6.0 Thermal Analysis

By Gregory Berkeley

The thermodynamics of an auto engine are very complex and require a high degree of understanding to perform any type of precise analysis. This will be an attempt to simplify the thermal interactions in order to produce results for a more energy efficient engine for Formula One Racing. Prior to introducing any theory and mathematics it is first important to understand the interworking mechanisms inside of an engine.

6.1 Brief Description of Auto Mechanics: Four-Stroke Cycle

Formula One Racing implements internal combustion engines, which is common among cars, trucks, and motorcycles. These engines work using what is called a four-stroke cycle. This cycle allows for the heat that is produced from the spark plug to be converted into mechanical energy through the rotation of the engine's crankshaft. It begins when the piston is at a maximum displacement from the axis of the crankshaft, known as "top-dead center." After combustion the piston is forced downward to a minimum displacement from the crankshaft, known as "bottom-dead center." Then by momentum of the crankshaft the piston returns to it's initial position. One full cycle includes four "strokes," each with their own purpose. Each stroke refers to the full travel of the piston from top-dead center to bottom-dead center. A description of each stroke follows:

1. Intake-stroke: The piston descends from top-dead center to bottom dead center, reducing the pressure inside the cylinder. A mixture of fuel and air is forced by atmospheric (or greater) pressure into the cylinder through the intake port. The intake valve then closes.

2. Compression-stroke: With both intake and exhaust valves closed, the piston returns to the top of the cylinder compressing the fuel-air mixture. This is will cause the mixture to increase in pressure and temperature.

3. Power-stroke: While the piston is close top-dead center, the compressed air–fuel mixture is ignited by a spark plug. The resulting massive pressure from the combustion of the compressed fuel-air mixture drives the piston back down toward bottom-dead center with tremendous force rotating the crankshaft. This is the main source of the engine's torque and power.

4. Exhaust-stroke: During the exhaust stroke, the piston once again returns to top dead center while the exhaust valve is open. This action evacuates the products of combustion from the cylinder by

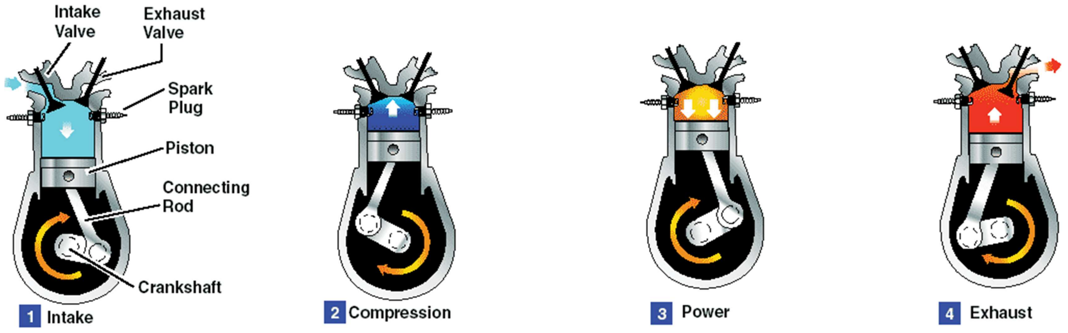

Figure 1.0 Four-Stroke Cycle

Preface

It is first important to mention that all of the proceeding research will be conducted at the maximum allowable power in Formula One Racing, 19,2560 rpm of the engines crankshaft. This is equivalent to about 750 horsepower with a torque of 279 $N \cdot m$. The goal of this study is to conjuncture a method that will allow for another 100 horsepower by utilizing the low thermal conductive property of Silicon Nitride (SiN_3). The following is a breakdown of all the methods used in this study.

6.2 Summary of Thermal Analysis

Since we are modeling at 19,250 rpm, the entire four-stroke cycle repeats every 6 milliseconds. This process happens so rapidly that the energy coming in from the spark plug can be described as a constant rate heat transfer into a system. The work coming out of the system, due to rotation of the crankshaft, can then be expressed as constant shaft power and the remaining heat is lost due to material heat conduction as well as exhaust. This allows for the use of a closed steady state[1] model. The following diagram gives a representation of the energy interactions in the system.

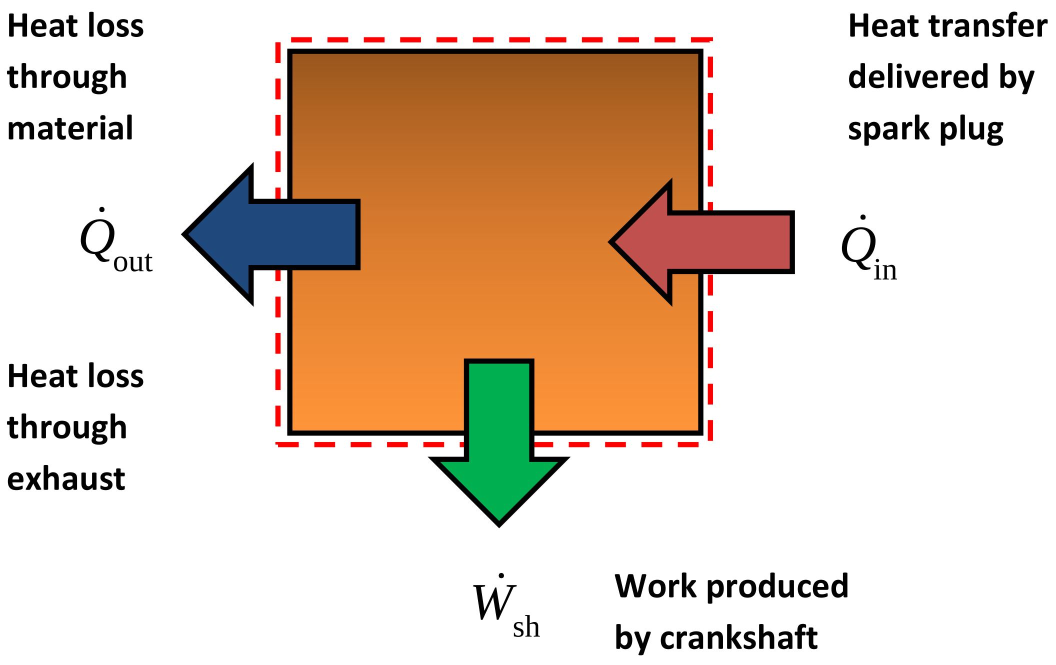

Figure 2.0 Closed Steady State Model

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[1] Closed steady state: a system with no mass interactions with its surroundings and does not change properties over time.

Due to the first law of thermodynamics we know that the energy can neither be created nor destroyed but only converted from one form to another. For any system the First Law states that the net result of heat or work will be a change in the energy of the system (Obert 47). The general equation for energy can be algebraically expressed by the following:

$$\Delta E = Q - W$$

$Q =$ *ne*t heat transferred	+ for heat added to the system
	− for heat subtracted from the system
$W =$ *net* work done	+ for work done *by* the system
	− for work done *on* the system
$\Delta \mathrm{E} =$ change in total energy	

By definition of a system at steady state we know the change in energy of the system must be equal to zero. By simplifying the First Law and taking a time derivative we can show that the output power will equal the net heat transfer.

$$\dot{W} = \dot{Q}$$

or

$$\dot{W} = \dot{Q}_{\mathrm{in}} - \dot{Q}_{\mathrm{out}}$$

We now have a relationship between the energy interactions in our model (Figure 2.0). Before we continue in the analysis it will be critical to understand another aspect of our system, its thermal efficiency. This combined with the above equation can be used to determine the increase of power in our system. The following section will discuss the conditions for determining values for engine efficiency, allowing us to provide a numerical representation for our research.

6.3 Engine Efficiency

The efficiency of an engine is determined by the amount of work being produced compared with the amount of heat (energy) put into the system (Moran 66). It can be expressed by the following ratio:

$$\text{efficiency} = \frac{\dot{W}}{\dot{Q}_{\text{in}}} = 1 - \frac{\dot{Q}_{\text{out}}}{\dot{Q}_{\text{in}}}$$

By inspection of this equation we see that by decreasing the heat loss while still maintaining a constant heat transfer into the system will allow for a more efficient engine. The heat being lost during the working cycles of the piston can be separated into two forms: material heat conduction and exhaust. This analysis will pertain explicitly to the heat transfer through the material as an attempt to achieve an increase in horsepower.

6.4 Current Thermodynamics of Formula One

Let us first consider how much power is being produced when the vehicle is traveling at maximum power. The work done by a torque in rotating a shaft is related to its displaced angle of orientation (Bhattacharjee 25). Taking a time derivative of the expression for work will provide an equation for the power being produced at a given rpm.

$$W_{\text{sh}} = F\Delta s = Fr\Delta\theta = T\Delta\theta$$

$$\dot{W}_{\text{sh}} = \lim_{\Delta t \to 0} \frac{T\Delta\theta}{\Delta t} = T\omega = 2\pi\frac{\dot{n}}{60}T$$

where T is the torque exerted on the crankshaft and $\dot{n}$ is its angular velocity in rpm. By applying 19.250 rpm we are able to find a measurement of power being produced. Keep in mind the torque that is exerted at this rotational rate is 279 $\text{N}\cdot\text{m}$.

$$\dot{W} = 2\pi\frac{\dot{n}}{60}T = 2\pi\left(\frac{19{,}250\,\text{rpm}}{60\,\text{s}}\right)0.279\,\text{kN}\cdot\text{m}$$

$$\boldsymbol{\dot{W} = 562.4\,\text{kW} \approx 750\,\text{hp}}$$

Formula One engines run at roughly 33% thermal efficiency (f1technical.net par.). This means that one-third of the heat produced by the combustion stroke generates as work through the piston rotating the crankshaft. Since two-thirds of the heat produced by the engine is lost after the full four-stroke cycle we can conclude the following by using our previous equation:

$$\dot{Q}_{\text{out}} = \frac{2}{3}\dot{Q}_{\text{in}} \quad \Rightarrow \quad \dot{Q}_{\text{in}} - \frac{2}{3}\dot{Q}_{\text{in}} = \dot{W}$$

$$\dot{Q}_{\text{in}} - \frac{2}{3}\dot{Q}_{\text{out}} = 562.4\ \text{kW}$$

so

$$\boldsymbol{\dot{Q}_{\text{in}} = 1{,}687.2\ \text{kW} \quad \dot{Q}_{\text{out}} = 1{,}124.8\ \text{kW}}$$

This tells us that 1,124.8 kW of heat are being lost through either the material or exhaust stroke of the engine. Let us now take a closer look at how the heat is being lost through the material. The following section will utilize accepted methods of thermal analysis in order to give this quantity a numerical representation for both the use of current cylinder material as well as a prototype made of Silicon Nitride. By comparing the results we will be able to determine an increase in our power output.

6.5 Thermal Conductivity Analysis

At every instant in the model there is a flow of heat along the cylinder walls throughout its volume. The amount of heat that travels through the cylinder is dependent on the thermal conductive property of the material. The thermal conductivity k of the material of the cylinder is defined by the equation

$$\dot{Q}_{\text{out, mat}} = kA\frac{dT}{dx}$$

where A is the inner area of the cylinder and dT/dx is the temperature gradient at any point throughout the cylinder's thickness. However, the temperature must be the same throughout each cross section in order for the state to remain steady. In other words, dT/dx is a constant. If this were not so, the quantity of heat flowing into an element of the cylinder would not be the same as the heat flowing out. The heat would then accumulate inside the cylinder walls and its temperature would change, contradicting the definition of steady state (Sears 348). On the next page, Figure 5.0 gives a graphical representation of steady state temperature distribution through the cylinder's thickness.

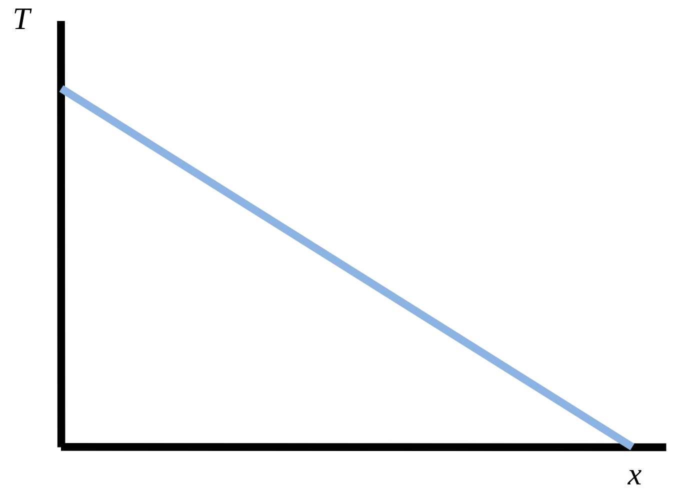

Figure 5.0 Temperature vs Thickness of steady state cylinder

This allows us to simplify the above equation to something much more feasible:

$$\dot{Q}_{\text{out, mat}} = kA\frac{T_H - T_C}{L}$$

where T_H is the hot temperature inside of the system due to combustion, T_C is the cold temperature in the system's surroundings, and L is the thickness of the cylinder wall.

With this expression as well as empirical equations of heat transfer, we are able to achieve a clear approach for increasing engine efficiency with a material of considerably low thermal conductivity. Let us now determine values for the rate of energy lost through both a cylinder made of Aluminum Alloy as well as Silicon Nitride.

6.6 Heat Transfer: Aluminum Alloy

The information presented in Table 6.0 will allow us to calculate for the heat lost through an Aluminum Alloy cylinder of a Formula One race engine.

k thermal conductivity	A area of inner wall of cylinder	T_H hot temperature inside of system	T_C cold temperature outside of system	L thickness of cylinder
120 kJ/m•K (aluminum)	0.01225 m^2	500° C (see Appendix)	30° C (ambient temp.)	0.005 m

Table 6.0 Current Formula One Design Specifications

By inserting these values into Equation we are able to evaluate the rate of heat being lost through the walls of an Auluminum Alloy cylinder as the engine performs at 750 hp. Knowing that the sum of the heat lost through material conduction and through the exhaust we are also able to determine the amount of heat lost through exhaust.

$$\dot{Q}_{\text{out, mat}} = 120 \text{ kJ/m} \cdot \text{K } (0.01225 \text{ m}^2) \frac{500° \text{ C} - 30° \text{ C}}{0.005 \text{ m}}$$

$$\dot{Q}_{\textbf{out, mat}} = \textbf{138 kW} \qquad \dot{Q}_{\textbf{out, exh}} = \textbf{987.6 kW}$$

6.7 Heat Transfer: Silicon Nitride

The information presented in Table 7.0 will allow us to calculate for the heat lost through a cylinder composed of Silicon Nitride.

k thermal conductivity	*A* area of inner wall of cylinder	T_H hot temperature inside of system	T_C cold temperature outside of system	*L* thickness of cylinder
30 kJ/m•K (SiN_3)	0.01225 m^2	500° C (see Appendix)	30° C (ambient temp.)	0.005 m

Table 7.0 Silicon Nitride Cylinder Design Specifications

By inserting these values into Equation we are able to evaluate the rate of heat being lost through the walls of a Silicon Nitride cylinder. **It is important to notice that the heat being lost through exhaust will not differ for this analysis since we are not changing the heat being provided to the system. The heat that is stored through insulation will instead be transferred as additional work being produced by the engine.**

$$\dot{Q}_{\text{out, mat}} = 30 \text{ kJ/m} \cdot \text{K } (0.01225 \text{ m}^2) \frac{500° \text{ C} - 30° \text{ C}}{0.005 \text{ m}}$$

$$\dot{Q}_{\textbf{out, mat}} = \textbf{34.5 kW} \qquad \dot{Q}_{\textbf{out, exh}} = \textbf{987.6 kW}$$

6.8 Silicon Nitride Results

We now have obtained all of the data necessary to demonstrate an increase in power output as well as energy efficiency for a Formula One engine. Using Equation with the calculated values from Section 6.7 we are able to evaluate how much more power a Formula One car will produce by implementing a Silicon Nitride cylinder.

$$\dot{W} = 1{,}687.2\,\mathrm{kW} - \left(34.5\,\mathrm{kW} + 987.6\,\mathrm{kW}\right)$$

$$\boldsymbol{\dot{W} = 665.1\,\mathrm{kW} \approx 900\,\mathrm{hp}}$$

Using Equation we are able to determine the new engine efficiency:

$$\text{efficiency} = \frac{665.1}{1{,}687.2}$$

$$\textbf{efficiency} = \mathbf{0.394} \;\Rightarrow\; \mathbf{39.4\%}$$

6.9 Conclusion of Thermal Analysis

Decreasing the rate of heat being lost through the cylinder has allowed for a greater power output from the engine. The heat that is stored from implementing a more thermally insulated material is allowing for more pressure to be exerted on the piston causing an increase of torque on the crankshaft. Using Silicon Nitride as a replacement material selection for Formula One race cylinders will increase the engine’s maximum power by 150 hp and provide a 7% raise in engine efficiency.

Works Cited

Sears, Francis Weston. Mechanics, Heat and Sound. Addison-Wesley Press, Inc: Cambridge. 1952.

Obert, Edward F. Thermodynamics. McGraw-Hill Book Company, Inc: New York. 1948.

Moran, Michael J. Fundamentals of Engineering Thermodynamics. John Wiley & Sons, Inc: USA. 2008.

Bhattacharjee, Subrata. Classical Thermodynamics. Pearson Education, Inc: Upper Saddle River. 2004.

http://www.f1technical.net/articles/4

Appendix

The primary function of the spark plug is to ignite the air/fuel mixture within the combustion chamber under any operating condition. The spark plug firing end temperature must be kept low enough to prevent pre-ignition, but high enough to prevent fouling. This is called "Thermal Performance", and is determined by the heat range selected. The two most common causes of spark plug problems are carbon fouling (occurs bellows 450° C) and pre-ignition (occurs above 800° C). Carbon fouling occurs when deposits from combustion start to form on the tip of the spark plug. Pre-ignition occurs when the average temperature from the spark plug is high enough to prematurely cause the fuel/air mixture to combust, damaging the engine.. The optimum heat range for spark plug ignition lies between these two temperatures as it helps to self-clean itself of combustion deposits. If the engine is to be operated at high RPM, under a heavy load, or at high temperatures for long periods a colder ignition will be required. For Formula One race engines, there optimum combustion temperature is approximately 500° C due their high rates of speed for extensive periods of time. The following graph demonstrates the relationship between ignition temperature and engine speed of a Formula One car.

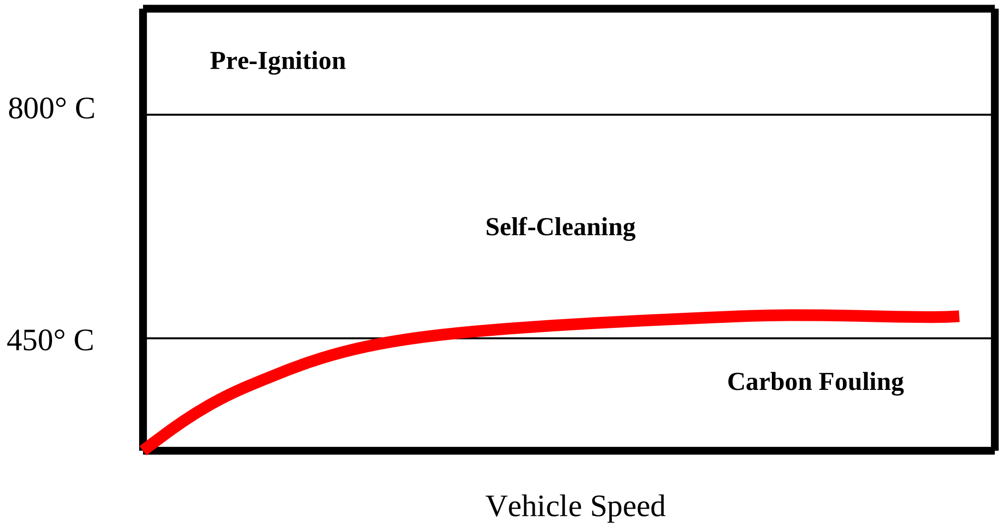

Table ?? Temperature vs Vehicle Speed for Formula One