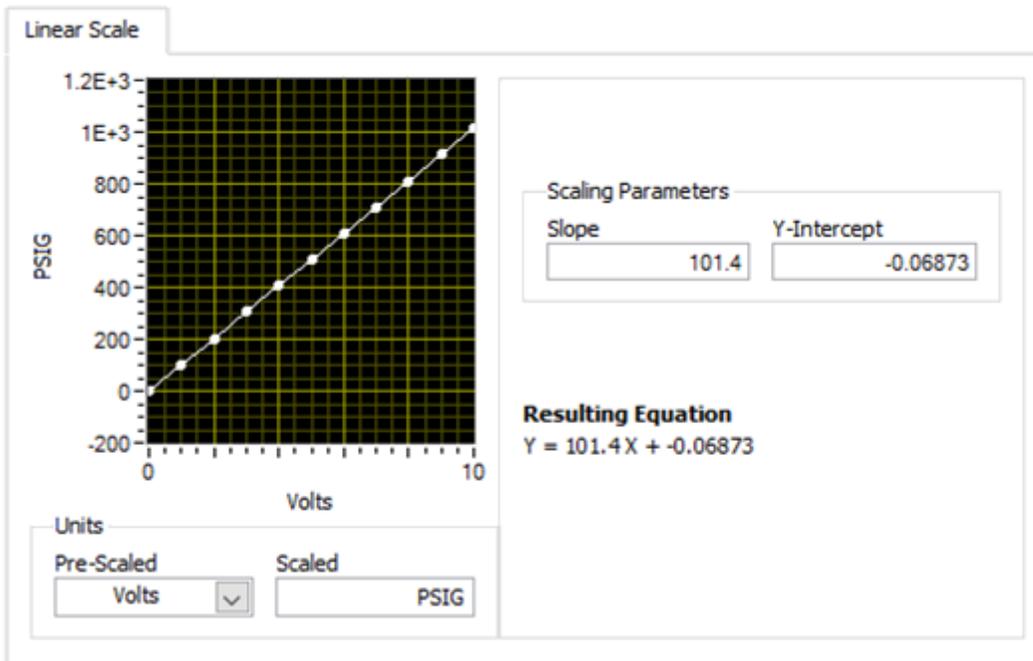
Figure 26. Turbine Exit Pressure (P4) Calibration Curve
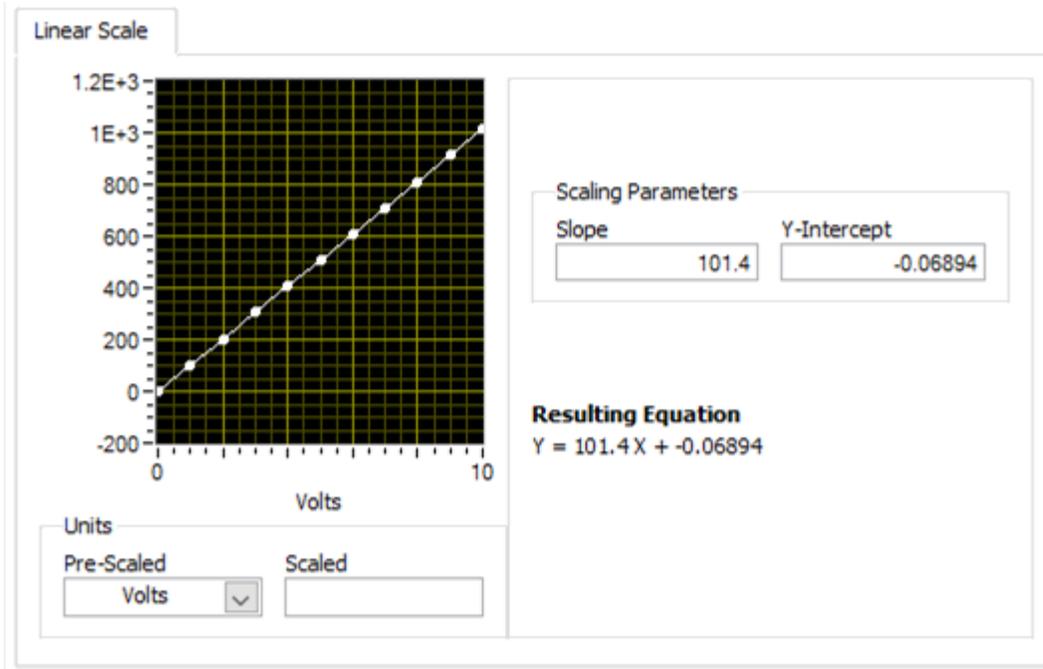
Figure 27. Exhaust Gas Pressure (P5) Calibration Curve

Inlet Mass Flow Rate
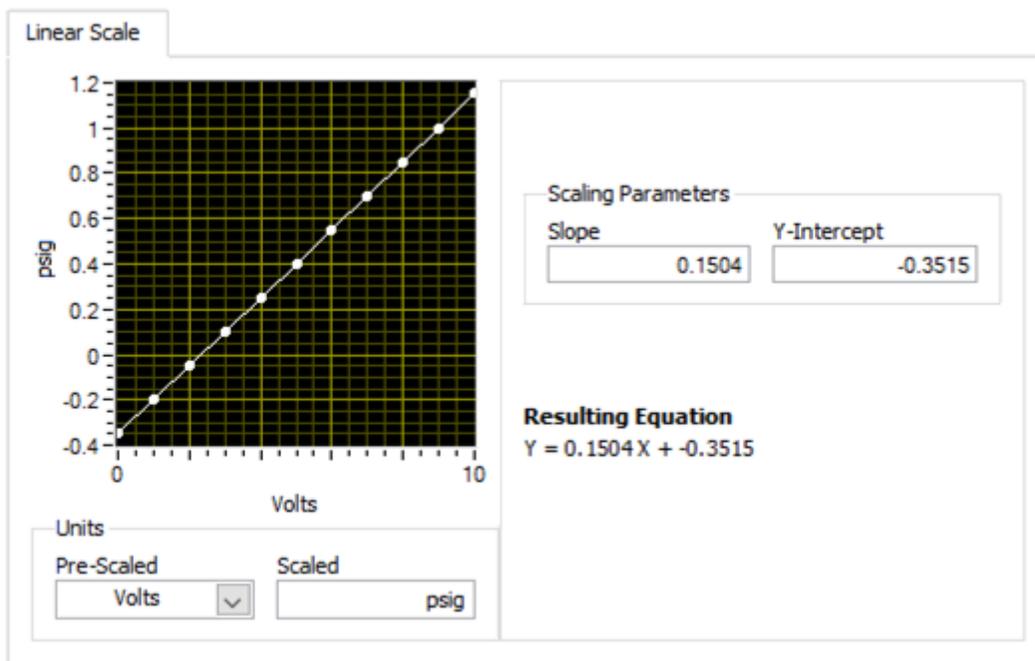
Figure 28. Compressor Inlet Static Pressure Calibration Curve

In order to calculate the Inlet Mass Flow Rate to the turbine engine, the static pressure is needed. The static pressure is obtained by connecting a pressure transducer directly to the static pressure port on the inlet pitot tube. Next, the density of the air is calculated using this static pressure. The

air velocity is calculated next using the Dynamic Pressure which is the difference between the total pressure and the static pressure. The Mass Flow Rate is finally obtained knowing the density, velocity and cross sectional area of the inlet nozzle at the location of the pitot tube. This calculation is performed in the LabVIEW program (Figure 29). See following report section for mass flow rate governing equations.
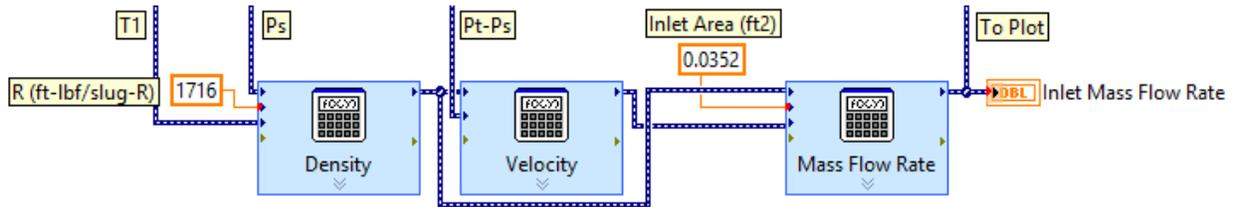
Figure 29. Mass Flow Rate Calibration

The fuel flow rate is determined from measuring the fuel pressure. If the fuel pressure as well as the fuel properties are known, the flow rate can be determined. The fuel flow rate calibration curve is shown below in Figure 30.
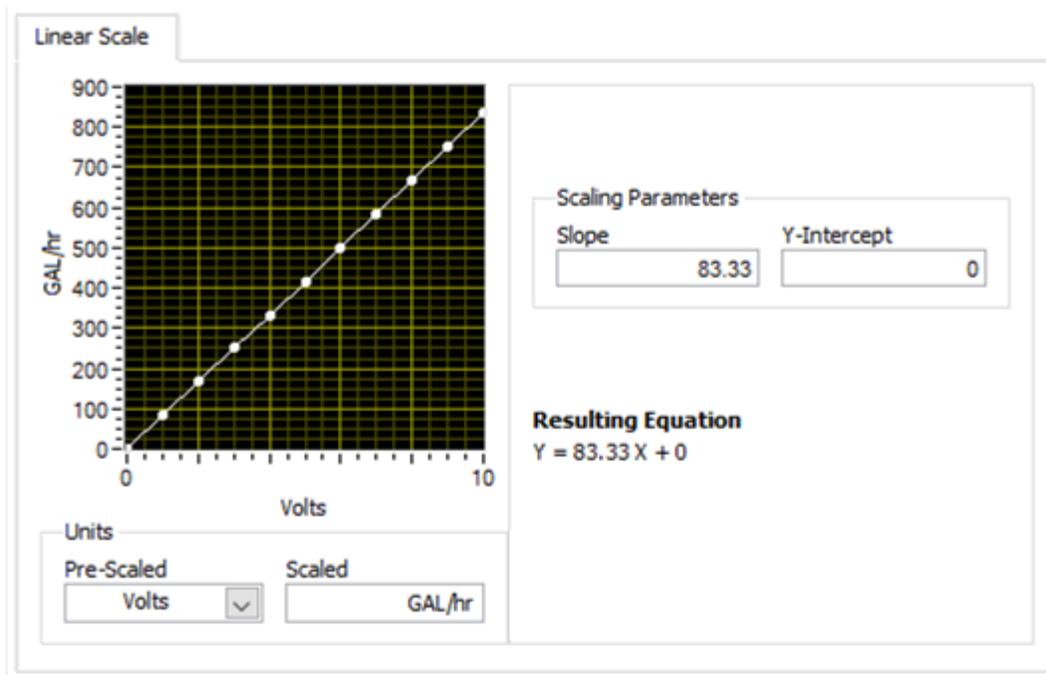
Figure 30. Fuel Flow Rate Calibration Curve

6.2.3. LabVIEW Software

Acquiring data from the new instrumentation system on the turbine engine is performed through a LabVIEW program. LabVIEW is installed on the new computer that has been installed onto the engine system. Users of this program will easily be able to acquire all necessary data in order to perform a thermodynamic analysis on the engine.

The user interface of the LabVIEW program includes a front panel that contains two main interfaces – the "Main" tab which includes numerical values for each sensor on the engine as well as a diagram indicating the location of each sensor, and a "Plot" tab which includes a graph in which the user can determine what quantities are plotted.

This program is installed onto the lab computer as an executable application. The result of this is such that the code controlling the program cannot be modified directly. If changes are needed in the program, the original source code will need to be modified and a new application will need to be created. This is done through the VI – "Tools" > "Build Application (EXE) From VI".

When the program is opened, live data values will begin displaying on all indicators and graphs. It is important to note, that due to the nature of the RPM sensor it will not read an accurate value until the engine beings spinning at several hundred RPM. This can be tested through the air start on the engine chassis.

An option is available to toggle data collection on and off. The default value is off. First, a filename and save location need to be inputted. Next, the "Collect Data" option will need to be pressed to begin data collection and data collection will end once it is disabled. The next time the "Collect Data" toggle is enabled, if the user does not update the filename, a new filename will be created with a sequential number added to the end. This will help avoid overwriting existing data files created by the user.

Figure 31 below shows the LabView main tab layout of the DAQ display.
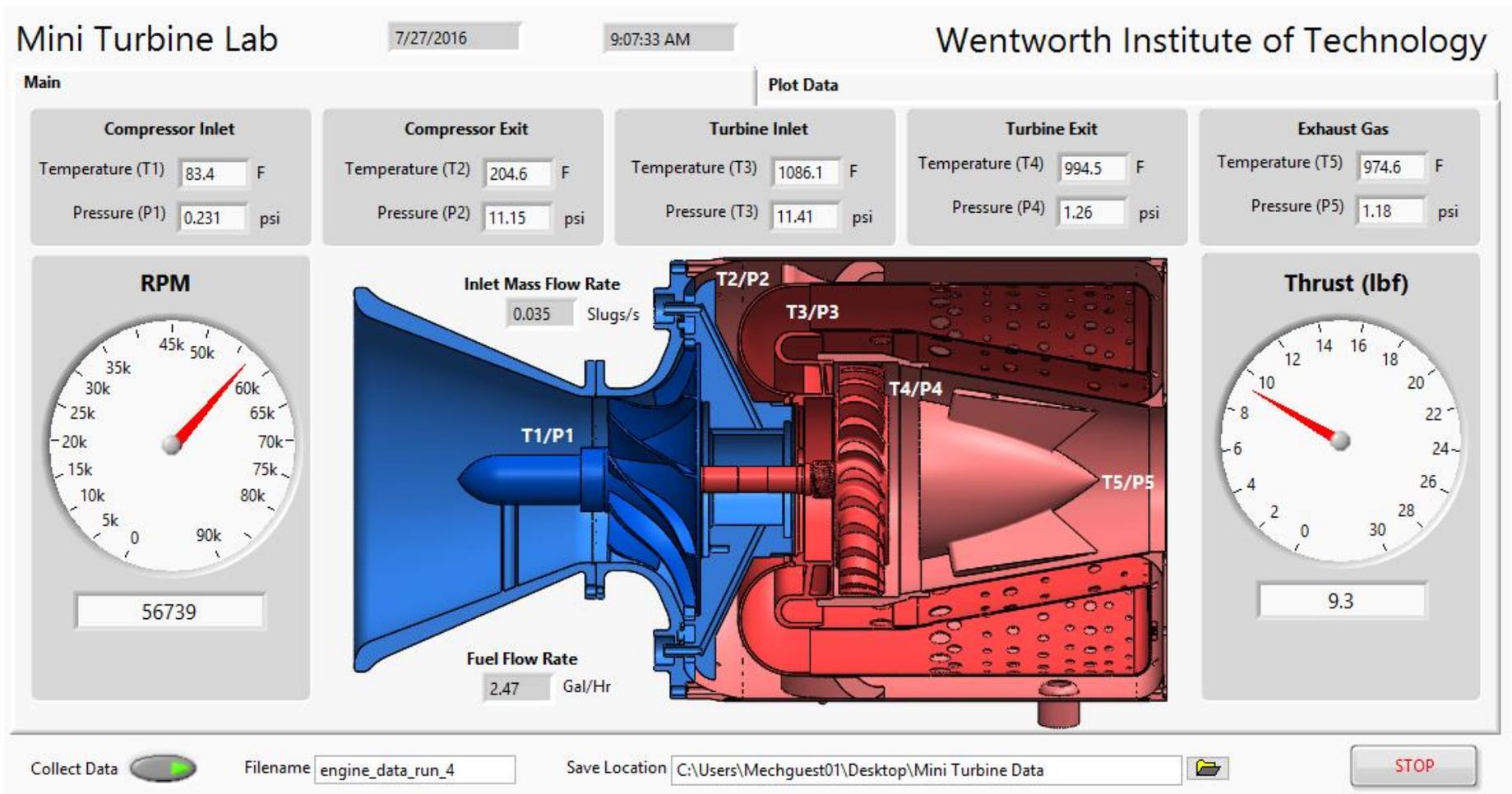
Figure 31. LabVIEW Data Acquisition Front Panel User Interface (Main Tab)

Figure 32 belows shows the LabView plot tab layout of the DAQ display.
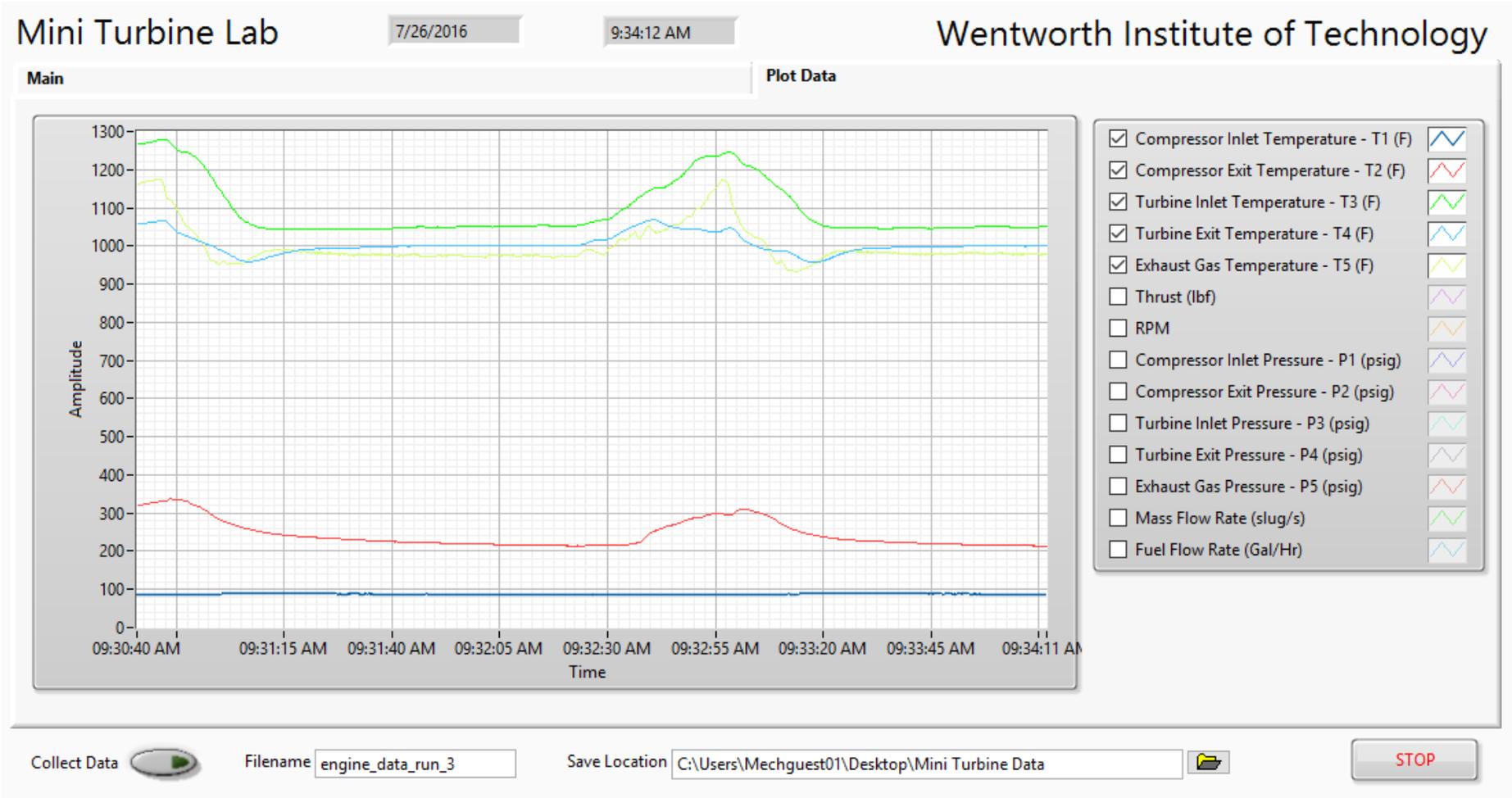
Figure 32. LabVIEW Data Acquisition Front Panel User Interface (Plot Tab)
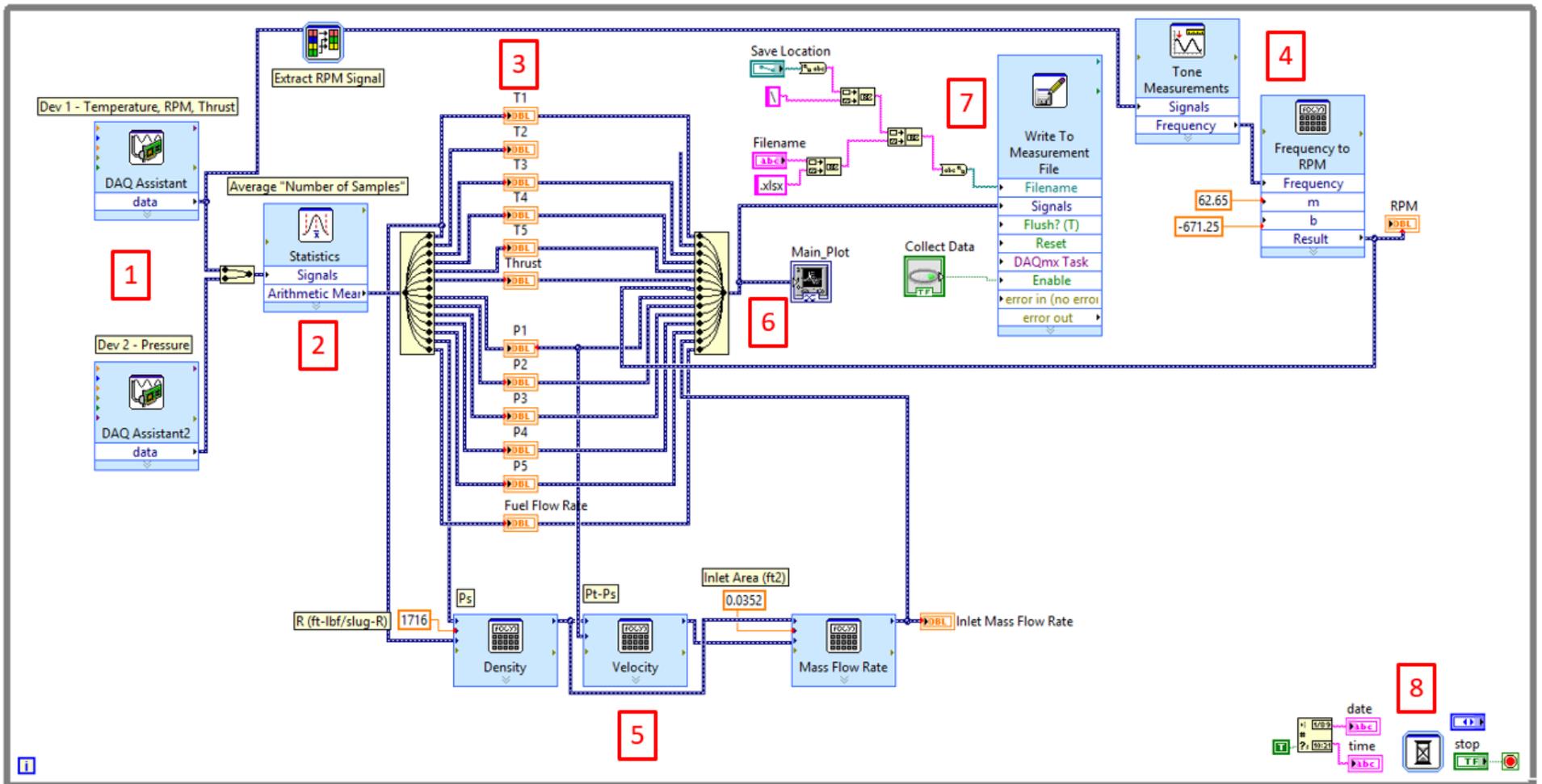
Figure 33. LabVIEW Block Diagram

Shown above in Figure 33 is the LabVIEW program block diagram. The structure of the program is such that the code is all contained within a while loop. The while loop will run the code until a condition is met. The condition is true until the "Stop" button on the front panel is pressed, sending a false Boolean signal to the case structure. The following sections describe the corresponding red labels on the above figure.

1. The data is acquired through the LabVIEW Express functions, DAQ Assistant. There are two DAQ Assistant functions, each corresponding to the two NI SCB-68's. Within the DAQ Assistant, signal parameters are set such as Number of Samples, Sampling Rate, Terminal Configuration, Scaling, and Acquisition Mode. In order to simplify further signal processing, both DAQ Assistants are set to 1000 Samples to Read at a rate of 10,000 Hz with an Acquisition Mode set to "N Samples". All temperature channels are set to degrees Fahrenheit, Thermocouple Type K, with a Built-In CJC Source. All remaining channels are set to Differential Terminal Configuration with the correct Custom Scaling option selected.

2. After the signal leaves the DAQ Assistant, they are averaged using the Express Statistics function. The number of samples that are averaged together correspond to the number of Samples to Read which is set in the DAQ Assistant to be 1000 samples. The arithmetic mean is outputted from the function. Averaging a large sample set helps to remove noise from the signal.

3. The signal leaving the Express Statistics function is a 1D array of Dynamic Data Type Signals. A "Split Signals" function is used to separate the Dynamic signals from the 1D array. The corresponding signals are then brought to their numeric indicators for display on the front panel.

4. All signals, except for RPM, are voltage signals that are scaled to the correct dimension. The RPM signal is a frequency not a voltage. Because of this, further processing of the signal is needed. An Express Select Signals function is used to index the RPM signal from the 1D array of Dynamic signals. The RPM signal is then brought to an Express Tone Measurements function where the frequency of the signal is determined. Through manual calibration, a scale was determined. The frequency output from the Tone Measurements function is then manually scaled to the correct value corresponding to the RPM of the engine. The result is then connected to the RPM numeric indicator for display on the front panel.

5. The Inlet Mass Flow Rate numeric indicator value is calculated, not measured. The calculated value is dependent on the measured values of Compressor Inlet Temperature (T1), Compressor Inlet Static Pressure (Ps), and Compressor Inlet Dynamic Pressure (Pt-Ps). Using Express Formula functions, the density of the air is first calculated, then the velocity of the air is calculated, and finally the Inlet Mass Flow Rate can be calculated. The following equations are contained within these functions for Density (ρ), Velocity (v) and Mass Flow Rate ($\dot{m}$).

$$\rho = \frac{(P_s + 14.7)144}{R(T_1 + 460)} \ (slug/ft^3)$$

$$v = \sqrt{\frac{2P_1 * 144}{\rho}} \ (ft/s)$$

$$\dot{m} = \rho A v \ (slug/s)$$

Where,
A = Compressor Inlet Area
R = Ideal Gas Constant for Air

6. The data leaving the numeric indicators is put back into a 1D array using the Merge Signals function. The merged signal is then brought to a Waveform Chart function to be displayed on the front panel Plot Data tab. The plot on this tab contains an interactive legend in which values can be toggled on or off to be displayed.

7. The same set of merged signals that is going to the Main Plot is also brought to the Express Write to Measurement File function. A file extension is added to the filename string and then concatenated with the Save Location string in order to be valid for the Filename input on the Write to Measurement File function. The Collect Data toggle switch is wired to the Enable input on the Write to Measurement File function.

8. The date and time displayed on the front panel are obtained through the Get Date/Get Time function. A Time Delay function is implemented to control how fast the while loop iterates. This controls how fast values are updated on the front panel. The Time Delay is set to 0.10 Seconds.

6.3. Engine Testing

In order to validate the new DAQ hardware, sensors, and software, the Turbine Engine has gone through several test runs. The following steps illustrate the operating procedure for the Turbine Engine.

1. Prior to engine start-up, ensure the following:
   a. Air compressor is plugged in (located behind engine) and the air compressor pressure gage reads 100 psi or greater.
   b. There is a sufficient amount of fuel in the tank – use dipstick to get fuel level.
   c. The air exhaust vent is running.
2. Rotate key to on position.
3. Turn electrical master toggle switch to on position.
4. Position throttle handle at approximately 50%.
5. Turn ignition toggle switch to on position.
6. Turn air toggle switch to on position and wait until RPM indicator displays approximately 10,000 to 13,000 RPM.
7. Turn fuel toggle switch to on position.

a. If Exhaust Gas Temperature does not begin to increase after approximately 3 seconds, increase throttle position to approximately 60-75%. If Exhaust Gas Temperature still does not begin to increase after approximately 1-2 seconds, turn fuel toggle switch to off position along with the ignition and air toggle switches. Wait for unburned fuel to dry from engine. Consult lab technician for further instructions.
8. Once engine is running, turn air and ignition toggle switches to off position.
9. Back throttle positon off so that the engine idles at approximately 48,000 to 50,000 RPM.

NOTE: Try to keep idle rpm above 48,000 minimum. If hang flame appears behind the exhaust, bring throttle down and then push back up in order to suck flame away.

To spin down and turn off:
1. Position throttle all the way down.
2. Turn the fuel toggle switch to off position.
3. As engine is spinning down, turn the air switch on momentarily to help cool.

A sample set of data collected from an engine test run is shown in Appendix C at the end of this report. This same data is represented below in Figure 34 through Figure 37. These plots contain important characteristics of the engine such as the relationship between engine RPM and Thrust, Temperature, Inlet Mass Flow Rate, and Pressure.
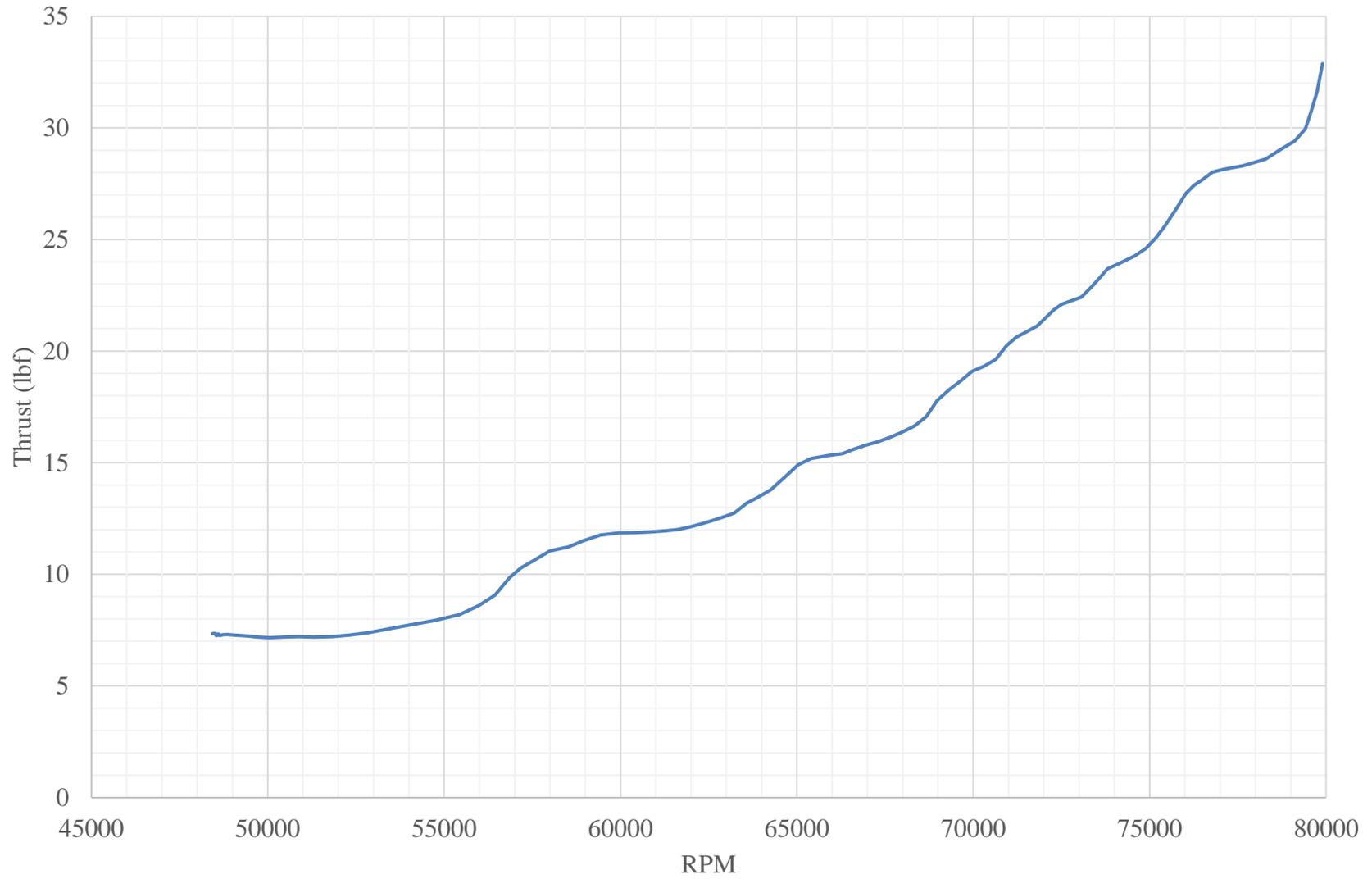
Figure 34. Engine Testing Data Plot – Thrust vs RPM
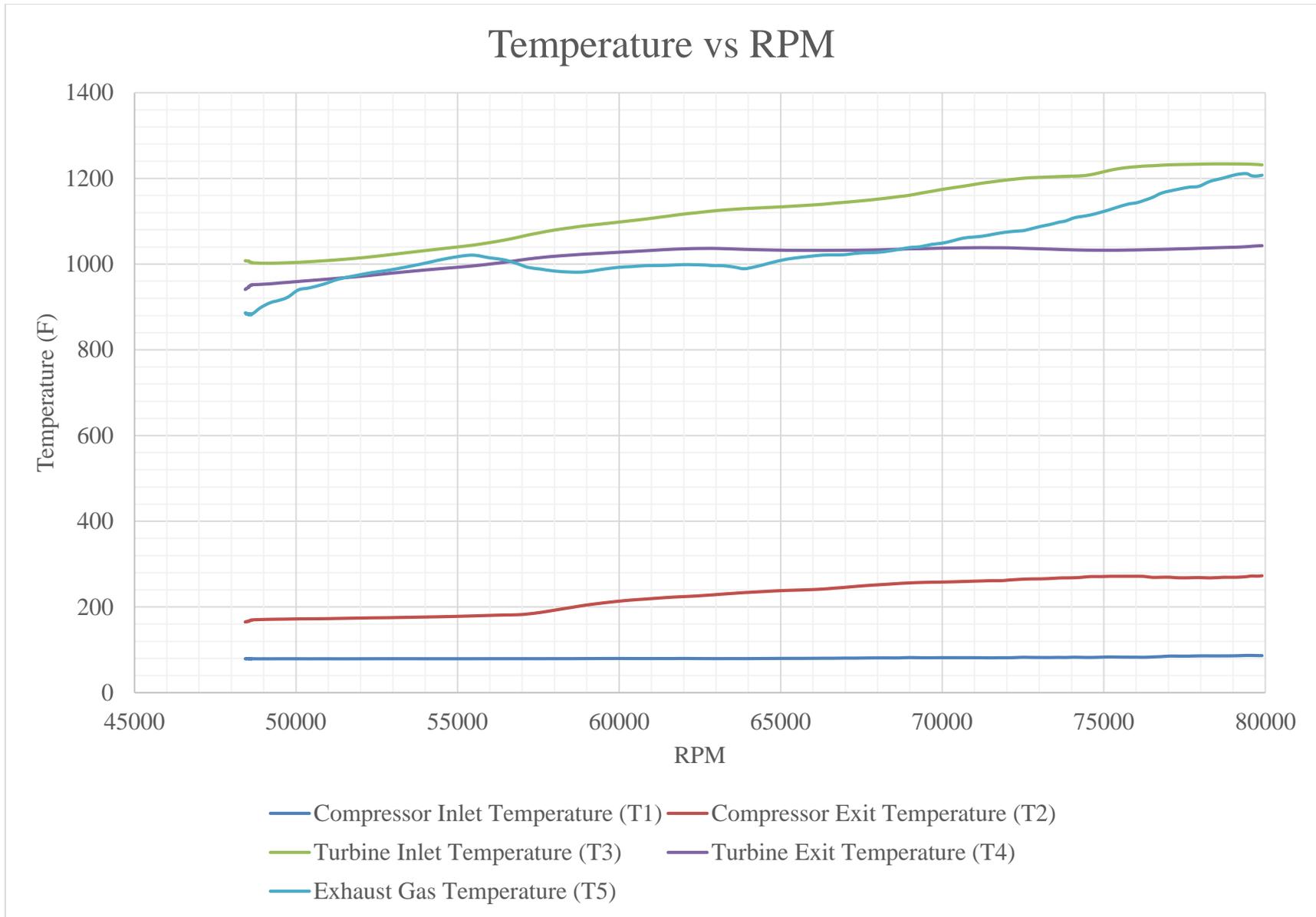
Figure 35. Engine Testing Data Plot – Temperature vs RPM

Figure 36. Engine Testing Data Plot – Inlet Mass Flow Rate vs RPM
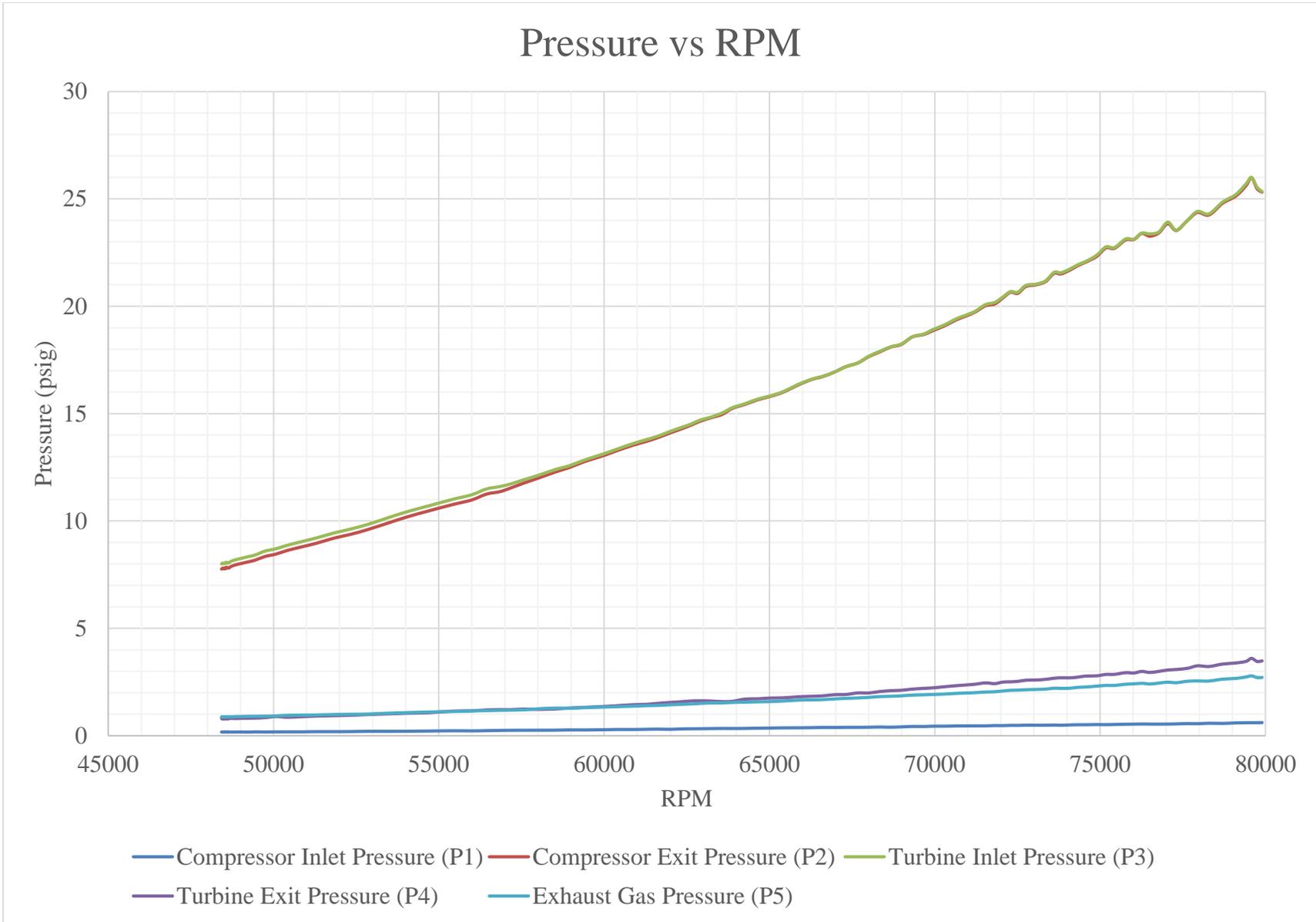
Figure 37. Engine Testing Data Plot – Pressure vs RPM

6.4. Engineering Equation Solver (EES)

One of the critical tasks was to create a program in EES which analyzes the engine using the first and second laws of thermodynamics. Ideally this program would be displayed on the second monitor so you can take the data directly from LabView and plug it into the EES program. After plugging in the different temperatures and pressures as inputs in the EES program, it will calculate the compressor efficiency, turbine efficiency, overall efficiency of the engine and the thrust of the engine. These values can be calculated using each set of data output from LabView. Since the engine has a large range in RPM, the ranges in efficiencies can be seen as the engine accelerates and decelerates. A diagram window interface was created in EES to make it easy for the user to run the program without understanding the entirety of the code. Figure 41 below shows the equations window section of the EES program. Figure 42 below shows the diagram window section of the EES program.

Shown below in the following set of EES formatted equations are fluid property calculations in order to obtain enthalpy and entropy values at locations throughout the engine cycle. These values are obtained through the built in EES thermo-physical property calculator.

Known Information

$Fluid\$ = 'air_{ha}'$

Compressor Inlet

$h2 = h[Fluid\$, T = T_2 + 459.67, P = P_2 + 14.7]$

$s2 = s[Fluid\$, T = T_2 + 459.67, P = P_2 + 14.7]$

Compressor Outlet

$h3 = h[Fluid\$, T = T_3 + 459.67, P = P_3 + 14.7]$

$h3_s = h[Fluid\$, s = s2, P = P_3 + 14.7]$

Turbine Inlet

$h4 = h[Fluid\$, T = T_4 + 459.67, P = P_4 + 14.7]$

$s4 = s[Fluid\$, T = T_4 + 459.67, P = P_4 + 14.7]$

Turbine Outlet

$h5 = h[Fluid\$, T = T_5 + 459.67, P = P_5 + 14.7]$

$h5_s = h[Fluid\$, s = s4, P = P_5 + 14.7]$

Nozzle Outlet

$h6 = h[Fluid\$, T = T_6 + 459.67, P = P_6 + 14.7]$

$s6 = s[Fluid\$, T = T_6 + 459.67, P = P_6 + 14.7]$

Figure 38. EES Formatted Equations - Enthalpy and Entropy

Shown below in Figure 39 are EES formatted equations that calculate work and efficiency for the turbine, compressor, and of the engine overall. These calculations utilize enthalpy and entropy values obtained in the above set of formatted equations.

Turbine Work and Efficiency

$$w_t = h4 - h5$$

$$\eta_t = \frac{h4 - h5}{h4 - h5_s}$$

Compressor Work and Efficiency

$$w_c = h3 - h2$$

$$\eta_c = \frac{h3_s - h2}{h3 - h2}$$

Work, Heat Transfer and Efficiency

$$q_{in} = h4 - h3$$

$$q_{out} = h2 - h6$$

$$w_{net} = w_t + w_c$$

$$\eta = \frac{w_{net}}{q_{in}}$$

Figure 39. EES Formatted Equations - Efficiency

Shown below in Figure 40 are calculations involved in calculating the thrust of the engine. In order to calculate the thrust, the inlet velocity and exit velocity of the air through the engine is calculated through continuity equation as well as Bernoulli's equation assuming incompressible flow.

Inlet Velocity

$$D_2 = \frac{2.535}{12}$$

$$A_2 = \frac{\pi \cdot D_2^2}{4}$$

$$\rho_2 = \rho\left[\text{Fluid\$}, T = T_2 + 459.67, P = P_2 + 14.7\right]$$

$$V_2^2 = 2 \cdot \frac{P_2 \cdot 144}{\dfrac{\rho_2}{32.174}}$$

$$D_1 = \frac{5.5}{12}$$

$$A_1 = \frac{\pi \cdot D_1^2}{4}$$

$$A_1 \cdot V_1 = A_2 \cdot V_2$$

Exit Velocity

$$D_6 = \frac{2.21}{12}$$

$$A_6 = \frac{\pi \cdot D_6^2}{4}$$

$$\rho_6 = \rho\left[\text{Fluid\$}, T = T_6 + 459.67, P = P_6 + 14.7\right]$$

$$V_6^2 = 2 \cdot \frac{P_6 \cdot 144}{\dfrac{\rho_6}{32.174}}$$

Thrust

$$F = \dot{m} \cdot \left[V_6 - V_1\right]$$

Figure 40. EES Formatted Equations - Thrust

```
$UnitSystem Eng R psig mass
$Tabstops 0.25 3.5 in

"!Known Information"
$ifnot DiagramWindow
P[2]=.3 [psig]
T[2]=84.9 [F]
P[3]=14 [psig]
T[3]=1207 [F]
P[4]=196 [psig]
T[4]=2500 [F]
P[5]=14 [psig]
T[5]=1452 [F]
P[6]=14.7 [psig]
T[6]=1200 [F]
m_dot=.015 [slug/s]
$endif

Fluid$='air_ha'

"!Compressor Inlet"
h2=enthalpy(Fluid$,T=(T[2]+459.67),P=(P[2]+14.7))
s2=entropy(Fluid$,T=(T[2]+459.67),P=(P[2]+14.7))

"!Compressor Outlet"
h3=enthalpy(Fluid$,T=(T[3]+459.67),P=(P[3]+14.7))
h3_s=enthalpy(Fluid$,s=s2,P=(P[3]+14.7))

"!Turbine Inlet"
h4=enthalpy(Fluid$,T=(T[4]+459.67),P=(P[4]+14.7))
s4=entropy(Fluid$,T=(T[4]+459.67),P=(P[4]+14.7))

"!Turbine Outlet"
h5=enthalpy(Fluid$,T=(T[5]+459.67),P=(P[5]+14.7))
h5_s=enthalpy(Fluid$,s=s4,P=(P[5]+14.7))

"!Nozzle Outlet"
h6=enthalpy(Fluid$,T=(T[6]+459.67),P=(P[6]+14.7))
s6=entropy(Fluid$,T=(T[6]+459.67),P=(P[6]+14.7))

"!Turbine Work and Efficiency"
w_t=h4-h5
eta_t=(h4-h5)/(h4-h5_s)

"!Compressor Work and Efficiency"
w_c=h3-h2
eta_c=(h3_s-h2)/(h3-h2)

"!Work, Heat Transfer and Efficiency"
q_in=h4-h3
q_out=h2-h6
w_net=w_t+w_c
eta=w_net/q_in

"!Inlet Velocity"
D_2=2.535/12
A_2=(pi*(D_2^2))/4
rho_2=density(Fluid$,T=(T[2]+459.67),P=(P[2]+14.7))
V_2^2=2*((P[2])*144)/(rho_2/32.174)
D_1=5.5/12
A_1=(pi*(D_1)^2)/4
A_1*V_1=A_2*V_2

"!Exit Velocity"
D_6=2.210/12
A_6=(pi*(D_6^2))/4
rho_6=density(Fluid$,T=(T[6]+459.67),P=(P[6]+14.7))
V_6^2=2*((P[6])*144)/(rho_6/32.174)

"!Thrust"
F=m_dot*(V_6-V_1)
```
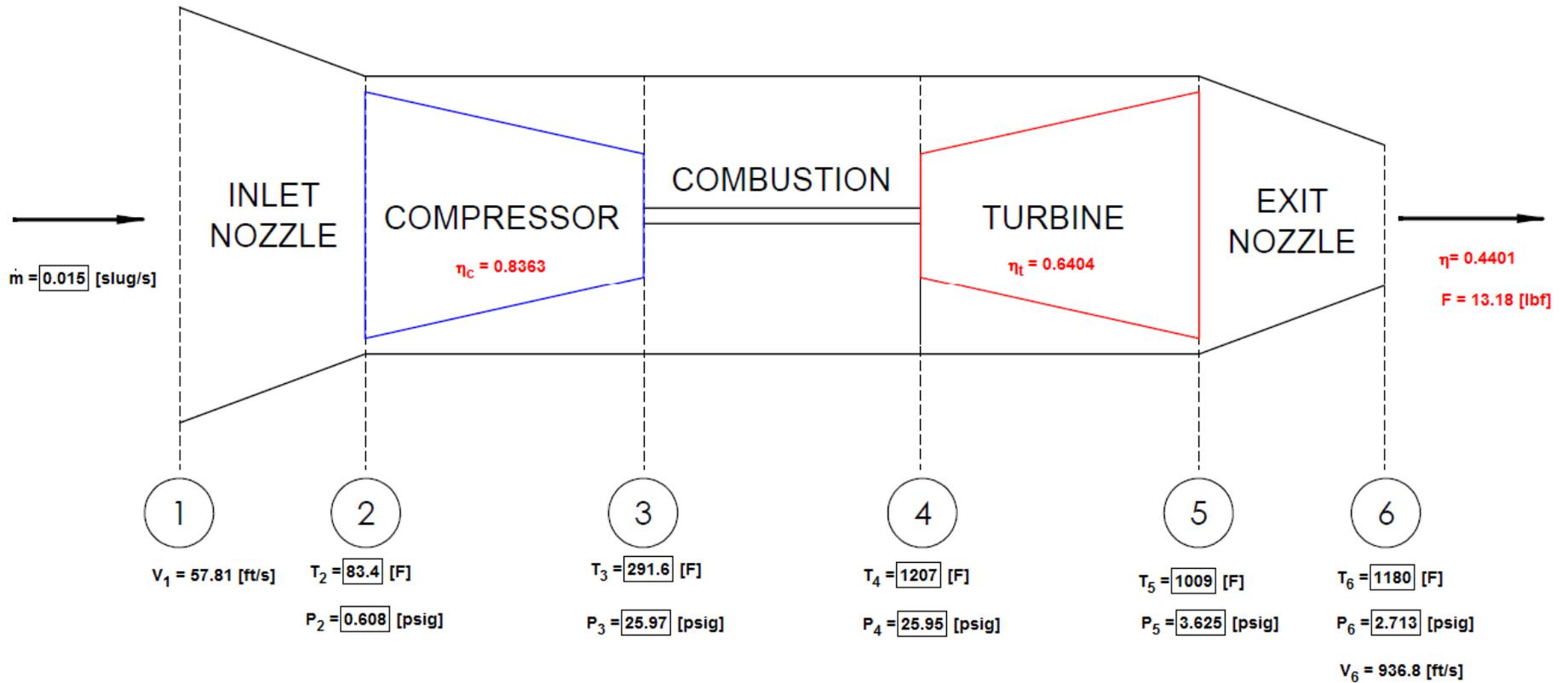
Figure 41. EES Code

Figure 42. EES Diagram Window

6.5. <u>Thermodynamics Laboratory Experiment</u>

Engineering Thermodynamics II Project Draft

While redeveloping the mini-turbine DAQ system, a new project for Engineering Thermodynamics II students was created. The current document is still in its draft stage and under review for implementation. The ultimate goal of the semester long project is for students to develop an understanding of a standard Brayton Cycle. The initial objective of the project is for students to successfully run and collect data from the mini-turbine. Upon retrieving data, the students are then to analyze the results and calculate various properties of the mini-turbine. Through the use of EES, students are expected to create their own program which will solve for efficiencies and work of the different components and overall engine.

Revised Mini-Turbine Lab

After updating the pre-existing DAQ system and implementing a new LabVIEW program, the lab instructions needed to be updated. Revisions to the old lab consisted mainly of updates to the experimental procedure which went through the steps of starting the engine and recording data. The new LabVIEW program required a new procedure in which a file name and location is set before a data collection toggle switch is turned on. In addition to the new collection process, the user can also view plots of the data on another tab. Aside from the implementation of the new DAQ instructions, the overall lab remained the same. This revised lab is contained within Appendix D.

7. <u>CONCLUSION</u>

The completion of our capstone project produced quality and timely task completion. The mini turbine engine is now ready to be used in student experimental settings. Each data acquisition component of the system is calibrated including all thermocouples and pressure transducers, RPM measurement and thrust measurement. The LabVIEW program will be used for real time data display and data acquisition of the complete run cycle of the system. Using this data exported to Excel by the LabVIEW program, these values can be inputted into the first and second law of thermodynamics EES program to determine the efficiencies of the compressor, turbine, and the overall system as well as the work done by the system in BTU/hr.

Many tasks and sub-tasks have been completed leading us to our final goal. These tasks and sub-tasks include but are not limited to preliminary research and component identification, mounting of a new laptop arm and laptop, design and manufacturing of a mounting bracket for the DAQ hardware, an up to date Microsoft project file, a completed formal proposal report, an EES program, a DAQ and user-friendly display LabVIEW program, a thermodynamics laboratory report, our engineering notebooks, and this final report.

8. <u>REFERENCES</u>

[1] Moran, Michael J., and Howard N. Shapiro. *Fundamentals of Engineering Thermodynamics*.Seventh ed. New York: Wiley, 2011. Print
[2] Klein, S. A.. *Engineering Equation Solver for Microsoft Windows Operating Systems*. F-ChartSoftware. 2014
[3] National Instruments. *SCB-68 User Manual*. National Instruments Corporation. Austin, Texas.2009.
[4] National Instruments. *USB-6251 User Manual*. National Instruments Corporation. Austin, TX.2008.
[5] Omega. *Thermocouple Selection Guide*. Omega Engineering Inc.. Stamford, CT. 2016
[6] Omega. *PX139 Series Pressure Sensor User Guide*. Omega Engineering Inc.. Stamford, CT.2008

9. APPENDIX

9.1. Appendix A – Team Contract

Team Contract

As a member of team number 1, I agree that coordinated teamwork is essential for successfully completing assigned projects. I understand my individual performance will affect the success of the entire project. I also understand that all members of successful teams need to exhibit the following behaviors during the execution of the project:

1. Fulfills duties of team role
a. Attend all team meetings
b. Actively participate in team meetings
c. Be prepared to present work assigned from previous meeting
2. Researches and gathers pertinent information
3. Listens to other teammates
4. Shares work evenly
5. Regularly scheduled meetings will meet:

a. Time/Day:10/Wed Place: Class

b. Time/Day:11/Wed Place: Meeting w/Professor

c. Time/Day: 12/Mon Place: 610 make shift library

Printed Team Member Name	Team Member Signature
1. Matt Dietter	
2. Jon Sewell	
3. Kurt Madden	
4. Kyle Lavoie	
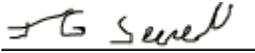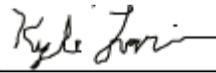
Kyle Lavoie

66 North Fairview Street, Littleton, NH 03561
lavoiek1@wit.edu (603) 991-0082

EDUCATION

Wentworth Institute of Technology, Boston, MA   August 2016 *exp.*
Bachelor of Science Mechanical Engineering, Aerospace Minor; GPA: 3.92/4.00
President's Award Recipient for Academic Excellence & Co-curricular Involvement – Mechanical Engineering 2016

TECHNICAL COMPETENCIES

Finite element analysis with ANSYS Mechanical through Workbench and Classic interface - including writing APDL scripts, computational fluid dynamics with ANSYS Fluent and SolidWorks Flow Simulation, solid modeling & drafting with Creo Parametric & SolidWorks (Certified SolidWorks Associate), proficient programming in Python for software development and numerical analysis, proficient with Microsoft Office Suite, experience programming with MATLAB

EXPERIENCE

Raytheon Integrated Defense Systems

Requirements, Analysis & Verification Section - Mechanical Engineer Co-op   August 2015 –December 2015
- Performed structural analysis on mechanical parts and assemblies to verify that all components meet structural requirements. Analysis is performed through finite element analysis with ANSYS Workbench as well as through hand calculations. Primary load cases investigated include vibration, shock, static loading, and fatigue analysis. All analysis results are reported in a formal memo.

Environmental Test Lab Section- Mechanical Engineer Co-op   January 2015 – May 2015
- Performed engineering laboratory testing of electromechanical components and assemblies through various tests including environmental stress screening, vibration, static, dynamic, thermal, and climatic tests. I was involved with the full scope of the tests including instrumentation, data acquisition set-up and operation, post processing the data, interpreting the results, and reporting on the results and conclusions of each test.
- Design of fixtures for upcoming engineering tests including conceptual design, solid modeling, and production of detailed drawings for manufacturing in accordance with company standards.

Mechanical Solutions, Inc. – *Mechanical Engineer Co-op*   Summers 2012-2014

- Performed finite element analysis of turbomachinery and other mechanical components with ANSYS Mechanical.
- Development of multidisciplinary design, analysis, and optimization software written in Python. Upon completion I assisted in a software demonstration and instruction of a training course at the NASA Glenn Research Center.
- International Society of Automation standard development – ISA107 Advanced Measurement Techniques for Gas Turbine Engines, (ISA107.1 Waveform Quality for Blade Tip Timing).
- Performed research and testing for improvement in test and measurement capabilities for fan blade dynamic response as well as develop and validate a non-contacting blade vibration measurement system for unducted fans. This project involved the development of a radar based sensor to measure dynamic response on the composite airfoils of helicopter main rotor blades. The sensor was flight tested on a Bell 407 helicopter.
- Design of radar based sensors capable of measuring blade vibration in gas turbine engines
  - Mechanical design, FEA, and production of detailed drawings for prototype manufacturing
  - Capable of measuring blade dynamics in a high temperature, high pressure, and high vibration environment
  - Performed increasingly refined rig testing, data acquisition, and high temperature nonlinear material analysis

ACTIVITIES

- International Society of Automation – Student Membership
  - Author of Technical Paper, "Design Process for Gas Turbine Engine Sensors", for the 2015 International Instrumentation Symposium and Mechanical Failure Prevention Technology Joint Conference
- American Institute of Aeronautics and Astronautics
  - Vice President of WITAero – 2015 Term (Wentworth AIAA Accredited Chapter)
  - Co-author of a Technical Paper, "Effect of Geometrical Parameters on an Airfoils Drag Force", AIAA Student Conference at Cornell University
  - Chief Mechanical Engineer for 2014/15 Student Design/Build/Fly Competition

MATTHEW T DIETTER

9 Sunny Lane ▪ Sherman, CT 06874
Phone: (203)788-6855 ▪ Email: dietterm@wit.edu

EDUCATION

Wentworth Institute of Technology: Bachelor of Science: Mechanical Engineering Major & Aerospace Engineering Minor
GPA: 3.48 on 4.00 Scale

Completed Engineering Courses: Heat Transfer, Computational Fluid Dynamics & Numerical Simulation, Instrumentation and Design of Experiments, Thermodynamics, Fluids, Dynamics, Materials Science, Engineering Statistics, Design of Machine Elements, Mechanics of Materials, Statics, Mechanical Design & Analysis, Engineering Graphics (SolidWorks), Engineering Chemistry, Circuit Theory, Engineering Physics I & II, Engineering Differential Equations, Engineering Calculus I, II, & III

EXPERIENCE

Fall 2015 (4 months): Mechanical Engineering Co-op at DRS Power Technologies, Inc. (Defense & Commercial)

- Worked as a member of the Internal Research and Design team. Goal was to design, analyze, manufacture, and test two different 2 foot diameter PM electric motors for commercial application.
- Used ANSYS Mechanical to analyze main load bearing member and modal behaviors of a PM electric motor. Verified by hand calculations.
- Fit checks and tolerance analysis of both PM electric motor designs.
- SolidWorks – Created part and assembly files. Also, produced toleranced drawings with manufacturing notes.
- Data input and analysis of material discomformities with gas and steam turbine housing structures.

Spring 2015 (4 months): Manufacturing Engineer Co-op at ConforMIS, Inc.

- Worked with the manufacturing engineering team to qualify a new manufacturing facility for production (i.e. qualifying new and transported equipment, operator workspaces, production floor layout, cleanroom validation, clean line function, etc). Reported directly to Sr. Process Engineer.
- 3D Systems SLS sPro60 HD-HS 3D printers:
    - Installation, Operational and Process Qualification (IQ/OQ/PQ) reports for three 3D printers.
    - Build setup, build cake breakout, bead blast, and dimensional tolerance inspection.
- Conducted qualification protocols and report (IQ/OQ/PQ) for Fuji impulse pouch sealer.
- Conducted cleanroom product pouching time-study and informed upper engineering management of process inefficiencies and potential solutions.

February 2014 – August 2015: President of WITAero/AIAA (American Institute of Aeronautics and Astronautics) Student Chapter at Wentworth Institute of Technology

- Cessna/Raytheon Missile Systems Student Design/Build/Fly Competition, 2015: Project Director/Systems Engineer
    - Designed and documented 5 foot wingspan RC aircraft creation.
    - Project Director/Systems Engineer: managed and optimized efficiency of 25 team members.
    - Lead author.
    - Aerodynamics team leader. Engineered and manufactured airfoils (laser cutting).

KEY SKILLS

- Personable
- Passionate about engineering
- Strong leadership, communication, and team collaboration skills
- Versatile learner
- Thorough comprehension of engineering design and analysis process

Personal interests: Golfing, aerodynamic research, road biking, hiking, camping, playing soccer, and reading about past/present military aircraft.

Kurtis Madden

603-903-9101 ◆ 74 Hayes Rd, Walpole, NH 03608 ◆ maddenk@wit.edu

EDUCATION

Wentworth Institute of Technology - Boston, MA - GPA: 3.64/4.0   Graduation Date: August 2016
    Bachelor of Science in Mechanical Engineering
    Minor in Aerospace Engineering

River Valley Technical Center - Springfield, VT   Fall 2010 - Spring 2012
    Concentration: Engineering and Manufacturing

EXPERIENCE

Tesla Motors - Fremont, CA   September 2015 – December 2015

- Product Excellence Engineering Intern – Interior team
- Worked mainly on the instrument panel assembly for the Model S and Model X
- Made process changes and part reworks to improve the quality of the IP
- Ran tests and trials and provided design team with data necessary to make permanent design changes

iRobot Corporation - Bedford, MA   January 2015 – May 2015

- Mechanical Engineering Intern for Defense & Security (D&S) Robots
- Strong use of Creo (and Windchill) - advanced modeling, drawings, and assemblies
- Design and analysis of new concepts for D&S robots
- Mill and lathe work for building prototypes, testing prototypes, and making design changes

J&L Metrology - Springfield, VT   February 2011 - Present

- Design optical comparators and other precision measurement tools
- Strong use of SolidWorks - advanced modeling, drawings, and assemblies
- Utilize an understanding of mechanical systems, optics, precision measuring instruments, etc.

Vermont Yankee Nuclear Power Plant - Vernon, VT   June 2013 - August 2013

- Programs and Components Engineering
- Analyzed flow accelerated corrosion (FAC) of pipes
- Understanding of major components in a boiling water reactor (BWR) nuclear power plant

SKILLS / QUALIFICATIONS

- Certified SolidWorks Professional (CSWP) and Certified SolidWorks Associate (CSWA)
- PTC Creo and PTC Windchill
- Microsoft Office: Word, Excel, PowerPoint, Outlook, OneNote, Project
- ANSYS, Mastercam, AutoCAD, MATLAB, LabVIEW, EES, Inventor
- GD&T – Geometric dimensioning and tolerancing
- FEA – Finite Element Analysis and CFD – Computational Fluid Dynamics
- CNC programming, manual programming (G code), manual machining (mills, lathes, etc.)
- Design castings, patterns, fixtures, sheet metal, gears, etc.
- Strong understanding of thermodynamics, statics, fluids, materials, dynamics, vibrations
- Hands-on labs: heat exchangers, boilers, mixing chambers, heat pumps, diesel engines, etc.
- Work well with teams - good communication and organization
- Skills USA – Silver Medal for Technical Drafting in the Nation – Kansas City, MO (2012)
- Skills USA – 2 times Gold Medal for Technical Drafting in Vermont – Burlington VT (2011, 2012)

Jonathan Sewell

(908) 887-0950   sewellj@wit.edu   Hackettstown, NJ

Education

Wentworth Institute of Technology, Boston, MA
Candidate for Bachelor of Science Degree in Mechanical Engineering

GPA: 3.50/4.00
August 2016
Dean's List: Sophomore Year
Junior Year

Engineering Experience

Co-Op/ Internship

Electrochem Solutions – Raynham, MA   January 2015 – April 2015

- Reverse engineered and created SolidWorks drawings for undocumented fixtures used on the manufacturing floor.
- Designed and 3D printed prototype fixtures using SolidWorks and Objet30Pro 3D Printer.
- Participated in Kaizen event to improve productivity of the Moderate Rate Battery Pack Department. Conducted time studies to create standard work and switch from batch manufacturing to single-piece flow.
- Conducted failure analysis on Printed Computer Boards (PCBs) to determine mode of failure and document problem components.
- Conducted pull tests using Chatillon Motorized Force Tester to verify welding machines were to spec.
- Created Manufacturing Process Instructions (MPIs) for new products.
- Trained and worked under ISO 9001 and ISO 13485 Quality Systems.
- Gained knowledge of lean manufacturing principles.

Clubs

WITAero – Student Chapter of the American Institute of Aeronautics and Astronautics (AIAA)
Design/Build/Fly Competition

- Designed the fuselage structure and payload release system of a radio-controlled aircraft capable of completing various missions. Created SolidWorks parts for the fuselage components and assemblies for the entire aircraft.
- Laser cut and assembled aircraft parts made from balsa and basswood.
- Attained synergistic skills through collaboration with other departments for design decisions and correct interfacing.

Lab Work

- Mechanical Design and Analysis: Analyzed the mechanics and thermodynamics of an air engine within a Rankine cycle.
- Manufacturing Processes: Used lathes to create strain testing specimens.
- Mechanical Engineering Design: Designed and analyzed a universal wrench socket.
- Mechanics of Materials: Used Tinius Olsen machines to conduct strain, shear, and torsion tests of various materials.
- Design of Machine Elements: Designed and analyzed a single-reduction gear box capable of withstanding given parameters.
- Engineering Fluid Mechanics: Used various flow measuring devices to determine flow losses through pipes, valves, and joints.

Technical Skills

Engineering: Materials testing, flow devices, strain gauges, Tinius Olsen strain tester, FEA, tolerances
Software: SolidWorks, MatLab, Microsoft Office (Word, Excel, Outlook, Access, PowerPoint), Engineering Equation Solver (EES)
Manufacturing: G programming language (G-code), Benchman, sand casting, milling, 3D printing
Certifications: Certified SolidWorks Associate

Coursework

Engineering Fluid Mechanics	Design of Machine Elements	Engineering Graphics (SolidWorks)
Engineering Statics	Mechanical Design and Analysis	Engineering Thermodynamics II
Mechanics of Materials	Circuit Theory and Application	Differential Equations
Numerical Simulation and CFD	Engineering Heat Transfer	Engineering Dynamics

Leadership/Volunteer Work

Trinity United Methodist Church   March 2012 - Present
Eagle Scout / Troop 416 Assistant Scoutmaster

- Mentored scouts and taught both outdoor and life skills.
- Gained logistical skills through the planning and carrying out of trips and meetings.

Other Employment

Walgreens – Hackettstown, NJ
Service Clerk and Stock Person   April 2011 - March 2012
Photo Technician   April 2012 - August 2014

- Provided customer service, maintained an organized stockroom and sales floor, developed film negatives, and performed routine maintenance on photo machines.

9.3. Appendix C – Sample of Engine Testing Data

Table 4. Engine Testing Data Sample

Time	T1_F_ai1	T2_F_ai2	T3_F_ai3	T4_F_ai4	T5_F_ai5	Thrust_lbf_ai6	RPM_ai7	P1_psig_ai1	P2_psig_ai2	P3_psig_ai3	P4_psig_ai4	P5_psig_ai5	Mass_Flow_Rate_slug-s_ai6	Fuel_Flow_gal-Hr_ai7
8/3/2016 10:03:26.450	79.5	165.0	1007.9	940.7	886.3	7.34	48429	0.164	7.76	8.00	0.79	0.865	0.0114	1.81
8/3/2016 10:03:26.703	79.4	165.4	1007.7	941.9	886.2	7.34	48464	0.166	7.79	8.02	0.78	0.868	0.0115	1.81
8/3/2016 10:03:26.930	79.4	165.8	1007.4	942.9	883.4	7.35	48460	0.166	7.81	8.04	0.78	0.871	0.0115	1.81
8/3/2016 10:03:27.184	79.4	166.0	1007.2	944.0	884.3	7.35	48502	0.168	7.78	8.01	0.78	0.868	0.0116	1.81
8/3/2016 10:03:27.421	79.4	166.2	1007.0	945.0	884.7	7.33	48535	0.170	7.78	8.02	0.79	0.867	0.0117	1.81
8/3/2016 10:03:27.649	79.4	166.6	1006.8	945.8	883.6	7.29	48540	0.159	7.80	8.04	0.78	0.873	0.0113	1.81
8/3/2016 10:03:27.933	79.4	166.8	1006.4	947.0	882.9	7.26	48552	0.164	7.80	8.03	0.79	0.874	0.0115	1.81
8/3/2016 10:03:28.211	79.4	167.4	1005.9	947.7	881.5	7.26	48535	0.164	7.82	8.05	0.79	0.874	0.0115	1.81
8/3/2016 10:03:28.443	79.4	167.7	1005.5	948.4	883.6	7.25	48564	0.166	7.83	8.07	0.79	0.869	0.0115	1.81
8/3/2016 10:03:28.687	79.4	168.1	1005.0	949.0	883.0	7.29	48574	0.166	7.80	8.03	0.79	0.869	0.0115	1.81
8/3/2016 10:03:28.926	79.3	168.4	1004.7	949.7	883.9	7.33	48587	0.164	7.83	8.06	0.79	0.871	0.0115	1.81
8/3/2016 10:03:29.156	79.3	168.6	1004.3	950.0	883.9	7.33	48606	0.171	7.82	8.05	0.79	0.877	0.0117	1.81
8/3/2016 10:03:29.399	79.4	169.0	1003.9	950.6	884.3	7.29	48623	0.168	7.82	8.06	0.79	0.871	0.0116	1.81
8/3/2016 10:03:29.636	79.3	169.2	1003.4	950.9	881.5	7.27	48604	0.163	7.83	8.06	0.79	0.873	0.0114	1.81
8/3/2016 10:03:29.881	79.3	169.6	1003.0	951.4	884.1	7.26	48650	0.167	7.81	8.04	0.79	0.875	0.0116	1.84
8/3/2016 10:03:30.118	79.4	170.1	1002.6	951.9	887.6	7.29	48718	0.162	7.89	8.12	0.80	0.873	0.0114	1.90
8/3/2016 10:03:30.357	79.3	170.4	1002.3	952.3	896.2	7.30	48858	0.165	7.96	8.19	0.79	0.883	0.0115	1.96
8/3/2016 10:03:30.594	79.3	170.8	1002.0	953.0	903.8	7.28	49024	0.167	8.02	8.26	0.80	0.888	0.0116	1.99
8/3/2016 10:03:30.840	79.3	171.2	1002.0	954.0	911.5	7.26	49252	0.162	8.10	8.34	0.81	0.895	0.0114	2.02
8/3/2016 10:03:31.090	79.4	171.3	1002.4	955.4	915.1	7.24	49449	0.172	8.18	8.42	0.81	0.898	0.0117	2.05
8/3/2016 10:03:31.368	79.4	171.6	1003.1	957.2	922.8	7.18	49740	0.167	8.35	8.59	0.83	0.902	0.0115	2.10
8/3/2016 10:03:31.629	79.4	172.1	1004.1	959.2	940.0	7.17	50074	0.171	8.46	8.70	0.89	0.913	0.0117	2.15
8/3/2016 10:03:31.874	79.3	172.3	1005.6	961.3	944.7	7.19	50416	0.172	8.63	8.87	0.85	0.941	0.0117	2.19
8/3/2016 10:03:32.138	79.4	172.5	1007.7	963.9	953.5	7.21	50862	0.173	8.80	9.04	0.88	0.950	0.0118	2.24
8/3/2016 10:03:32.379	79.3	173.1	1010.0	966.7	964.8	7.19	51302	0.181	8.97	9.21	0.91	0.958	0.0121	2.29
8/3/2016 10:03:32.660	79.4	173.8	1013.4	970.2	973.2	7.21	51843	0.182	9.21	9.44	0.93	0.979	0.0121	2.34
8/3/2016 10:03:32.911	79.4	174.5	1017.0	973.8	980.2	7.28	52335	0.185	9.38	9.62	0.95	0.991	0.0122	2.38
8/3/2016 10:03:33.158	79.5	174.9	1021.4	977.8	985.6	7.38	52849	0.197	9.60	9.84	0.98	1.002	0.0126	2.40
8/3/2016 10:03:33.429	79.5	175.7	1026.8	982.3	994.0	7.56	53453	0.196	9.90	10.14	1.01	1.040	0.0125	2.43
8/3/2016 10:03:33.667	79.4	176.5	1031.8	986.4	1003.0	7.74	54043	0.201	10.19	10.43	1.04	1.068	0.0127	2.45
8/3/2016 10:03:33.910	79.4	177.5	1037.5	990.6	1013.7	7.92	54704	0.210	10.48	10.71	1.06	1.095	0.0130	2.48

Full engine testing data set contained within report package.

9.4. Appendix D – Revised Thermodynamics Laboratory Experiment

Brayton Cycle Experiment – Jet Engine

OBJECTIVE

1. To understand the basic operation of a Brayton cycle.

2. To demonstrate the application of basic equations for Brayton cycle analysis.

BACKGROUND

The Brayton cycle depicts the air-standard model of a gas turbine power cycle. A simple gas turbine is comprised of three main components: a compressor, a combustor, and a turbine. According to the principle of the Brayton cycle, air is compressed in the compressor. The air is then mixed with fuel, and burned under constant pressure conditions in the combustor. The resulting hot gas is allowed to expand through a turbine to perform work. Most of the work produced in the turbine is used to run the compressor and the rest is available to run auxiliary equipment and produce power. The gas turbine is used in a wide range of applications. Common uses include stationary power generation plants (electric utilities) and mobile power generation engines (ships and aircraft). In power plant applications, the power output of the turbine is used to provide shaft power to drive a generator, a helicopter rotor, etc. A jet engine powered aircraft is propelled by the reaction thrust of the exiting gas stream. The turbine provides just enough power to drive the compressor and produce the auxiliary power. The gas stream acquires more energy in the cycle than is needed to drive the compressor. The remaining available energy is used to propel the aircraft forward.

A schematic of the Brayton (simple gas turbine) cycle is given in Figure 1. Low-pressure air is drawn into a compressor (state 1) where it is compressed to a higher pressure (state 2). Fuel is added to the compressed air and the mixture is burnt in a combustion chamber. The resulting hot gases enter the turbine (state 3) and expand to state 4. The Brayton cycle consists of four basic processes:

  a) 1 2 : Isentropic Compression
  b) 2 3 : Reversible Constant Pressure Heat Addition
  c) 3 4 : Isentropic Expansion
  d) 4 1 : Reversible Constant Pressure Heat Rejection (Exhaust and Intake in the open cycle)

1

Figure 1. Basic Brayton Cycle
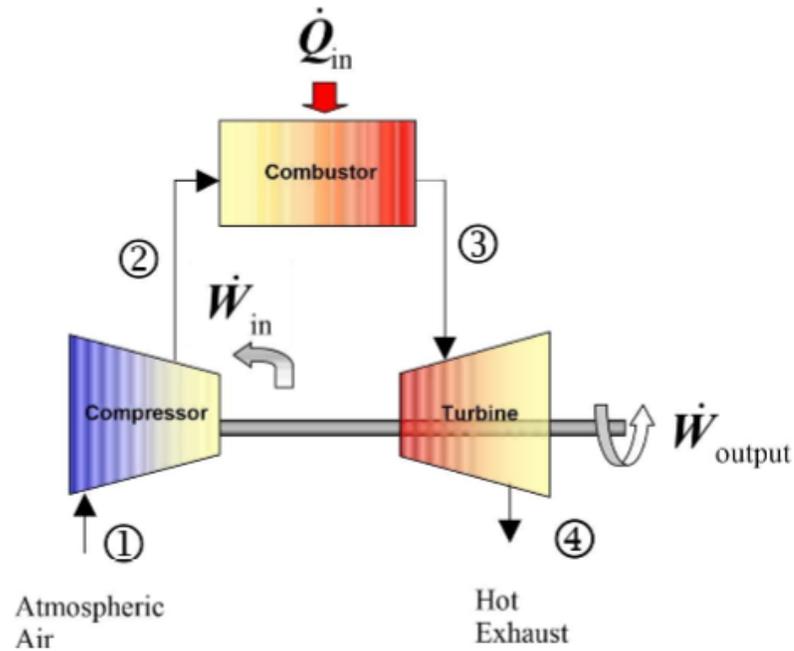
CYCLE ANALYSIS

Thermodynamics and the First Law of Thermodynamics determine the overall energy transfer. To analyze the cycle, we need to evaluate all the states as completely as possible. Air standard models are very useful for this purpose and provide acceptable quantitative results for gas turbine cycles. In these models the following assumptions are made.

> 1. The working fluid is air and treated as an ideal gas throughout the cycle; 2.
> The combustion process is modeled as a constant-pressure heat addition;
> 3. The exhaust is modeled as a constant-pressure heat rejection process.

In cold air standard (CAS) models, the specific heat of air is assumed constant (perfect gas model) at the lowest temperature in the cycle. The effect of temperature on the specific heat can be included in the analysis at a modest increase in effort. However, closed form solutions would no longer be possible. To perform the thermodynamic analysis on the cycle, we consider a control volume containing each component of the cycle shown in Figure 1. This step is summarized below.

2

Compressor

Consider the following control volume for the compressor,

Figure 2. Compressor Control Volume Model
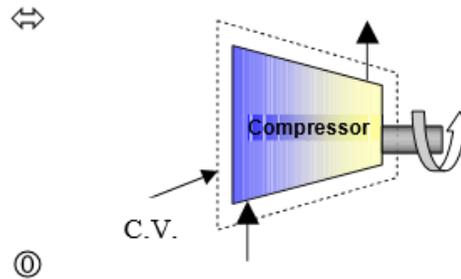
Note that ideally there is no heat transfer from the control volume (C.V.) to the surroundings. Under steady-state conditions, and neglecting the kinetic and potential energy effects, the first law for this control volume is then written as

$$\dot{H}_{in} - \dot{W}_{in} = \dot{H}_{out} \tag{1}$$

Considering that we have one flow into the control volume and one flow out of the control volume, we may write a more specific form of the first law as

$$\dot{m}h_{in} - \dot{m}w_C = \dot{m}h_{out} \tag{2}$$

Or, rearranging by grouping the terms associated with each stream,

$$-w_C = h_{out} - h_{in} \tag{3}$$

This is the general form of the First Law for a compressor. However, if the fluid stream is assumed to ideal gases we may represent the enthalpies in terms of temperature (a much more measurable quantity) by using the appropriate equation of state ($dh = c_p dT$), which will introduce the specific

Assuming constant specific heats, enthalpy differences are readily expressed as temperature differences as

$$-w_C = c_{p,C} \left(T_{C,out} - T_{C,in} \right) \tag{4}$$

To be more accurate, the specific heat of each fluid should be evaluated at the linear average between

3

inlet and outlet temperature, $\left[\dfrac{T_{in}+T_{out}}{2} \right]$ its

The irreversibilities present in the real process can be modeled by introducing the compressor efficiency,

$$\eta_{COMP} = \frac{w_{C,s}}{w_{C,a}} = \frac{h_{out,s} - h_{in}}{h_{out,a} - h_{in}} \tag{5}$$

where the subscript s refers to the ideal (isentropic) process and the subscript a refers to the actual process. For a perfect gas the above equation is reduced to

$$\eta_{COMP} = \frac{T_{out,s} - T_{in}}{T_{out,a} - T_{in}} \tag{6}$$

Combustor

For the combustor,

Figure 3. Combustor Control Volume Model

C.V.
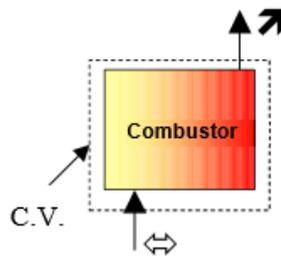
Note that ideally there is work transfer from the control volume (C.V.) to the surroundings. Under steady-state conditions, and neglecting the kinetic and potential energy effects, the first law for this control volume is then written as

$$\dot{H}_{in} + \dot{Q}_{in} = \dot{H}_{out} \tag{7}$$

4

Considering that we have one flow into the control volume and one flow out of the control volume, we may write a more specific form of the first law as

$$\dot{m}h_{in} + \dot{m}q_C = \dot{m}h_{out} \tag{8}$$

Or, rearranging by grouping the terms associated with each stream,

$$q_B = h_{out} - h_{in} \tag{9}$$

Assuming ideal gases with constant specific heats, enthalpy differences are readily expressed as temperature differences as

$$q_B = c_{p,B}\left(T_{B,out} - T_{B,in}\right) \tag{10}$$

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

Turbine

Consider the following control volume for the turbine,

Figure 4. Turbine Control Volume Model
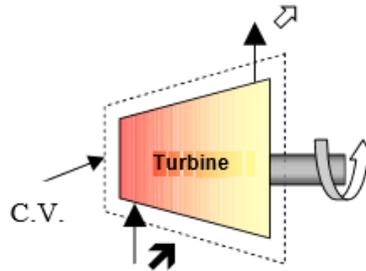
Note that ideally there is no heat transfer from the control volume (C.V.) to the surroundings. Under steady-state conditions, and neglecting the kinetic and potential energy effects, the first law for this control volume is then written as

$$\dot{H}_{in} - \dot{W}_{out} = \dot{H}_{out} \tag{11}$$

Considering that we have one flow into the control volume and one flow out of the control volume, we may write a more specific form of the first law as

$$m\&h_{in} - m\&w_T = m\&h_{out} \tag{12}$$

Or, rearranging by grouping the terms associated with each stream,

$$-w_T = h_{out} - h_{in} \tag{13}$$

Assuming ideal gases with constant specific heats, enthalpy differences are readily expressed as temperature differences as

$$-w_T = c_{p,T}\left(T_{T,out} - T_{T,in}\right) \tag{14}$$

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

The irreversibilities present in the real process can be modeled by introducing the turbine isentropic efficiency,

$$\eta_{TURB} = \frac{w_{C,a}}{w_{C,s}} = \frac{h_{out,a} - h_{in}}{h_{out,s} - h_{in}} \tag{15}$$

where the subscript s refers to the ideal (isentropic) process and the subscript a refers to the actual process. For a perfect gas the above equation is reduced to

$$\eta_{TURB} = \frac{T_{out,a} - T_{in}}{T_{out,s} - T_{in}} \tag{16}$$

EXPERIMENTAL SETUP

The laboratory setup is a self-contained, turnkey and portable propulsion laboratory manufactured by Turbine Technologies Ltd. called TTL Mini-Lab. The Mini-Lab consists of a real jet engine. Therefore, the same safety concerns of running a jet engine are present. Care must be taken to follow all the safety procedures precisely as outlined in the laboratory and stated by your lab instructors. The following description of the setup is provided by the manufacturer.

"A Turbine Technologies Model SR-30 turbojet engine is the systems primary component. Operational sound and smell are hard to distinguish from any idling, small business jet. The engine's axial turbine wheel and vane guide ring are vacuum investment castings. They are produced from modern, high cobalt and nickel content super alloys (MAR-M-247 and Inconnel 718). The combustion chamber consists of an annular, counterflow system, including internal film cooling strips.

Fuel and oil tanks, filters, oil cooler, all necessary plumbing and wiring is located in the lower part of the Mini-Lab structure. A throttle lever is located on the right side of the operator and above the slanted instrument panel. The throttle enables the operator to perform smooth power changes between idle and maximum N1. Digital engine RPM and E.G.T. gauges, mechanical E.P.R., Oil, Fuel, Air start pressure gauges are also part of the standard panel. Annunciator lights indicate low oil pressure, ignitor on, and air-start status. A key operated master switch controls the main electric power bus. Other panel-mounted switches control igniter, air start, and activate fuel flow. The SR-30 engine's fuel system is very similar to large-scale engines—fuel atomization via 6 return flow high-pressure nozzles that allow operation with a wide variety of kerosene based liquid fuels (e.g. diesel, Jet A, JP-4 through 8)."

7

Figure 5. Turbine Technologies's "MiniLab" Engine
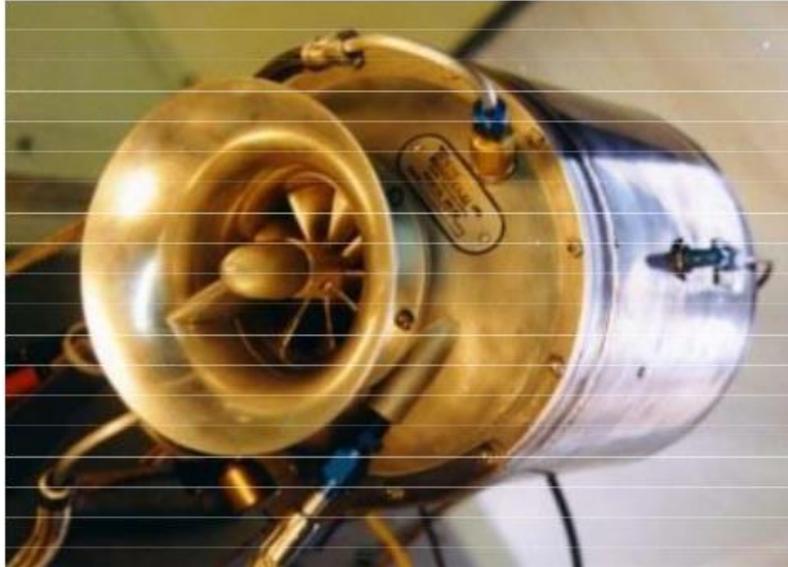
Engine Components.

The engine consists of a single stage radial compressor, a counterflow annular combustor and a single stage axial turbine which directs the combustion products into a converging nozzle for further expansion. Details of the engine may be viewed from the 'cutaway' provided in Fig. 6.

Instrumentation.

The sensors are routed to a central access panel and interfaced with data acquisition hardware and software from National Instruments. The manufacturer provides the following description of the sensors and their location.

8

"The integrated sensor system (Mini-Lab) option includes the following probes: Compressor inlet static pressure (P_1), Compressor stage exit stagnation pressure (P_{02}), Combustion chamber pressure (P_3), Turbine exit stagnation pressure (P_{04}), Thrust nozzle exit stagnation pressure (P_{05}), Compressor inlet static temperature (T_1), Compressor stage exit stagnation temperature (T_{02}), Turbine stage inlet stagnation temperature (T_{03}), Turbine stage exit stagnation temperature (T_{04}), and thrust nozzle exit stagnation temperature (T_{05}). Additionally, the system includes a fuel flow sensor and a digital thrust readout measuring real time thrust force based upon a strain gage thrust yoke system."

Figure 6. Turbine Technologies's SR-30 Engine
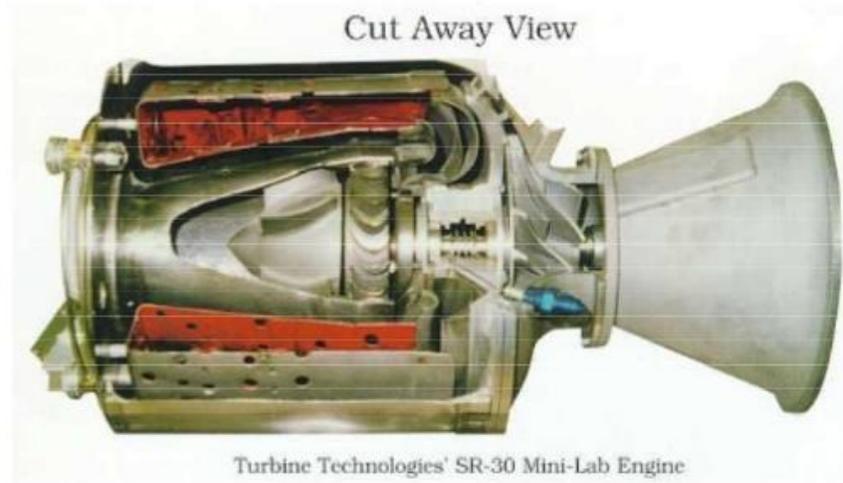
Cut Away View of SR-30 Engine

EXPERIMENTAL PROCEDURE

SAFETY NOTES:

1. Make sure you are wearing ear protection. If you are not sure how the earplugs are properly used, ask you lab instructor for a demonstration. Never stay in the laboratory without ear protection while the engine is in operation.

2. The SR-30 engine operates at high rotational speeds. Although there is a protective pane that separates the engine from the operator, make certain that you do not lean too close to this pane.

3. Make sure the low-oil-pressure light goes off immediately after an engine start. If it stays on or comes on **at any time** during the engine operation cut off the fuel flow **immediately**.

4. There is a vibration sensor whose indicator is to the far right of the operator's panel. If this indicator shows any activity (increase in voltage) shut-off the engine **immediately**.

5. If at any time you suspect something is wrong shut off the fuel immediately and notify the lab instructor.

6. If the engine is hung (starts but does not speed up to idle speed of about 40,000 rpm) turn the air-start back on for a short while until the engine speeds up to about 30,000 rpm. Then turn off the air-start switch.

ª **MAKE SURE NEITHER YOU NOR ANY OF YOUR BELONGINGS ARE PLACED IN FRONT OF THE INTAKE TO OR EXHAUST FROM THE ENGINE WHEN THE ENGINE IS RUNNING.**

10

1. Open the LabView executable file found on the laptop desktop. Upon opening the program, you will notice it reading data already, this is normal. Prior to starting the engine, designate the appropriate file name and save location, found at the bottom of the display.

2. Make sure that the air pressure in the compressed-air-start line is at least 100 psia (not exceeding 120 psia). Ask your lab instructor to check the oil level. Also, check the fuel level and fill up if necessary.

3. Ask the help of your lab instructor turn on the system and start the engine. Startup Procedure is as follows:

    a. Turn the main key to the ON position
    b. Turn the electrical master switch ON
    c. Position throttle handle at 50%
    d. Turn the ignition switch ON
    e. Turn the air switch ON and wait until engine is spinning at ~10-13k rpm
    f. Upon engine spinning at ~10-13k rpm, turn the fuel switch ON (flame should appear and engine is running). If there is no change to the EGT (exhaust gas temperature) readout and no flame appears, it may be necessary to throttle up to 75%.
    g. Once engine is running, turn air and ignition switches OFF
    h. Back the throttle off so that the engine idles at 48-50k rpm
    *NOTE: try to keep idle rpm above 48k minimum. If hang flame appears behind the exhaust, bring throttle down and then push back up in order to suck flame away.

4. After the engine is successfully started, you must first allow the engine to achieve the idle speed before making any measurements.

5. To begin recording data, first verify the file name and save location, then press the "Record Data" toggle switch to the ON position. The switch can be found in the bottom right. Data will be recorded until the "Record Data" toggle switch is turned OFF.

6. Slowly open the throttle. Start taking data at about 48,000 rpm during idle. Make sure that you allow the engine time to reach steady state by monitoring the digital engine rpm indicator on panel. The reading fluctuates somewhat so use your judgement.

7. Take data at different engine speeds. You will use the data to study how cycle and component efficiencies change with speed. An entire sweep of the RPM range can also be conducted at a steady rate.

8. After you are done taking data, toggle the "Record Data" switch to the OFF position.

11

9. The data will be stored in Excel spreadsheet format

10. To turn the engine off, bring the throttle all the way down, and then turn the fuel switch OFF. While the engine is spinning down, turn the air on briefly to help the engine cool down.

DATA ANALYSIS

Using the collected data determine the turbine isentropic efficiency, compressor isentropic efficiency, the thermal efficiency of the cycle and the corresponding Carnot efficiency.

REPORT

In your report determine the performance of the ideal cycle operating with the same maximum cycle temperature, mass flow rate, and compression ratio. Compare the performance of the ideal cycle with measured performance. Discuss the differences.

SUGGESTIONS FOR DISCUSSION
1. How does the cycle efficiency compare with the ideal Brayton cycle? with the Carnot cycle?
2. How does the component efficiency affect the cycle efficiency?
3. How do the component efficiencies you calculated based on your test data compare with those of typical of those gas turbine engines?

12