Design of an Automobile Turbocharger
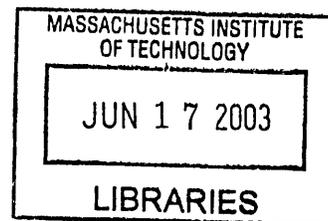Gas Turbine Engine

By

Keane T. Nishimoto

Submitted to the Department of Mechanical Engineering
In Partial Fulfillment of the Requirements
For the Degree of

Bachelor of Science

At the

Massachusetts Institute of Technology

June 2003

© 2003 Keane T. Nishimoto

The author hereby grants to MIT permission to reproduce and to distribute publicly paper
and electronic copies of this thesis document in whole or in part.

Signature of Author . . . .
Department of Mechanical Engineering
May 9, 2003

Certified by . . . .
Ernest G. Cravalho
Professor of Mechanical Engineering
Thesis Supervisor

Accepted by . . . .
Ernest G. Cravalho
Chairman of the Undergraduate Thesis Committee

1

Design of an Automobile Turbocharger
Gas Turbine Engine

By

Keane T. Nishimoto

Abstract

The turbocharger gas turbine engine was designed with the intent of being built as a demonstration for the Massachusetts Institute of Technology Department of Mechanical Engineering courses 2.005 and 2.006 to supplement material covered. A gas turbine operates on an open version of the Brayton cycle and consists of a compressor, a combustion chamber and a turbine.

An automobile turbocharger was chosen because it contains a compressor and turbine on a common shaft. Designs for the combustion chamber, oil system, fuel system, and ignition system were created based on research of similar projects. Many of the necessary parts were also specified.

Thesis Supervisor: Ernest G. Cravalho
Title: Professor of Mechanical Engineering

Introduction

The Massachusetts Institute of Technology Mechanical Engineering courses 2.005 and 2.006 teach concepts of thermodynamics and fluid mechanics as a coupled pair. The purpose of this project is to design and eventually create a classroom demonstration to illustrate a coupled thermal-fluid system, the Brayton cycle.

Learning in the classroom is often limited to equations of work, heat transfer and efficiency and diagrams on the temperature-entropy and pressure-specific volume planes. However, it is generally helpful to be able to see actual systems in action. Moreover, a classroom demonstration can engage students in what they are learning by showing them an example of the real-world applications of what they are learning as well as presenting them with a break from lecture and homework.

A somewhat separate motivation for this project is the challenge of creating a seemingly complex device, a jet engine, from readily available parts. Although similar projects have been completed prior to this one, due to inconsistencies in the available parts and resources, it is almost certain that every attempt has been faced with very different difficulties.

The Brayton Cycle

The Brayton cycle is also known as the Joule cycle or the gas turbine cycle. The cycle uses a gas as a working fluid and cycles it through 4 states as shown in Figures 1 and 2. From state 1 to state 2, the gas undergoes an isentropic, adiabatic compression to
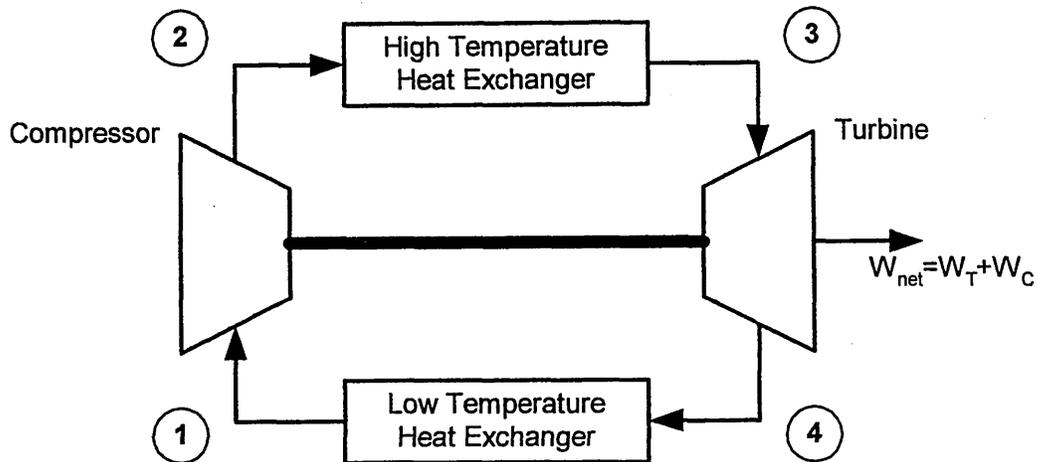
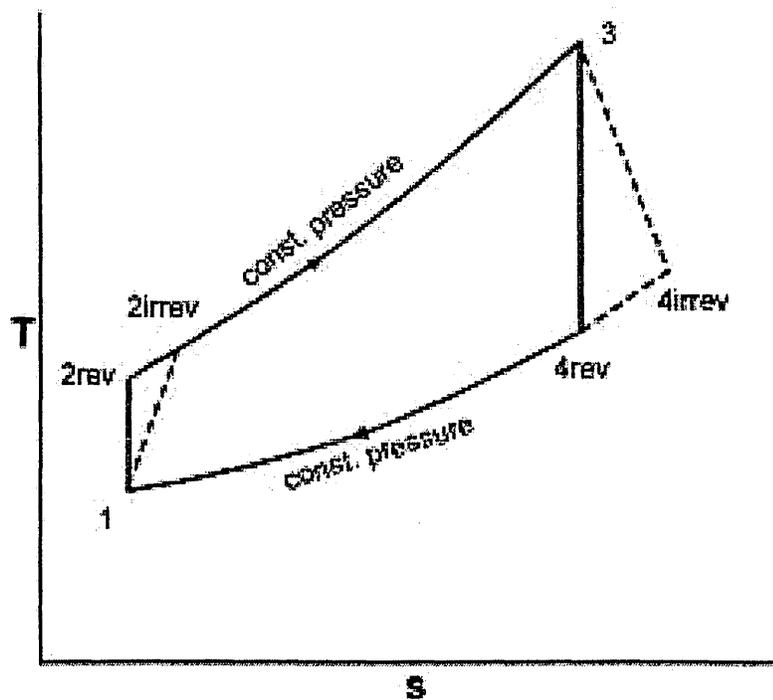Figure 1: The ideal gas closed Brayton cycle with the states labeled.

Figure 2: The temperature-entropy diagram for the Brayton cycle with the reversible and irreversible cycle states indicated.

a state of elevated pressure, temperature and density. From state 2 to 3 heat is added to

the gas under constant pressure either in through a combustion process or by means of a

heat exchanger. From there the working fluid runs through an adiabatic, isentropic turbine to reach state 4. In that process, the temperature and pressure fall and the gas is expanded.

The efficiency of the Brayton cycle is expressed as,

$$\eta = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{\dot{W}_{turbine} + \dot{W}_{compressor}}{\dot{Q}_{in}},$$ (1)

where η is the thermal efficiency of the cycle, $\dot{W}_{turbine}$ is the shaft power output of the turbine, $\dot{W}_{compressor}$ is the shaft power consumption of the compressor, and $\dot{Q}_{in}$ is the rate of heat transfer in the high temperature heat exchanger. These parameters can also be represented as

$$\dot{W}_{turbine} = \dot{m}(h_3 - h_4) = \dot{m}c_p(T_3 - T_4),$$ (2)

$$\dot{W}_{compressor} = \dot{m}(h_1 - h_2) = \dot{m}c_p(T_1 - T_2),$$ (3)

and

$$\dot{Q}_{in} = \dot{m}(h_3 - h_2) = \dot{m}c_p(T_3 - T_2).$$ (4)

Where we have modeled the fluid as an ideal gas with constant c_p and where $\dot{m}$ is the mass flow rate through the system, h is the enthalpy in each state, T is the temperature in each state, and c_p is the specific heat of the gas at constant pressure. By combining equations, the overall efficiency of an ideal Brayton cycle can be given as

$$\eta = 1 - \frac{T_4 - T_1}{T_3 - T_2},$$ (5)

or

$$\eta = 1 - \left(\frac{P_1}{P_2}\right)^{\frac{\gamma-1}{\gamma}}.$$ (6)

7

Where P is the pressure for each state and γ is the heat capacity ratio. As shown in Figure 2, irreversibilities in the compressor and turbine raise the temperature of states 2 and 4 for the same boost pressure in the compressor and pressure drop in the turbine as the ideal case. From Equation 5 it can be seen that a rise in T4 and T2 will increase the value of the second term, resulting in a lowering of the efficiency.

Gas Turbines

The gas turbine is a constant flow, shaft work machine composed of three parts, a compressor, a combustor and a turbine. Gas turbines are an example of a piece of machinery that uses the Brayton cycle in its operation. Since there is typically no heat exchanger between states 4 and 1 in a gas turbine engine, the engine utilizes an open cycle version of the Brayton cycle. Air from the surrounding environment enters the
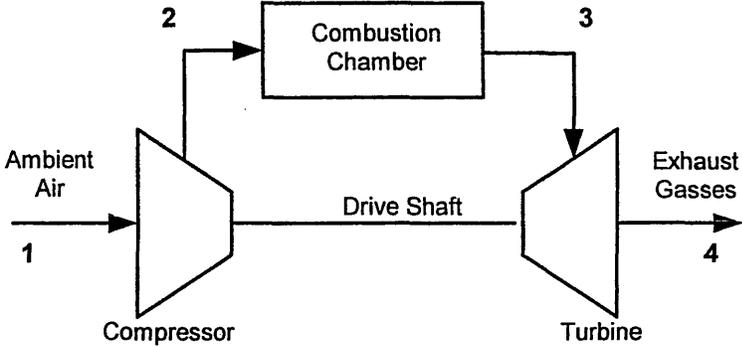
Figure 3: A block diagram of an open cycle gas turbine engine with states 1-4 labeled.
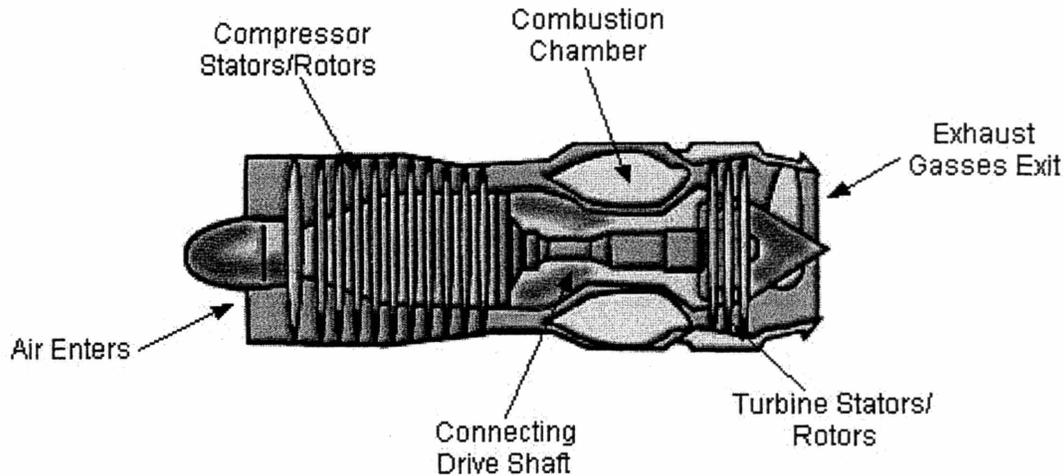
Figure 4: A cross sectional diagram of a typical gas turbine engine. The air enters on the left and exits on the right. (Copied from http://www.ueet.nasa.gov/Engines101.html)

compressor where its pressure is increased. The increase in pressure allows it to mix and combust more fuel as compared with uncompressed air in the same volume. The pressurized air then passes into the combustor where it is mixed with a fuel and burned. The high temperature mixture of combusted gasses is then ducted through the turbine where energy is extracted from the gas flowing. Part of the energy extracted by the turbine is used to turn the compressor to keep the unit running. The rest of the energy is free to be utilized as the user pleases.

Compressors can take form as either axial or radial flow mechanisms. In axial
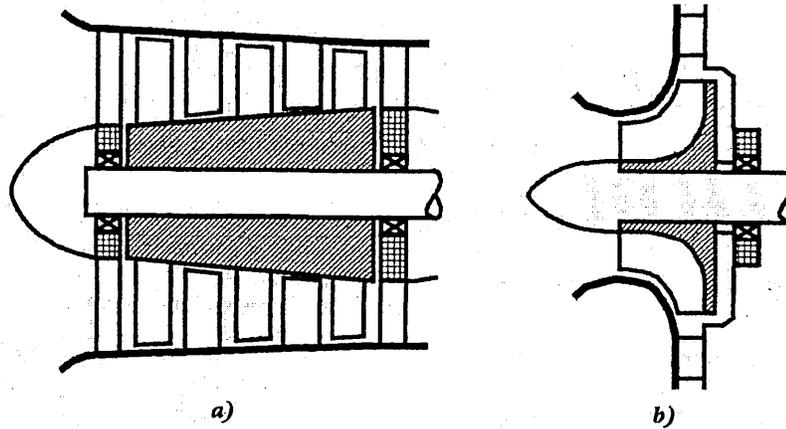
Figure 5: Example cross sectional diagrams of an a) axial flow compressor and a b) radial flow compressor. (Copied from Kamps 12)

flow compressors, the air flows parallel to the drive shaft. Compression usually takes place as the air passes through alternating stages of rotating wheels bristling with compressor blades and stationary diffuser or stator sections. The axial compressor is more common in large turbines and on jet aircraft where the resulting pressure ratios can reach over 30:1. Radial flow compressors take incoming air and accelerate it perpendicular to the drive shaft. Radial flow compressors feature a larger frontal area than their axial flow counterparts which makes them less desirable for use on high speed aircraft. However, this disadvantage is countered by the relatively high pressure increase per stage created within the radial flow mechanism as well as its simplicity and robust nature.

The combustor is the section of the gas turbine system where the compressed air coming from the compressor is mixed with fuel and burned to create a mixture of hot gasses. There are no moving parts in the combustor, but important features are included in it nonetheless. Once the engine is started, usually with the aid of some sort of ignitor, the flame must survive continuously. This feat is made more difficult with the high speed

air from the compressor swirling around within the combustor. To protect the flame, part of the combustion chamber's volume is sectioned off with a flame tube. In addition to protecting the flame, the flame tube must be designed to allow the right amount of air to pass through it to form the correct stoichiometric balance with the fuel being injected in the first third of the tube, also referred to as the primary region. Further down the tube, more air is allowed in to complete the combustion of the injected fuel. Finally, the remainder of the air is admitted near the end of the flame tube to lower the exhaust gas temperature to prevent the addition of heat stresses on the turbine blades.

The turbine is the final component of the gas turbine system. It is essentially a compressor in reverse as it takes the mixture of hot gasses from the combustion process and releases them to the atmosphere while extracting energy from them. As with the compressor, axial flow and radial flow versions of turbines exist. In axial flow turbines, the gas flows parallel to the drive shaft over several stages of stators and rotors. The stator sections contain guide vanes that act as nozzles to accelerate the working fluid in the correct direction to push the rotating rotor blades. The radial flow turbine has the hot gas ducted in tangential to the drive shaft. The blades of the turbine are driven by the entering gasses while at the same time redirecting them to exit the turbine housing along the axis of the drive shaft.

Automobile Turbochargers

A turbocharger is a device that combines a compressor and a turbine on a common shaft. The turbocharger is mounted on the exhaust system of an internal combustion engine. Exhaust gasses from the engine are ducted through the turbine side

of the turbocharger where energy is extracted to power the turbocharger compressor. The

exhaust gasses spin the turbine and are ducted out the tailpipe of the automobile. The

energy gathered by the turbine is used to power the compressor. Air from the

surrounding environment enters the compressor side of the turbocharger. The

compressed air is then sent to the engine either directly or via a heat exchanger. The heat
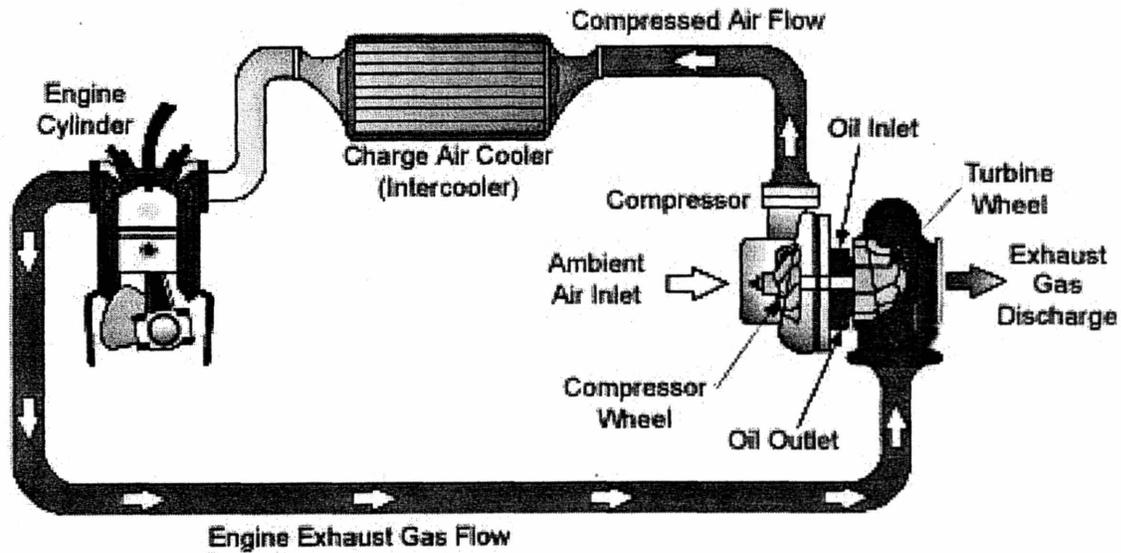

Figure 6: Diagram of how the turbocharger is integrated into the automobile combustion
cycle. (Copied from http://auto.howstuffworks.com/turbo2.htm)

exchanger is designed to further increase the density of the air entering the engine by

reducing its temperature. Once into the engine, the dense air allows the automobile to

combust more fuel in the volume afforded by the piston-cylinder compared with the

performance accorded by normal atmospheric air.

Turbocharger Gas Turbine

Turbochargers that are used to boost the performance of automobile engines

contain two of the three components in a gas turbine engine. Ambient air is pressurized

by the compressor and energy is provided for the compressor by a turbine spun up by the exhaust gasses of the car's engine. The addition of a combustor changes the turbocharger from an automobile accessory to a gas turbine.

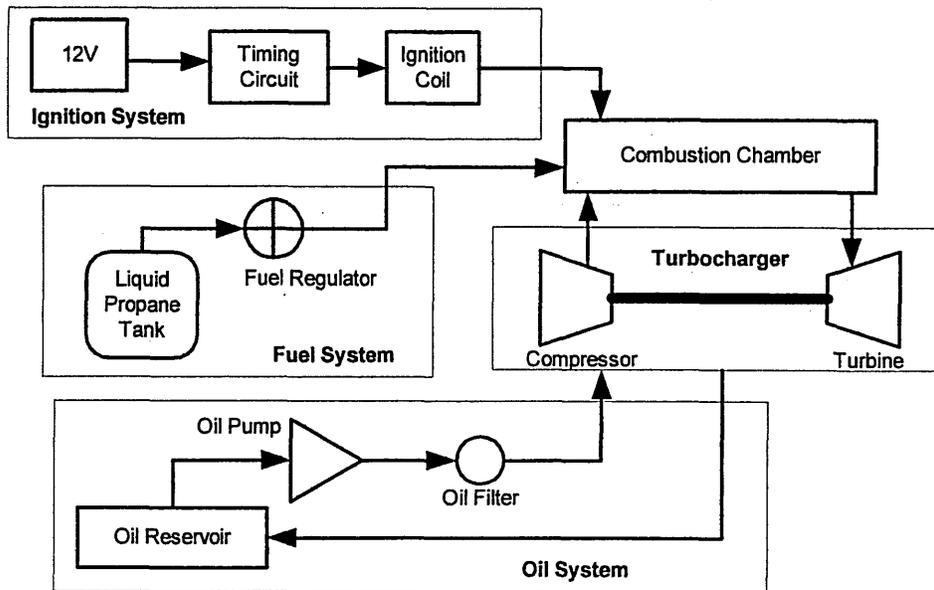To make the turbine run, other component systems are needed. The oil system

Figure 7: A block diagram of the turbocharger gas turbine separated by its different systems.

cools and lubricates the hydrodynamic bearings that the drive shaft is supported by. Normally the oil would be supplied by the same pump that circulates oil through the car's engine, but in the case of this project, a replacement system is necessary. Fuel handling and ignition systems are also required to start the engine and maintain its operation.

Turbocharger

The turbocharger that will be used on the gas turbine project is a KKK brand, model K26 turbocharger. It was removed from a 1985 Audi and purchased from an auto
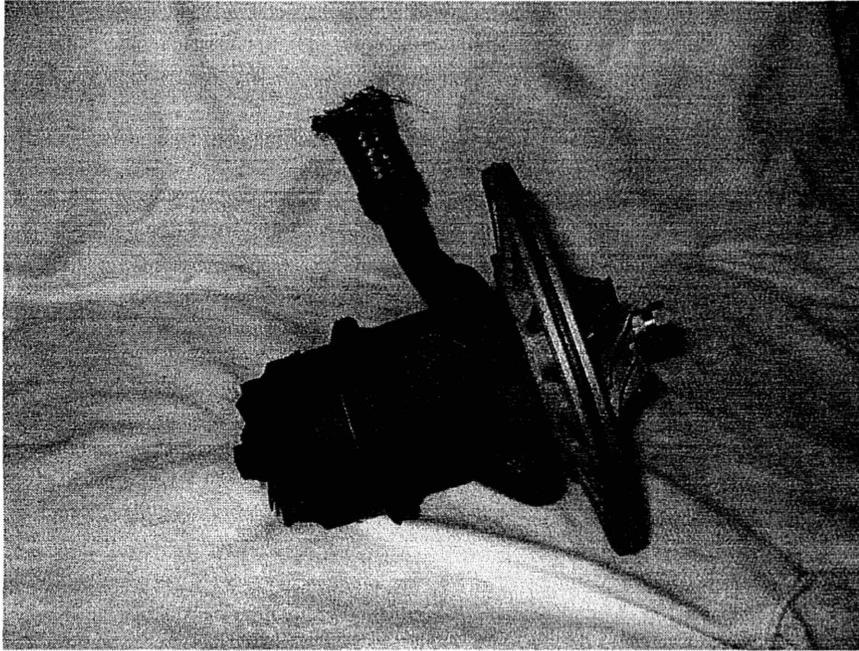
Figure 8: The K26 turbocharger with the compressor and turbine housings removed. The compressor is on the right and the turbine on the left.

salvage dealership. When purchasing the turbocharger unit, the main point of consideration was the state of the bearings in the housing and the turbine and compressor blades. The bearings seemed to be in good condition as they allowed a little radial play and no axial play at all. The main drive shaft spun smoothly and easily and the turbine and compressor blades had no visible damage. Secondary consideration was given to the ease with which the turbocharger would be able to be integrated into the gas turbine system. The chosen unit had housings that could be rotated with respect to each other. This feature allows for greater freedom in the positioning of the combustion chamber and the plumbing that connects the parts. This particular K26 also had the main oil inlet and outlet connectors intact. Since the oil system is very important to the life and functioning of the turbocharger, this was viewed as a particularly useful feature.

Oil System

Because the turbocharger being used was oil cooled, a well designed oil system is crucial to the performance of the engine. The turbocharger unit also has hydrodynamic bearings that ride on a thin film of oil at around 40-50 psi pressure. The pump being used to supply this pressure is a Melling model M-68 oil pump from a Ford 302 engine. This
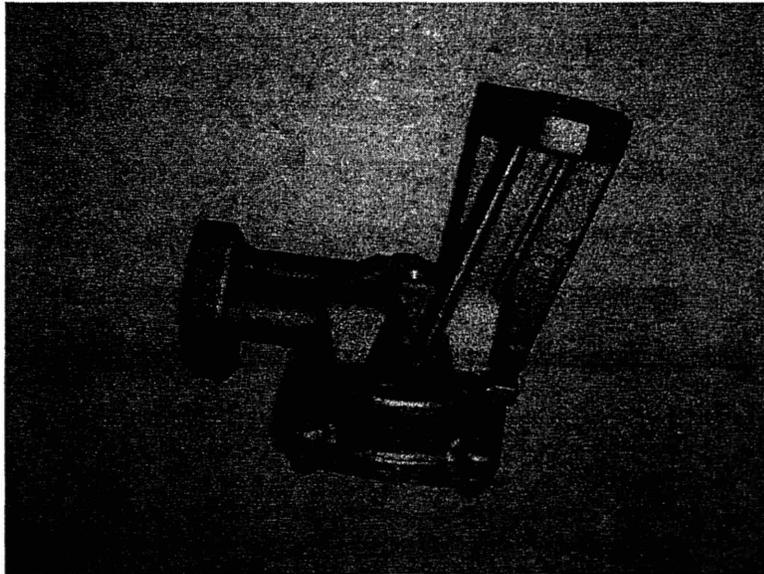

Figure 9: The Melling model M-68 oil pump that will be used to supply oil pressure to the turbocharger gas turbine.

pump was chosen because of its milled flat inlet and outlet ports and a 1/4" hex rod power shaft. Many oil pumps are built to fit into recesses in the automobile engine with special shafts to power them, so finding one that would be easy to mount adaptors for the oil hose to was an important task. A spring loaded pressure check valve may need to be incorporated to combat pressure spikes in the oil lines. Turning the pump is the motor and planetary gearbox from a Black & Decker cordless screwdriver. A speed controller should be connected to the motor so that the oil pressure can be varied to make it easier to start the engine. The planned speed controller will make use of a potentiometer

15

connected to a transistor to avoid too high a current running through the potentiometer. Due to the delicate insides of the turbocharger bearing housing, even the smallest particle could get wedged and wear away at the bearings or drive shaft, eventually leading to failure. For this reason, an oil filter must be incorporated. Remote oil filter locators, commonly used to relocate an oil filter in a car, will be placed between the pump and turbocharger in the oil system.

Fuel System

The gas turbine can be powered by almost any kind of combustible solid, fluid or gas provided that the correct air/fuel mixture can be obtained in the combustion chamber. For this gas turbine project, liquid propane gas has been chosen. Liquid propane is convenient to use because no fuel pump or special nozzle is required. Furthermore, it is easy to obtain and burns cleanly, leaving no carbon deposits. The alternative liquid fuels like kerosene or diesel require special 100 psi fuel pumps and atomizing nozzles. Another disadvantage of burning liquid fuels is a difficulty of handling the fluid and the smell and smoke associated with the combustion.

A liquid propane gas torch regulator will be used to control the flow of fuel into the combustion chamber. The specific model was chosen due to its ease of connection with both the propane tank and the propane rated hose used to connect the tank to the fuel injector. The fuel injector will be a 3/16 inch brass tube with a very small orifice attached to the end. The small opening is to prevent the flame from traveling back up the fuel hose.

Ignition System

The ignition system is only used when the engine is starting up. Once the flame is developed and the compressor spools up, the flame will be able to sustain itself. To get the flame started, an automobile spark plug will be used to ignite the fuel/air mixture in the combustion chamber. The input voltage necessary for the spark plug to fire is fairly high, so a timing circuit will be used in conjunction with an ignition coil to spark the plug.
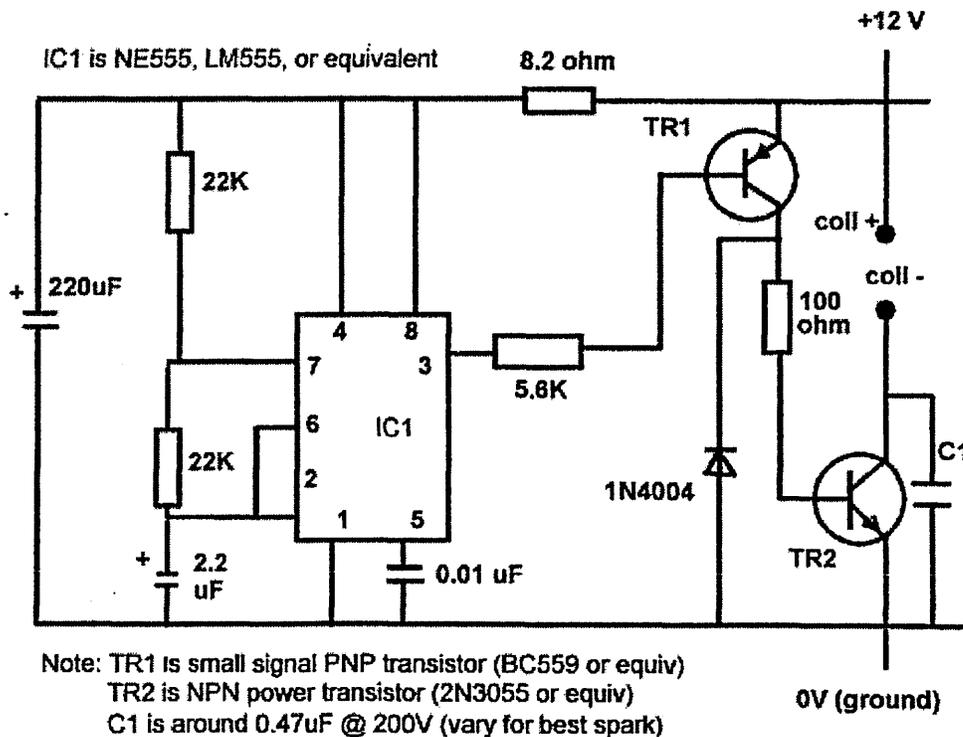

Figure 10: A schematic drawing of the ignition circuit. The spark plug connects to the output of the coil. (http://aardvark.co.nz/pjet/images/ignitor1.gif)

Combustion Chamber

The combustion chamber is arguably the most difficult part of the conversion to create. If the distribution of holes in the flame tube is not correct, the ratio of air and fuel

will not be correct and the flame will not sustain itself. Furthermore, if the combustion chamber is not large enough, the flames will extend into the turbine housing and damage the turbine blades. For these reasons, the combustion chamber is expected to take several tries before it works well and reliably.

The first iteration of the combustion chamber will be made with an outer housing
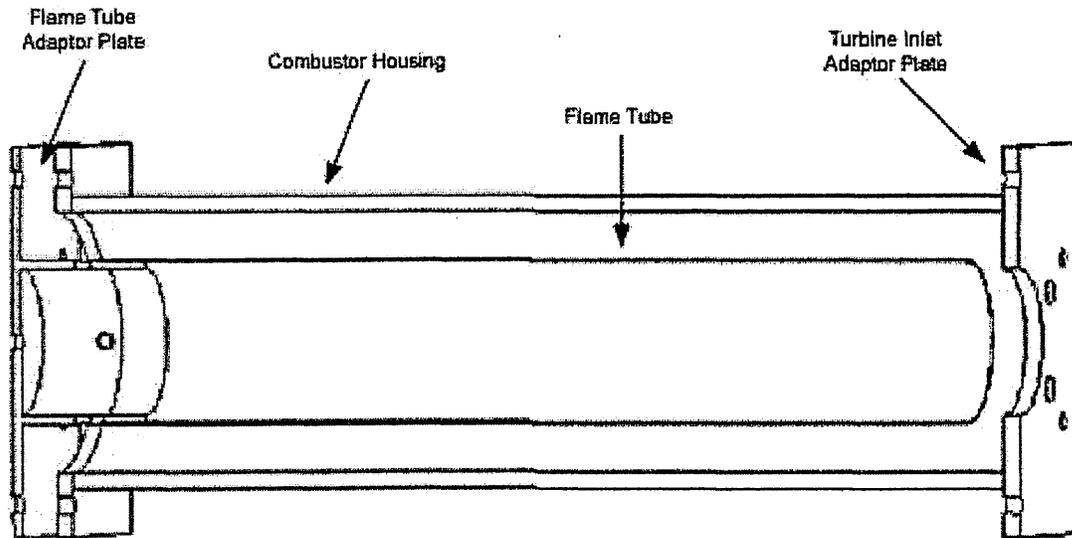

Figure 11: An expanded view of the combustion chamber assembly showing the main parts to be included.

cut from 4 inch steel pipe and a flame tube made out of 22 gauge perforated steel. The choice of the outer housing was made because a large volume was desired to keep the temperature within the combustor lower. The air that does not participate in combustion of the fuel remains outside the flame tube and cools it by means of forced convection. Perforated steel was chosen for the flame tube material because of its successful use in a similar project's design. The perforations should also facilitate lowering the metal temperature as well as lessen the number of holes needed to be drilled in the flame tube.

Air coming from the compressor will flow into the combustion chamber via a 2 inch pipe welded tangentially to the combustor housing. Normal combustors have swirl vanes to create a vortex in the flame tube that helps to keep the flame alive. By admitting the high pressure air to the combustion chamber tangentially, it may create a similar effect. The vortex formation will be aided by the design of the flame tube. The perforated steel will be rolled into a tube so that the ends overlap each other. Spot welds will secure the tube while allowing more air to enter the flame tube in the same tangential direction that it enters the combustion chamber housing.

Adaptor plates constructed from 1/4 inch and 1/8 inch steel plates will be used to make the combustor easier to take apart and modify. On the turbine side, the plates were necessary to connect the outer housing of the combustion chamber to the turbine inlet. On the other side of the combustor, the plate is used to seal off the chamber. The fuel injector and igniting spark plug will pass through the plates on that side.

Sensors

A variety of sensors is needed to monitor the performance of the engine. This requirement is to make sure that the engine is functioning properly as well as to gather data so that the engine is a useful classroom demonstration.

It is crucial that the turbocharger's bearings receive a constant supply of oil at the right pressure. Because of this fact, the oil pressure has to be carefully monitored with a pressure sensor tapped into the oil line as close to the turbocharger as possible. Motor oil will break down if its temperature gets too high, so the temperature of the oil must also be watched with a thermocouple in the oil reservoir.

The other major possible cause of failure in the engine is heat stress on the flame tube and turbine rotor blades. To make sure that these components remain in good working order, the exhaust gas temperature must be displayed to make sure that it does not get too close to the steel melting temperature of around 1200 degrees Celsius. This parameter will be measured with a type B or type K thermocouple. The type K only reads up to 1100 while the type B reads higher with an expanding error as the temperature rises.

The efficiency of the cycle can be determined if the temperatures of all four states is known along with the pressure after the compressor. The temperatures in states 1 and 4 are the ambient and exhaust gas temperatures and are easy enough to monitor since the exhaust temperature must be recorded for safety. The other two temperatures are the temperatures of the gas leaving the compressor and entering the turbine. These temperatures can also be monitored with thermocouples. The compressor outlet pressure is also known as the boost pressure and can be recorded with a pressure gauge.

The efficiency of each component can be found if the values mentioned above are known. For the turbine alone, the equation for its efficiency is given as

$$\eta_{turbine} = \frac{\dot{W}_{actual}}{\dot{W}_{reversible}} = \frac{(T_{in} - T_{out})_{actual}}{(T_{in} - T_{out})_{reversible}}, \tag{7}$$

where the actual temperatures are the values measured from the apparatus and the reversible temperatures are the ideal values. The reversible outlet temperature is found using the second law of thermodynamics,

$$\frac{\partial S}{\partial t} = \sum \frac{\dot{Q}}{T} + \sum_{in} \dot{m}s - \sum_{out} \dot{m}s + \dot{S}_{gen}, \tag{8}$$

where $\dfrac{\partial S}{\partial t}$ is the time rate of change of entropy in the system, $\dfrac{\dot{Q}}{T}$ is the entropy

transferred by heat exchange across the system boundary, $\dot{m}$ is the mass flow rate across

the boundary, s is the specific entropy, and $\dot{S}_{gen}$ is the rate of entropy generated. Since

the turbine is modeled as an adiabatic, reversible, constant flow component, the entropy

transfer, time rate of change of entropy in the system, and entropy generated terms are

zero and the mass flow rate in is equal to the mass flow rate out. This simplification

leaves the equation,

$$s_{out} - s_{in} = 0,\tag{9}$$

which can also be expressed as,

$$c_p \ln\left(\frac{T_{out}}{T_{in}}\right) - R\ln\left(\frac{P_{out}}{P_{in}}\right) = 0.\tag{10}$$

Now everything but T_{out} is known and the outlet temperature of the turbine for the

reversible case can be determined and used to find the turbine efficiency.

The compressor efficiency is expressed by the equation,

$$\eta_{compressor} = \frac{\dot{W}_{reversible}}{\dot{W}_{actual}} = \frac{(T_{in} - T_{out})_{reversible}}{(T_{in} - T_{out})_{actual}}.\tag{11}$$

By following the same steps as with the turbine, the outlet temperature for the reversible

case can be found and applied to Equation 11 to find the efficiency for the compressor.
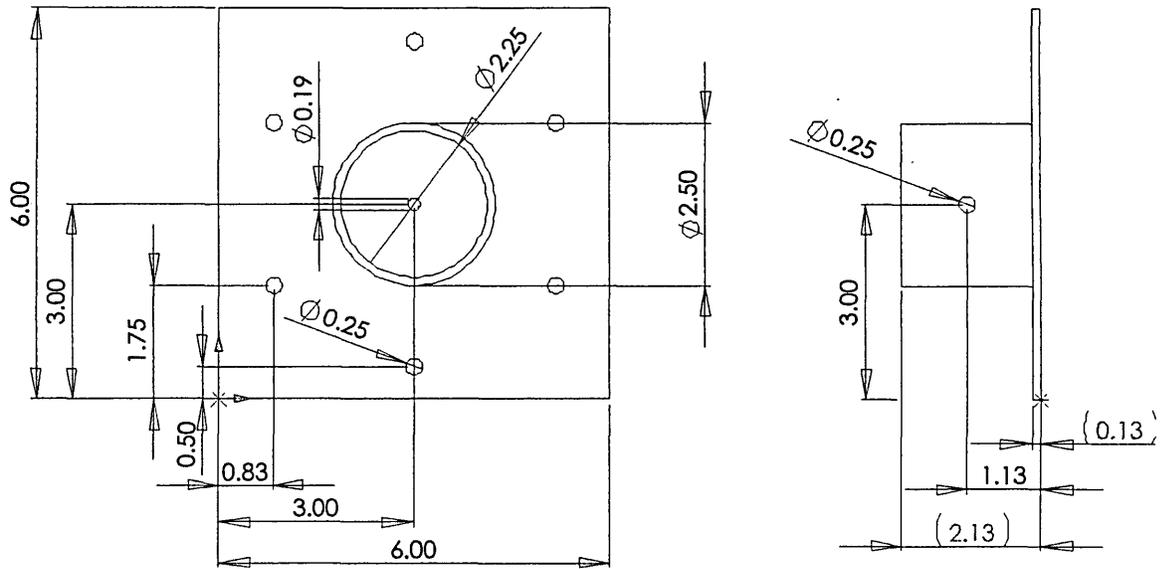
Appendix A:

Figure A.1: Dimentioned drawing of the plate on the side of the combustion chamber where the fuel injector and ignitor are located.
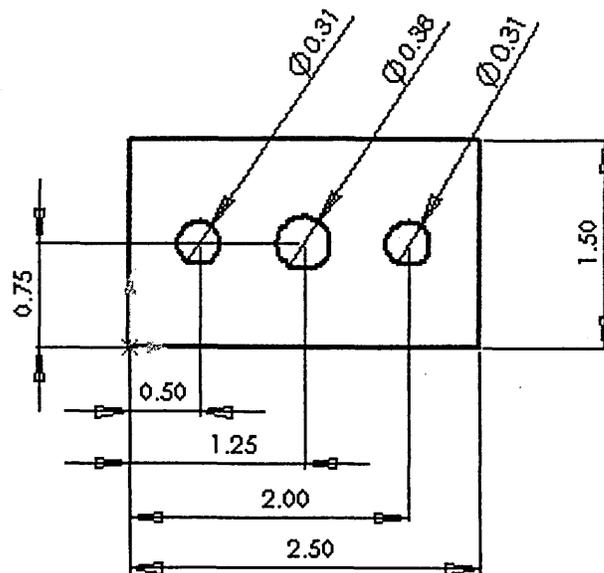

Figure A.2: Dimentioned drawing of the turbocharger oil adaptor plates that must be machined.
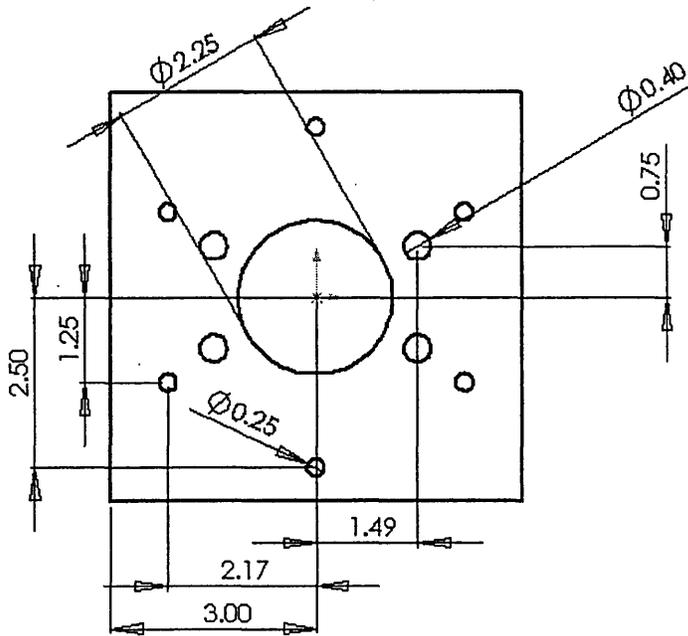
Figure A.3: Dimentioned drawing of the hole layout for the adaptor plate that fits the combustion chamber to the intake of the turbocharger turbine.
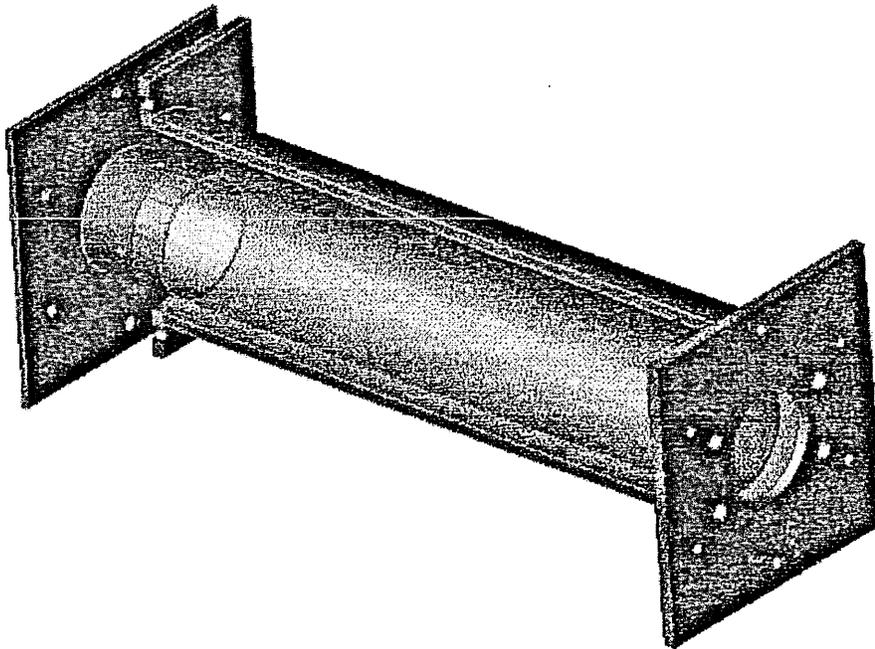

Figure A.4: Cross-sectional view of the combustion chamber assembly with adaptor plates and flame tube.

References

Jansen, Simon. "Turbocharger Gas Turbine." <u>Turbocharger Gas Turbine</u>. 18 March, 2003 <http://www.asciimation.co.nz/turbine/>.

Kamps, Thomas. <u>Model Jet Engines</u>. Worcestershire, UK: Traplet Publications Limited, 1995.

Simpson, Bruce. "Gas Turbine Project Diary." <u>Gas-Turbine Jet Engine: Project Diary</u>. 20 March 2003 <http://www.aardvark.co.nz/pjet/turbine1.htm>.