Waste Heat Recovery in Automobile Engines
Potential Solutions and Benefits

By

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ABSTRACT

Less than 30% of the energy in a gallon of gasoline reaches the wheels of a typical car; most of the remaining energy is lost as heat. Since most of the energy consumed by an internal combustion engine is wasted, capturing much of that wasted energy can provide a large increase in energy efficiency. For example, a typical engine producing 100 kilowatts of driveshaft power expels 68 kilowatts of heat energy through the radiator and 136 kilowatts through the exhaust. The possibilities of where and how to capture this lost energy are examined in this paper. The solution of recovering heat energy from the exhaust through the catalytic converter with a Stirling engine was examined due to its practicality. A novel approach for combining a Stirling engine and a catalytic converter that would be effective was designed. The power output and efficiency of the Stirling Engine were analyzed and it was found that the average overall car efficiency could be raised 7% with the new design.

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Chapter 1: Introduction and Background

Most car engines operate with an efficiency rate of about 30%, with most of the wasted energy lost as heat. There is an increased need to identify alternative energy sources and enhance the efficiency of car engines in order to reduce the consumption of fuel. The purpose of this paper is to examine whether lost energy can be recovered in the form of electricity to power the electrical components of a vehicle. Stirling engines, thermoelectrics, and turbines will be analyzed as possible solutions to recover this lost energy in order to improve the overall car engine efficiency.

1.1 Car Engine

Car engines operate at high temperatures due to the combustion process. Gasoline is combusted in order to provide the energy that propels the car. A very simple equation for this reaction would be:

$$\text{Gasoline} + O_2 + \text{Spark} \rightarrow CO_2 + H_2O + \text{Energy} \qquad (1)$$

This interaction takes place in the cylinders of the engine block. Gasoline, or fuel, and oxygen are compressed and "exploded" with a spark provided from the spark plugs. These tiny explosions create the energy needed to rotate the shaft which in essence makes a car go. The energy consists of heat and mechanical work. Water and carbon dioxide are the two main waste products found in exhaust. They are, however, not the only two products found in car exhaust. There are traces of carbon monoxide and other various forms of the partially burnt fuel. To simplify the theoretical analysis in Section 3 the exhaust is assumed to carry the properties of air.

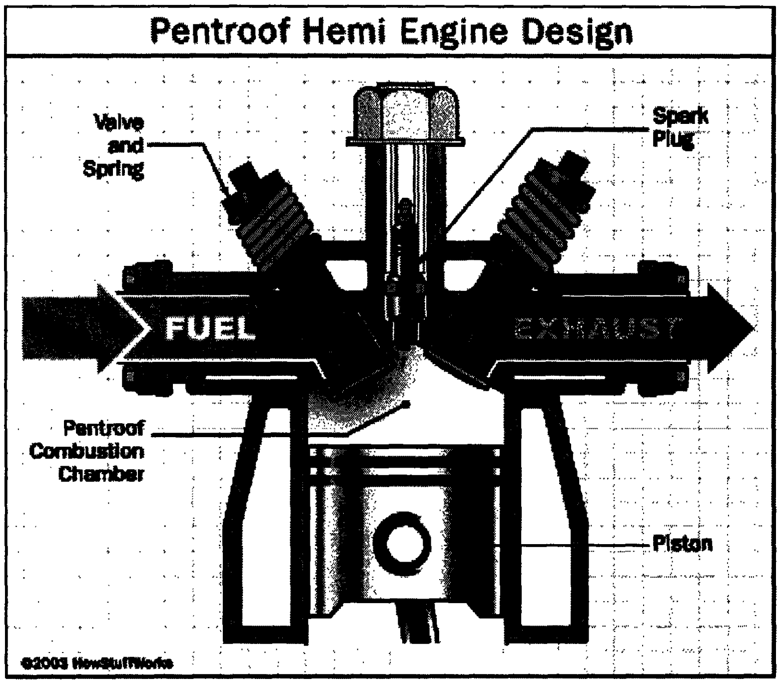

Figure 1 : Inside a typical car engine. Fuel is exploded in the combustion chamber to provide mechanical energy through the piston.

Heat generated from the combustion occurring in the cylinders of the engine block has to be dissipated quickly because it could possibly melt the aluminum block. The melting point of aluminum is 932K, according to *Fundamentals of Heat and Mass Transfer* [11]. In order to avoid serious damage to the engine, the block needs to be cooled with coolant that circulates throughout in small ducts around the combustion chamber. The other systems of the engine that do not get as hot as the block do not receive coolant. These parts are heated by friction or by the exhaust. The exhaust leaves the engine at very high temperatures which in turn heats the catalytic converter, an integral part of the exhaust system.

The best place to recover the wasted heat from the combustion is somewhere within the exhaust system, or from the radiator. The major components of interest are the catalytic converter and the turbo. All of these components run at very high temperatures and could be possible points of energy recovery. The following sections will discuss the background information of each possibility.

1.2 Catalytic Converter

The catalytic converter, or "cat," used on cars today was created in the United Kingdom sometime in the early 1990's, although early designs for the cat were used on vehicles in the late 1970's. Who invented it and what company first began manufacturing it is unclear because a few companies have claimed to be the founders of this technology. The cat is designed to work at high temperatures ranging anywhere from 300°C to 1200°C. At these temperatures the cat converts gasses considered pollutants into other non-harmful gasses, greatly reducing exhaust emissions.

Cars produce three main harmful emissions, mainly because the combustion process is never perfect. The cat, although efficient, cannot eliminate the production of carbon monoxide, hydrocarbons (also known as volatile organic compounds), and nitrogen oxides [1].

The most commonly used cat is the "three-way converter", known for helping reduce the three harmful emissions listed earlier. It is a triple purpose converter that reduces nitrous oxides into nitrogen and oxygen. It then oxidizes unburned harmful hydrocarbons and carbon monoxide into water and carbon dioxide. The converter uses two different types of catalysts, a reduction catalyst and an oxidization catalyst. Both types consist of a ceramic structure that looks like a honeycomb, coated with a metal catalyst, usually platinum, rhodium and/or palladium [2]. The idea is to create a structure that exposes the maximum surface area of catalyst to the exhaust stream, while also minimizing the amount of catalyst required. Figure 2 [2] shows the basic schematic of a catalytic converter.

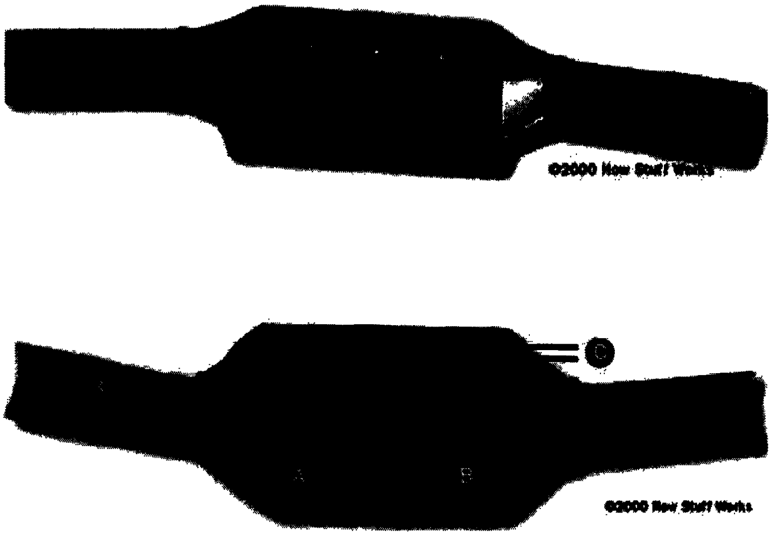

Figure 2: Basic Three-way Catalytic Converter.

Ⓐ Reduction catalyst
Ⓑ Oxidation catalyst
Ⓒ Honeycomb

The catalytic converter is of interest in trying to solve the heat recovery problem because of the high temperatures which it operates at. Other parts of the engine are deliberately cooled to make them more efficient, while the cat runs optimally at a high temperature. That makes it a good place to examine wasted heat in the engine. The heat lost could potentially be converted into electricity.

1.3 Turbocharger

The turbocharger, or the “turbo,” is a device that allows for more air to be compressed into a cylinder within a car engine, allowing for more fuel to be combusted. In turn, the car engine will produce more power providing a greater power to weight ratio in any given vehicle. Figure 3 and 4 [2] are good models of a turbo and how it uses exhaust from the engine cylinders to work.

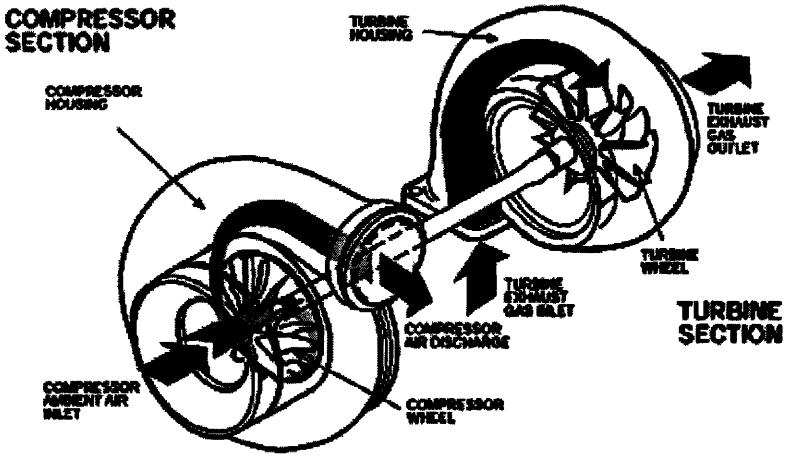

Figure 3: Inside a Turbocharger. High pressure/temperature exhaust gas from the cylinders is expanded and cooled across the turbine, which is coupled to a compressor to provide the cylinders with compressed air in order to burn fuel more efficiently.

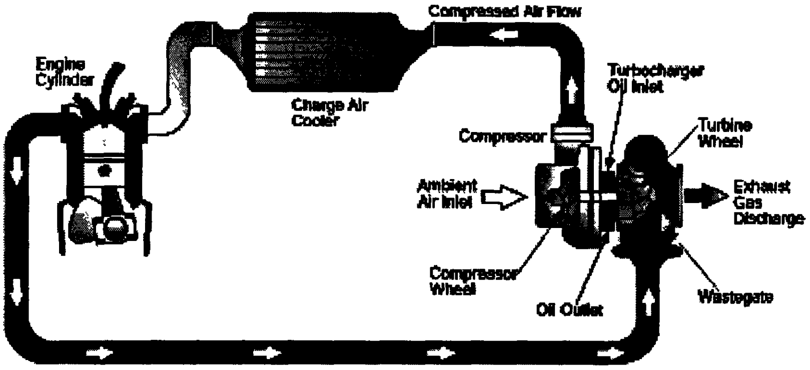

Figure 4: Basic Engine Schematic Incorporating the Turbocharger. This shows how the waste heat from the cylinders can be used to power other areas of the engine.

The turbo demonstrates a method that is presently utilized widely to convert wasted energy to improve the efficiency and power output of the car. The problem with current turbochargers is that they do not extract all the possible energy available.

1.4 Radiator

A radiator is a type of heat exchanger that transfers heat from the hot coolant that flows through it to the air blown through it by the fan. Coolant relieves the engine block of excess heat before going through the radiator, which cools it back down before returning to the block. Radiators are generally made out of aluminum and have extremely thin aluminum fins attached to tubes. The fins are the heat conductors that help transfer air through the radiator to be cooled. The tubes sometimes have a type of fin inserted into them called a turbulator, which increases the turbulence of the fluid flowing through the tubes. If the fluid that is in contact with the tube cools down quickly, less heat will be transferred. By creating turbulence inside the tube, all of the fluid mixes together, keeping the temperature of the fluid touching the tubes up so that more heat can be extracted, and all of the fluid inside the tube is used effectively.

A typical engine producing 100 kilowatts of driveshaft power expels 68 kilowatts of heat energy through the radiator. There is a possibility of using this heat to produce power rather than simply dispelling it to the environment. The best possibility of recovering this heat would be through the thermoelectrics discussed in Section 2.2 and 2.4.

Chapter 2: Possible Solutions

There are currently several technologies that can be exploited to remedy the problem of wasted energy. These technologies use differences in temperatures to produce energy. They all require a heat source and a heat sink. In a car, the exhaust system acts as the heat source and atmospheric air that flows over the system provides the heat sink. The different technologies that will be examined are Stirling engines, various types of thermoelectrics, and turbines. There is also a technology that is currently being developed in Europe called thermotunneling; which is a type of thermoelectric that will be discussed in Section 2.4 [8]. Each is a good candidate because they are all heat driven and can be manufactured relatively inexpensively and small in size.

2.1 Stirling Engines

Stirling engines operate on the Stirling cycle, a closed regenerative thermodynamic cycle. This cycle is useful to describe external combustion engines as well as solar-power systems [3].

Unlike an internal combustion engine, the Stirling engine has no valves and does not intake or exhaust gas. The air inside the engine is essentially trapped, which means there is no pollution. Heat is converted to mechanical work by alternately pushing the air from the cold side of the engine to the hot side. A Stirling engine can run off small differences in temperatures, even a difference of a couple of degrees. On the hot side the air heats, increasing the pressure inside the engine. On the cold side the air cools, decreasing the pressure inside the engine. This change in internal pressure drives a power piston in conventional two-piston engines or causes rotation in rotary engines (see Figure 5).

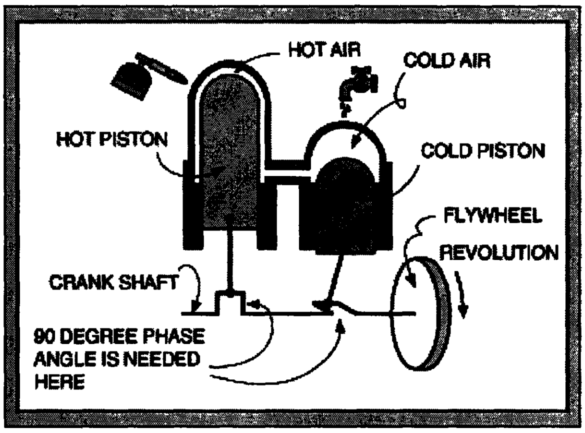

Figure 5: Basic Operation of a Two Piston Stirling Engine with a Flywheel

Stirling engines are used in many applications, most commonly for power generation when there is a large heat source and a quiet motor is needed. Figure 6 shows an actual Stirling engine used to generate electricity.

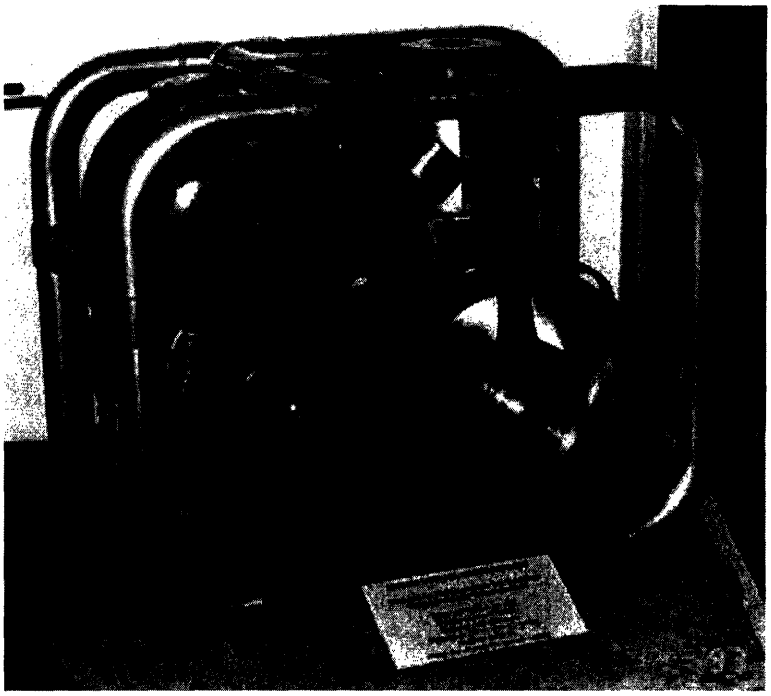

Figure 6: Stirling Generator of PHILIPS Corporation (the Netherlands).

In principle the Stirling cycle engine can have near ideal Carnot efficiency. The Carnot efficiency is the ratio of the effective, or useful output, to the total input. The Carnot efficiency (η) is given for the Stirling cycle as:

$$\eta = 1 - \frac{T_L}{T_H}, \tag{2}$$

where T_L is the temperature of the cold side and T_H is the temperature of the hot side. The efficiency goes up as the difference in temperatures gets larger. For example, if the hot side was running at 371° C and the cold side at 27° C, then the ideal efficiency of the motor would be 53 %. This makes it a very good candidate for waste heat recovery.

When coupling the Stirling engine to a turbine to extract electricity, the torque and friction present must be exceptionally small because friction can destroy the efficiency. Another downfall to consider is the heat source provided by the exhaust.

Since the heat source is external, it takes a short period of time for the engine to respond to changes in the amount of heat being applied because it takes time for the heat to be conducted through the cylinder walls and into the gas inside the engine. This means that the engine requires some time to warm up before it can produce useful power and that the engine can not change its power output quickly. Although the Stirling engine cannot start up simultaneously with the car engine to produce electricity, it can continue to run after the car engine has been turned off, and the extra power can be saved in the battery.

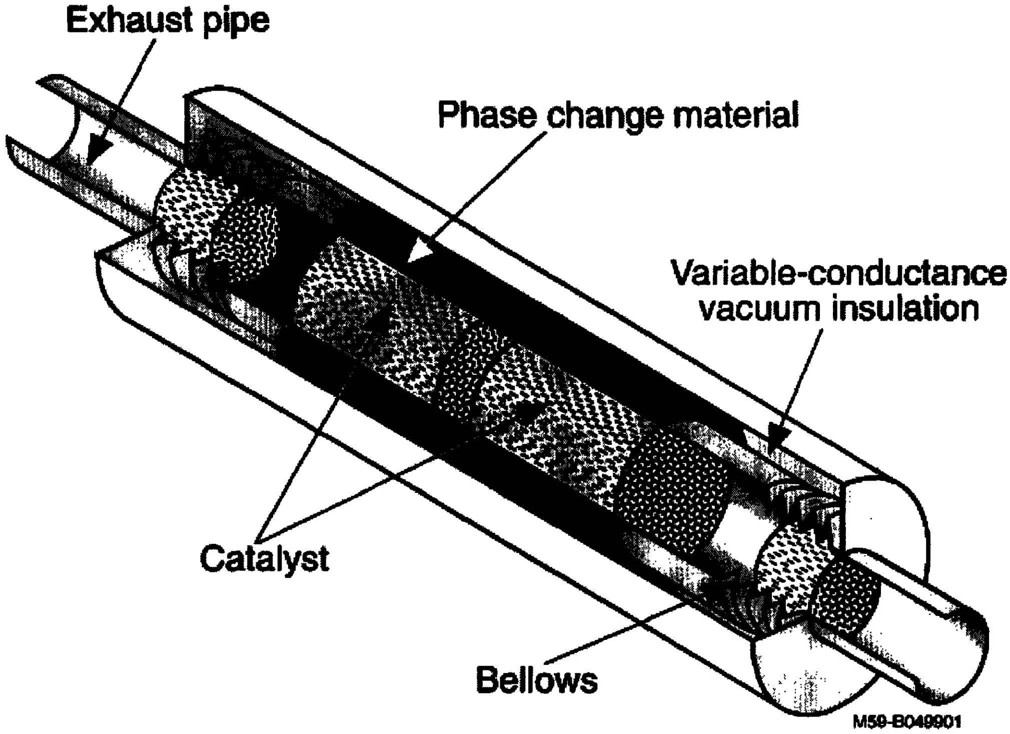

Figure 7: Inside View of a Catalytic Converter with Phase Change Material and Vacuum Insulation

New catalytic converters are being manufactured with a vacuum sealed case and phase change material (see Figure 7) [4]. These new features keep the cat hot for up to 36 hours to prevent cold starts. These innovations provide an excellent place to extract energy. If a Stirling engine was coupled to a cat on the inside of the vacuum it could produce electrical energy for hours after the engine was shut off. If this set up was used on a hybrid car the large batteries could be fully charged overnight without having to plug the car in and without having to burn gas to charge them.

2.2 Thermoelectrics

The second major option in waste heat recovery is thermoelectrics. Very simply, the principle of thermoelectrics is the creation of electric current from a temperature gradient or the creation of a temperature gradient from a current. Thermoelectrics are based on the Seebeck Effect and the Peltier Effect, which were both discovered in the early 1800's. The Peltier Effect is widely known and used in many electric cooling applications that vary from small digital cameras to large refrigeration units and air conditioners. The basic principle is that by providing a DC current to two dissimilar metals a temperature differential can be established. Figure 8 [5] is diagram of how a Peltier thermoelectric works.

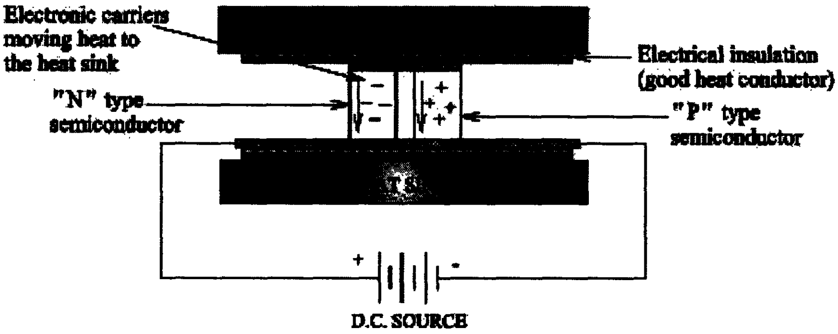

Figure 8: Cross Section of a Typical Thermoelectric Couple

Currently, thermoelectric modules are manufactured using "two thin ceramic wafers with a series of P and N doped bismuth-telluride semiconductor material sandwiched between them" [5]. The ceramic material on both sides of the thermoelectric adds rigidity and the necessary electrical insulation. The N type material has an excess of electrons, while the P type material has a deficit of electrons. One P and one N make up a couple, as shown in Figure 8. The thermoelectric couples are electrically in series and thermally in parallel. Using Peltier thermoelectrics, it is possible to provide either heating or cooling using only current.

The Seebeck Effect runs in reverse of the Peltier Effect. Physicist Thomas Seebeck found that if you placed a temperature gradient across the junctions of two dissimilar conductors, electrical current would flow [6]. This is the thermoelectric concept that would be of interest, because it takes the wasted heat and converts it to useful electricity. Thermoelectric power generators convert heat energy to electricity. When a temperature gradient is created across the thermoelectric device, a DC voltage develops across the terminals. When a load is properly connected, electrical current flows.

At first glance this technology seems like the perfect choice for this project. The technology has no moving parts making it practically maintenance free and it creates no pollution. Seebeck thermoelectrics can be manufactured in a variety of shapes and sizes that would fit the needs of this project. However there are several downfalls to this technology. The devices being manufactured today are very inefficient, usually under 10 %. Basically the amount of current you can get out of these does not equal the cost.

2.3 Turbine

The concept of using a turbine to recover energy comes from the turbocharger. The turbocharger is a mechanism that increases the power output of the engine using a turbine (see Section 1.3 for more information). Rather than using the turbine to power a compressor, the turbine could be connected to a generator. Alternatively, a series of turbines could be connected to a series of generators. If an efficient design was implemented the alternator could be removed from the car to improve the efficiency of the engine by lowering the load on it and by decreasing the weight of the car itself. A turbine of this nature would have to be situated after the catalytic converter or else the cat would not be able to reach operating temperature.

2.4 – New Technology

Several new technologies have been emerging in recent years. These new technologies aim to improve the efficiency of the Seebeck and Peltier thermocouple. Two recent developments in thermoelectrics could offer the solution to the problem of wasted heat in many applications. Section 2.4.1 covers an improvement to thermal diodes done by an MIT professor that has produced Seebeck devices with an efficiency of 18 %. The second development covered in Section 2.4.2 has produced devices with a Carnot efficiency of 40 % using a new technology called thermotunneling.

2.4.1 Thermal Diode

Associate Professor Peter Hagelstein of MIT's Department of Electrical Engineering and Computer Science and Dr. Yan Kucherov of ENECO, Inc., have developed a semiconductor technology known as a thermal diode that has an efficiency of 18 % [7]. This technology, based on thermions developed over a century ago, is a great improvement because only 10% of thermal energy is converted to electricity by current thermoelectric generators. The heat source for this new semiconductor must be between 200°C to 300°C as compared to some of the first semiconductors known as vacuum gaps. These vacuum gaps needed operating temperatures higher than 1000° C.

The researches plan to improve the efficiency above 30 % at higher temperatures using different materials. If they can get to a thermal efficiency of 30 %, their device would be a remedy for heat waste recovery, as no pollution would be generated from the process. Although no pollution is released into the environment, Hagelstein noted that "there are toxic parts to the device and this could pose disposal problems" [7].

2.4.2 Thermotunneling

A new technology out of Giralter is taking thermocouples to upwards of 40 % efficiency [8]. The company is called Cool Chips and they are working on prototyping a thermocouple based on a new technology they have developed called thermotunneling. The process utilized nano-technology to decrease the size of the gap between the two metals. Power Chips are "wafer-thin, fingernail-sized diodes that use quantum mechanical thermotunneling to generate electricity from heat". They are expected to have a wide range of applications and to produce electrical power more efficiently and less expensively than any existing technology.

By eliminating the drain on an internal combustion engine required to produce electricity, the engine's full power can be directed to the driveshaft. Automakers may thus be able to achieve the same horsepower and torque output with smaller, lighter, and more fuel-economical engines. And by using Power Chips to generate electricity, automotive manufacturers will be able to eliminate alternators and belts and obtain greater design flexibility.

Chapter 3: Stirling Engine Theoretical Analysis

It is known that great amounts of energy are lost through heat in the automobile engine. The remainder of this paper will focus on the potential recovery of energy using a Stirling engine. Section 3.1 will cover the available energy that can be taken from the catalytic converter. Section 3.2 will discuss the theoretical possibilities of energy transfer through a Stirling Engine. Finally, Section 3.3 will discuss actual models and their potential.

3.1 Available Energy from the Catalytic Converter

Because of the large variations amongst automobiles, a specific cat and car model was needed to provide data for analysis. The catalytic converter used in the 1999 Z28 Camaro was chosen because information pertaining to it was readily available [9]. The specific dimensions of the Random Technology 8000 Series catalytic converter [11] used on the Camaro can be found in Appendix A.

Under normal operating conditions, the catalytic process doesn't begin until temperatures inside the converter reach 315° C. If the air to fuel ratio is on target, and the exhaust is free of contaminants, internal converter temperature stays at about 650° C. But when unburned fuel enters the cat, temperatures can reach 1200° C and either burn the precious metals or literally cause a meltdown. Since extremely high temperatures are to be avoided, the removal of heat from the exhaust line can be beneficial to the performance of the car.

Many assumptions must be made in order to analyze the system. The most important assumption is that the car is operating at steady state. This means that the wall temperature is at a constant 650° C and the exhaust gas coming out of the car is flowing at a constant rate and temperature. In real applications the car never operates at steady state, due to external and internal variations. For example, the volumetric flow rate varies depending on the car's RPMs and the temperature of the exhaust line both of which depend on the speed of the car and the temperature of the air outside, which are constantly changing. However, the assumption that the car is at steady state can be considered an average approximation of all scenarios. Next, the cat is assumed to be manufactured out of plain carbon steel AISI 1010; the values of constants can be found in Appendix B [11]. The constant values of the exhaust gas are assumed to be those of air at 900K (650° C), found in *Fundamentals of Heat and Mass Transfer* [11]; these values are listed in Appendix B.

The first thing to consider is maximum potential energy available ($\dot{Q}_{\text{maximum}}$) in the exhaust. This is found knowing the flow rate ($\dot{m}$), specific heat (c_p), and the difference between the temperature of exhaust ($T_{exhaust}$) and the temperature of the environment (T_{atm}) as

$$\dot{Q}_{\text{maximum}} = \dot{m}c_p\left(T_{exhaust} - T_{atm}\right). \tag{3}$$

Using Equation 3 and assuming a constant mass flow of 40g/s, a steady state exhaust temperature of 650° C, and that the car is traveling on a hot day in Florida with an outside temperature of 40° C the maximum available energy is

$$\dot{Q}_{\text{maximum}} = 268\text{kW}. \tag{4}$$

Because the cat requires a minimum operating temperature of 315° C, only 335° C are available for heat transfer. This means that the available energy ($\dot{Q}_{\text{available}}$) is

$$\dot{Q}_{\text{available}} = 130\text{kW}. \tag{5}$$

Only about half of the maximum energy can be extracted, this is because the cat uses the rest of the energy to catalyze the exhaust gas.

3.2 Theoretical Stirling Engine Possibilities

Consider an ideal Stirling engine that converts thermal energy into mechanical work. The efficiency, η, of this engine can be defined as

$$\eta = \frac{\text{Mechanical Work Out}}{\text{Thermal Energy In}} = \frac{\dot{Q}_H - \dot{Q}_C}{\dot{Q}_H} \tag{6}$$

where Q_H is the rate of thermal energy transferred from the hot side of the engine and Q_c is the rate of thermal energy transferred from the cold side of the engine. Combining Equations 3 and 6 the ideal engine will have an efficiency defined by

$$\eta = \frac{T_H - T_C}{T_H} = 1 - \frac{T_L}{T_H}. \tag{7}$$

It is possible to roughly estimate the mechanical work per cycle that the engine is capable of by multiplying the efficiency by the thermal energy in,

$$W_{out,\max} = \eta Q_H. \tag{8}$$

Real engines will suffer from losses from friction and heat conduction, therefore Equation 8 will not hold true. A much better estimate of the mechanical work output can be arrived upon by analyzing its thermodynamic cycle. In order to study the thermodynamic cycle I designed a Stirling engine that could be practically used with a catalytic converter. Figure 9 shows a cut out view of the 4 piston assembly.

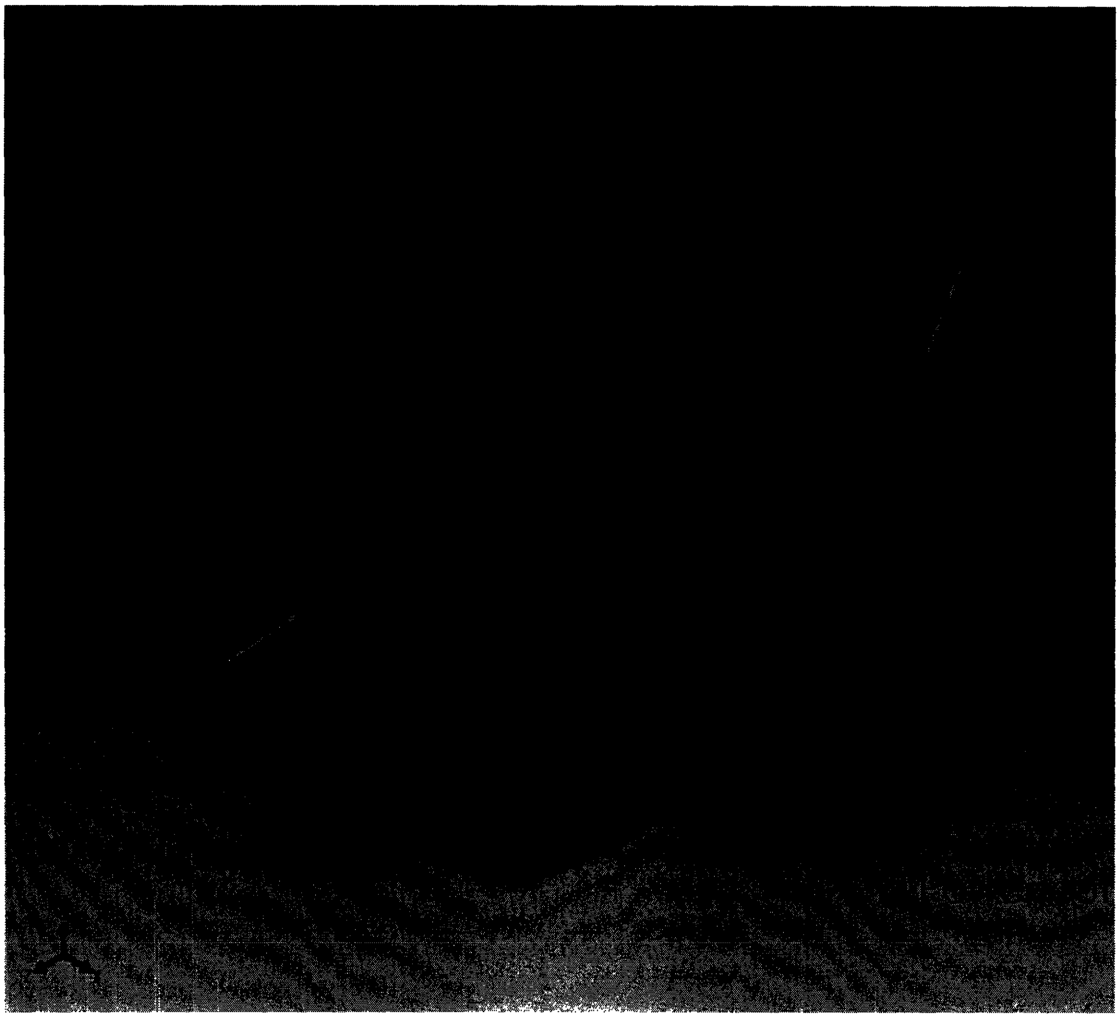

Figure 9: 4-Piston Stirling Engine. This engine was designed by me as a possible solution to waste heat recovery. This schematic is missing the fins that would wrap the outside of the case. The top half of the case is removed to see inside.

I chose a 4-piston assembly to balance the shaft that is powered by the pistons. The four pistons also cover more surface area along the cat in order to produce more power. Figure 10 shows a bottom view of the engine. Appendix D contains the drawings for the Engine.

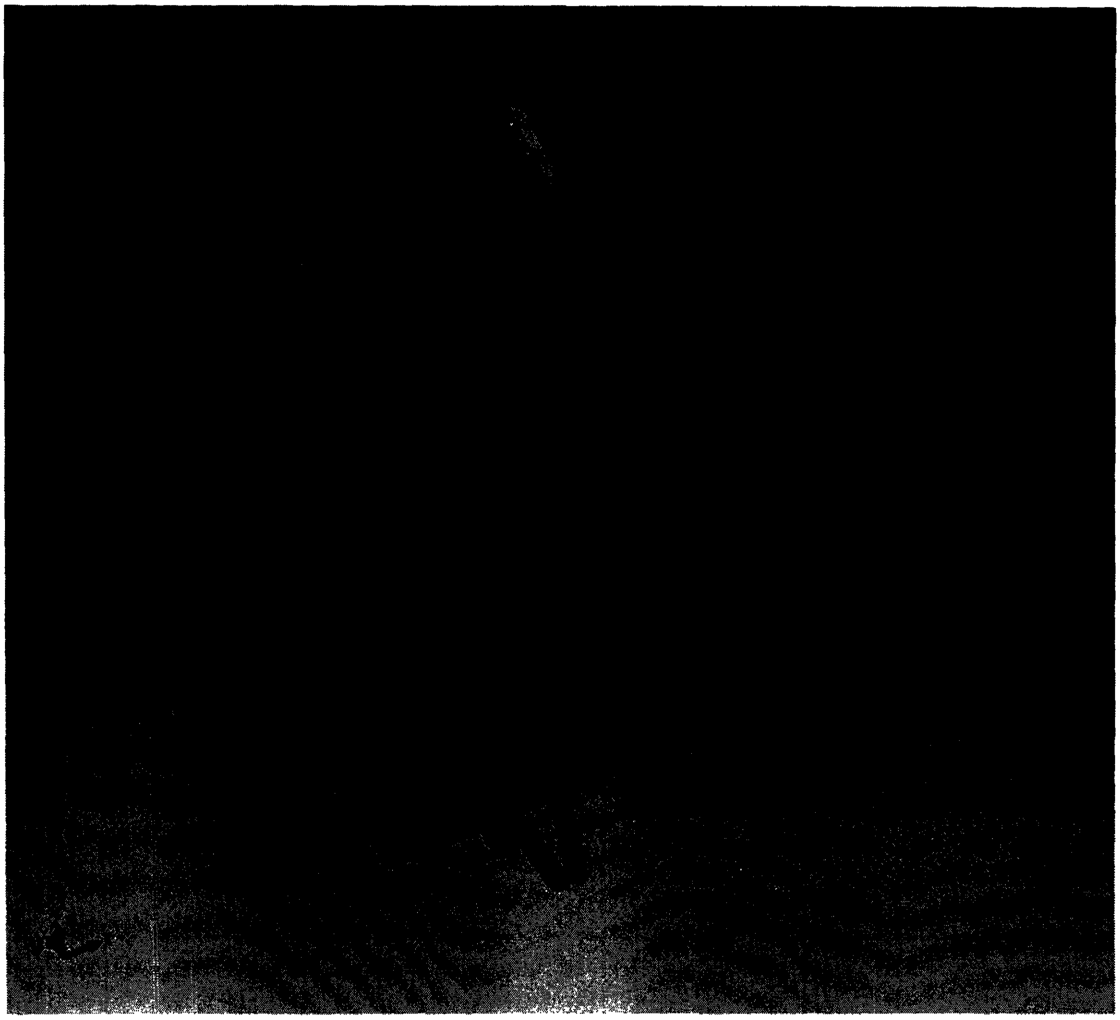

Figure 10: Stirling Engine Bottom View. Note the 90 degree offset of each piston.

In this design I abandoned the traditional power piston and displacer piston configuration for a two power piston arrangement. This allows for higher compression of air as the coupled pistons compress the gas near the cat together. Although all four pistons are coupled along the power shaft, the two pairs are isolated in their respective cylinders. The following analysis uses this design for all its parameters.

The basic definition of work is

$$Work = \int PdV . \tag{9}$$

where P is the air pressure inside the engine and V is the volume of air in the engine such that $V = V_C + V_H$ where V_C is the volume of air on cold side of the engine and V_H is the volume of air on the hot side of the engine. Assuming the two power piston displace a gas volume of V_{p1} and V_{p2} respectively then;

$$V_C = 2\left(\frac{1}{2}V_{p1}\cos\theta\right) \tag{10}$$

and

$$V_H = 2\left(\frac{1}{2}V_{p2}\sin\theta\right) \tag{11}$$

where θ is the phase angle of the two pistons. Thus, the total engine volume as a function of phase angle is

$$V = V_{p2}\sin\theta + V_{p1}\cos\theta \tag{12}$$

Since V_{p1} equals V_{p2} the terms add and

$$dV = V_{p1}(\sin\theta - \cos\theta)d\theta. \tag{13}$$

To express the engine air pressure, P, as a function of the air temperature the ideal gas law can be used as

$$P = \frac{MRT}{V}. \tag{14}$$

Thus, the engine mechanical work per cycle is

$$\frac{Work}{Cycle} = \int_0^{2\pi} \frac{MRT}{V} v_p \cos\theta d\theta. \tag{15}$$

Making this expression non-dimensional by dividing it by the average engine internal pressure times the two piston's displacements where $Vp = Vp1 + Vp2$ yields the equation

$$
{}'W \equiv \frac{\frac{Work}{Cycle}}{P_{engine}\cdot v_p} = \frac{\int_0^{2\pi} \frac{MRT}{V} v_p \cos\theta \, d\theta}{\frac{v_p}{2\pi}\int_0^{2\pi} P\, d\theta} . \tag{16}
$$

To be on the safe side the average pressure inside the engine is first set to run approximately equal to atmospheric pressure so that

$$
{}'W \equiv \frac{\frac{Work}{Cycle}}{P_{atm}\cdot v_p} = \frac{\int_0^{2\pi} \frac{MRT}{V} v_p \cos\theta \, d\theta}{\frac{v_p}{2\pi}\int_0^{2\pi} P\, d\theta} . \tag{17}
$$

Note that by pressurizing the engine, more power can be extracted. Using the ideal gas law and noting that the average temperature of the air inside the engine, T, is

$$
T \cong \frac{V_C T_C + V_H T_H}{V} , \tag{18}
$$

where T_C is the temperature of the air on the cold side and T_H is the temperature of the air on the hot side, the non-dimensional engine work per cycle becomes

$$
{}'W \equiv \frac{\frac{Work}{Cycle}}{P_{atm}\cdot v_p} = 2\pi \frac{\int_0^{2\pi} \left[\frac{V_C(\frac{T_C}{T_H}) + V_H}{V^2} \right] \cos\theta \, d\theta}{\int_0^{2\pi} \left[\frac{V_C(\frac{T_C}{T_H}) + V_H}{V^2} \right] d\theta} . \tag{19}
$$

Engine power can be found by multiplying the work per cycle times the engine speed,

$$
\text{Power} = P_{atm}\cdot v_p \cdot 2\pi \frac{\int_0^{2\pi} \left[\frac{V_C(\frac{T_C}{T_H}) + V_H}{V^2} \right] \cos\theta \, d\theta}{\int_0^{2\pi} \left[\frac{V_C(\frac{T_C}{T_H}) + V_H}{V^2} \right] d\theta} \cdot \text{engine speed} . \tag{20}
$$

Plugging in the volumes as a function of phase angle and the mechanical efficiency of the engine, η_S, Equation (20) becomes

$$\text{Power} = 4\pi P_{atm}\eta_S V_{p1}\frac{\int_0^{2\pi}\left[\frac{T_C\cos\theta + T_H\sin\theta}{(\cos\theta+\sin\theta)^2}\right]\cos\theta d\theta}{\int_0^{2\pi}\left[\frac{T_C\cos\theta + T_H\sin\theta}{(\cos\theta+\sin\theta)^2}\right]d\theta}\cdot\text{engine speed}. \qquad (21)$$

With a modest engine speed of 1000 RPM, perfect theoretical efficiency of 1, cold temperature of 40° C, hot temperature of 335° C, and a cylinder volume of 0.00061778 m^3 the power output would be 83kW. Appendix C has the MATLAB script used to solve the integral in Equation (21).

With a power output of 83kW, the overall theoretical efficiency would be 64%. This means that using a Stirling engine is a viable approach to recovering wasted heat, granted a high mechanical efficiency. By increasing the volume or the pressure of the engine the efficiency would be increased.

3.3 Recommendations

Using ideal processes and machines there exists a huge potential energy source. When looking at the real world application there are large design obstacles to overcome. There are two pitfalls to the proposed Stirling engine design. The first downside is that there will be a lot of energy lost due to heat transfer through different materials. The available energy must be transferred through convection to the steel cat then through conduction through the steel to the Stirling engine and then through convection to heat the air in the engine. There will be large losses through this process.

To overcome the problem of losing energy through heat transfer the design should minimize the amount of material between the piston area of the Stirling engine and the exhaust flow in the cat. Fins need to be placed on the cold side of the Stirling engine to maximize the heat transfer out of the engine.

The second design downfall is tradeoff of size and weight of the Stirling engine for extra power. The added weight will decrease the car's fuel efficiency. Further study must determine whether the electrical power produced will be good enough to warrant the extra weight and the extra cost of manufacture and maintenance. This application would be most beneficial in a hybrid car, so that the batteries could charge during the night.

The question of rotary engines arose while doing my research. There is a design for a quasiturbine Stirling engine which is claimed to have "up to 16 times more power than a piston [engine] with a comparable chamber volume!" [12]. At first glace the novel design looks amazing because it eliminates standard pistons and their inherent design constraints. Its benefit over typical Stirling engines is that it can be pressurized with gas and claims not to leak. On inspection, though, it has a number of flaws that require further "breakthroughs", and seems like an ill suited choice when considering the practicality of attaching this design to a catalytic converter or elsewhere in a car engine [13].

My design is better suited for the application of heat recovery than the rotary engine for a number of reasons. First, my engine could be self pressurized in the same way as the quasiturbine. Second, the size and shape of my engine is more practical for use under a car. And finally, the other engine suggested suffers from a very complex geometry that requires in depth study to verify that it is indeed more efficient than a standard Stirling engine.

Chapter 4: Conclusion

For this project I designed a Stirling engine taking size and weight into consideration. The engine is oriented in a flat manner because in operation it would be sitting under the car (an area with little room to spare). For the generic design the cat was assumed to be a circular tube; future designs will have to take the cat's truest geometry into consideration. The engine was designed with minimal parts to decrease the weight. Weight is a very important factor because adding heavy machinery to the car is going to decrease its fuel efficiency, so in order for this product to be viable it must be light. The design in Appendix D is completely my own, although inspiration for it was found in many places. A similar design may exist, but my research did not uncover anything quite like it.

I found that ideally my design could recover 64% of the available energy from the catalytic converter. In 3.1 I found that about half of the heat energy can be withdrawn from the exhaust without impeding the use of the catalytic converter itself. This means that there can theoretically be 32% waste heat recovery from heat trapped by the cat. This 32% efficiency is based on a frictionless ideal engine. If the engine was built to be 50% mechanically efficient then 16% of the heat coming out of the exhaust could be transformed into electrical energy. Since about 44% of the energy in fuel is lost to heat in the exhaust line, my Stirling design could increase the overall efficiency of the average car by 7%. This is a very promising number since the overall efficiency of a typical car is itself around 30%.

Overall, I have found that there exists a huge potential energy source that could be used to drastically change the efficiency of the automobile engine. I provided a simple design solution. Though my design requires more analysis to verify its validity and to specify its optimal dimensions, it represents an opportunity to make a large advancement in waste heat recovery. If viable this design would be a practical application of existing technology to solve an old problem.

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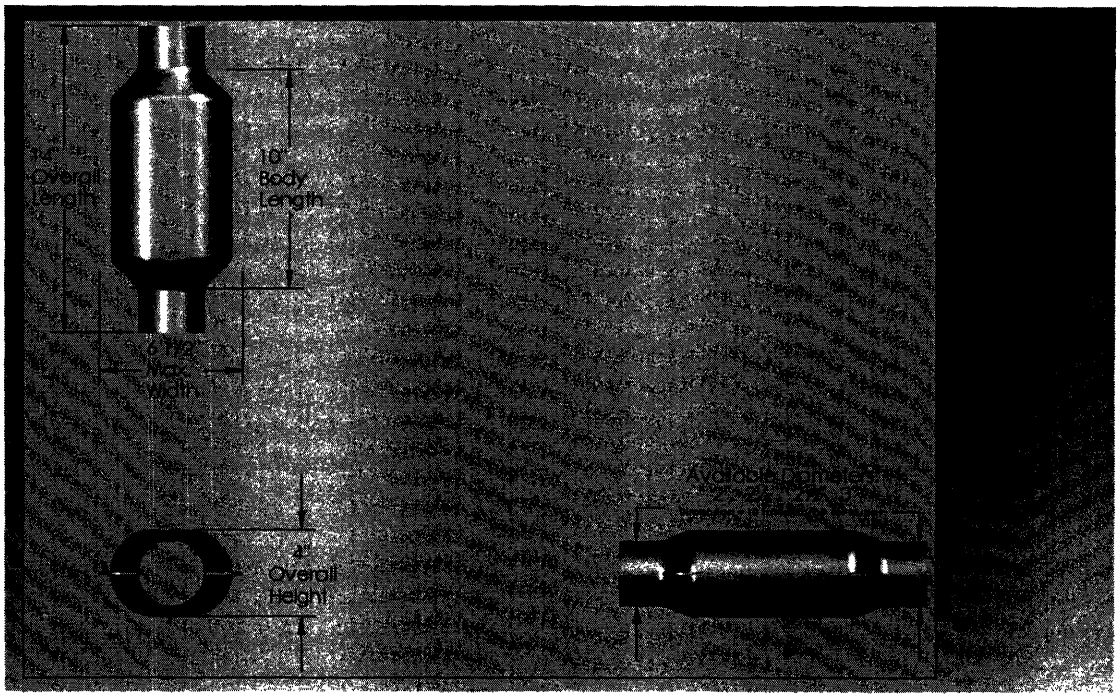
Appendix A:
Random Technologies 8000 Series Catalytic Converter Dimensions [9]



Catalytic Converter Parameter	Value	Units
Temperatures		
Operating	648.89	degrees C
Minimum	315.56	degrees C
Maximum	1204.44	degrees C
surface area		
total	0.129546	meters^2
half	0.064773	meters^3

Appendix B: Material Properties

Steel

Constant	Value	Units
Thermal Conductivity k	35	W/mK
Density ρ	7854	kg/m^3
Specific Heat c_p	900	J/kgK

Air

Constant	Value	Units
Thermal Conductivity k	0.596	W/mK
Density ρ	0.41	kg/m^3
Specific Heat c_p	1100	J/kgK
Prandtl Number Pr	0.716	

Appendix C: MATLAB Scripts

```
function dT = oddone(t,T)
Tc =313;%Kelvin
Th= 200+273;%kelvin

dT =
(Tc*cos(T)+Th*sin(T))/((cos(T)+sin(T))^2)/((Tc*cos(T)+Th*sin(T))/((cos(
T)+sin(T))^2)*cos(T));


function Ptop = dP(Tc,Th)
Tc=313;%Kelvin
Th=335+273;%kelvin
Vp1=.00061778;
RPM=10000;
Patm=101325;

[t,T]=ODE45('oddone',[0 6.282],0)
```

Appendix D: Stirling Engine Drawing