The Gasoline 4-Stroke Engine for Automobiles

Garrett W. Balich and Conrad R. Aschenbach

Department of Aerospace and Mechanical Engineering
University of Notre Dame
Notre Dame, IN 46556

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Preface

The purpose of this technical paper is to inform the reader about the modern automobile four-stroke engine. To accomplish this, we have assumed that the reader has an elementary knowledge of the mechanics of an engine which is gained by knowledge in the areas of solid mechanics, thermodynamics, fluids, dynamics, vibrations, machine elements, manufacturing, calculus, physics, and chemistry.

Part I

Introduction

Chapter 1

History of the Four-Stroke Automobile Engine

Perhaps the most well known engine type in the world, the automotive four-stroke engine has become the power plant of choice for today's consumers due to its greater efficiency and cost effectiveness over alternate reciprocating engines.

The story of the internal combustion engine began in 1680 with a Dutch physicist, Christian Huygens, who conceptually designed an engine fueled by gun powder. However, the first internal combustion engine was actually built by a Sweetish inventor by the name of Francios Isaac de Rivaz in 1807. Through the combustion of a hydrogen and oxygen mixture, his engine, with some difficulty, powered a crudely constructed automobile. As the years went on, other inventors modified the design to be fueled by anything from gasoline to coal. The next greatest leap came in 1862 when a French engineer, Alphonse Beau de Rochas, designed and patented the first four-stroke engine. In 1864 an Austrian engineer, Siegfried Marcus, build the first gasoline powered vehicle, which was comprised of a cart and a one cylinder engine. But the biggest break through came in 1876 when Nikolaus August Otto invented the first successful four-stroke engine, aptly nick-naming the four-stroke cycle the ”Otto Cycle.” [1]

The next great milestone in the development of the four stroke engine was achieved by Gottlieb Daimler in 1885, who invented an engine with a vertical positioned cylinder, fueled by gasoline injected into a cylinder chamber through a carburetor. The innovations from these important inventors over the years culminated in Daimler’s engine which is commonly referred to as the ”blue print” to the modern day internal combustion engine. [1]

From the inception of the four-stroke internal combustion engine, many paths have been explored and followed to create the superior design, especially in the configuration of the cylinders. In general, there are seven types of reciprocating engine designs, an engine that employs one or more cylinders in which a piston(s) reciprocates back and forth. The first of these designs was the single cylinder engine. After its success, designers began to play with twin engines, or two cylinder engines which lead to the In-Line Engine, the V Engine, the Opposed Cylinder Engine, the W engine, the Opposed Piston Engine, and the Radial Engine. These different setups where further explored with engines such as the Vauxhall Wyvern and Velox engines to the Ford V-Four engine, utilizing an even greater numbers of cylinders than the original twin engines.

Today’s four-stroke engine manufacturer’s mainly build In-Line or V configured engines. Perhaps the most widely recognized engine today is the Chevrolet Small Block V8 Engine. This engine was made popular through their dependability and through hobbyists and the performance market because of the interchangeability of parts. After 35 years, General Motors discontinued their infamous engine, replacing it with the new Generation II engine in 1992. Although Chevrolet seemingly has dominated today’s after market industry, other manufacturers have successfully made engines for their vehicles from the Ford V-Eight, to the Cadillac North Star, to the Porsche In-Line Six as well as mainly others.

Chapter 2

Principles of the 4 Stroke Gasoline Automobile Engine

The four-stroke gasoline engine is comprised of many integral parts: the induction system, the cylinder heads, the engine block, the pistons, the camshaft, the crankshaft, and the flywheel. All these parts are necessary for the four cycles of operation in the Otto cycle, illustrated in Fig. 2.1.

The first stroke in the Otto cycle is the induction stroke. This process starts with the carburetor or the electronic fuel injection system flowing air into the intake manifold. While the air is passing through the carburetor or electronic fuel injection system, gasoline is added into the air creating a fuel mixture. As the fuel mixture passes through the intake manifold, it is separated from one collective port to individual ports for each of the cylinders. The fuel mixture then progresses into the cylinder heads where an intake valve opens to allow the incoming mixture to flow to the cylinder chamber, while the cylinder head's exhaust valve is closed so the mixture can not escape from the chamber. During this stroke, the piston starts at the top of the cylinder moving backwards towards the bottom of the cylinder creating a vacuum which creates a vacuum pulling in the fuel mixture.

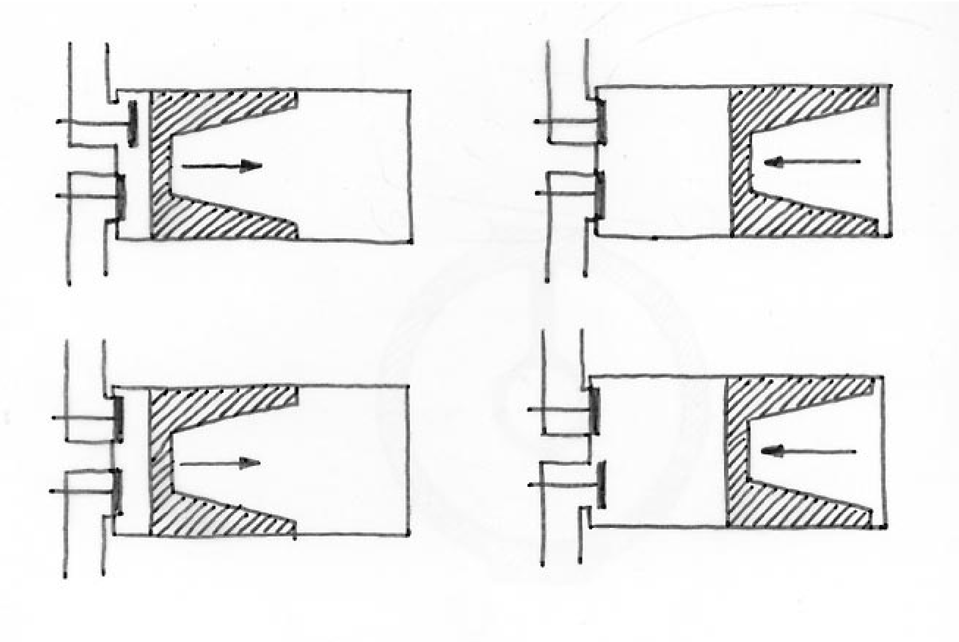

Figure 2.1: V Block Setup

The second stroke in the cycle is the Compression stroke. During this cycle, both the intake and exhaust valves are closed, and the piston moves from the bottom of the cylinder chamber to the top, thereby compressing the fuel mixture. The stroke ends when a spark is ignited to initiate the combustion of the fuel mixture.

The expansion stroke is the third stroke of the cycle. During the expansion stroke, the two valves in the cylinder head remain closed thereby containing the expansion of the ignited fuel mixture inside the cylinder chamber. The expanded gas propels the piston from the top to the bottom of the cylinder, providing the torque to drive the connecting mechanism.

The final stroke in the Otto cycle is the exhaust stroke. During this stroke, the combusted fuel mixture is forced from the cylinder chamber through the now open exhaust valve by the piston moving from the bottom to the top of the cylinder chamber. The exhaust gas flows into the cylinder head where it continues until it is discharged from the engine through an exhaust manifold pipe.

The four cycle process is assisted by several components. As the pistons reciprocate, they drive or are driven through connecting rods through the crank shaft, which in turn either drives or is drive by the flywheel. It is through the momentum generated in the revolving flywheel that the pistons are propelled in the first, second, and forth strokes of the Otto cycle and through the moment of inertia, which allows for smooth operation. Lastly, the camshaft, driven by a linkage connected to the crankshaft, opens and closes the intake and exhaust valves. Further additions to the engine, such as fuel additives and forced induction systems can provide further power gains from the engine, thereby improving on Nikolaus August Otto's innovations.

Part II

Fuel and Air Delivery

Chapter 3

Carburation

3.1 Introduction to the Carburetor

The earliest four-stroke engines used during the 1880's primarily were implemented for industrial applications. Because they were run at constant speeds, three very simple carburation devices were devised: the wick, the diffusion, and the surface type carburetors.

The wick type carburetor worked by absorbing fuel from a reservoir below the air intake. As the air flowed past the upper end of the wick, the fuel was evaporated and carried the fuel vapor into the cylinders for combustion.

The diffusion type carburetor consist of a small reservoir of fuel with two tubes passing through it. The first tube is for the exhaust gases, which is used to warm the fuel in the reservoir, and the second is used to deliver the air, which is released under the fuel through perforations in the walls of the tube. As the air surfaces through the fuel, it mixes and vaporizes at the surface carrying the fuel with it to the cylinders.

The surface type carburetor was first introduced by Gottlieb Daimler and Karl Benz in 1885. [2] Similarly to the diffusion carburetor, an exhaust tube runs through the reservoir warming the fuel. However, the air runs vertically down through a tube in which its end opens into a large diameter inverted dished plate. The plate's edge was placed just below the the fuel's surface, maintained at a constant level by a float switch mechanism. The incoming air is then distributed radially from beneath the plate and rises through the fuel. The air and fuel vapor then travel into the cylinders for combustion.

But non of these carburetors could overcome the complexities of the modern four-stroke engine. They did not satisfactorily start the engine in the cold, nor did they permit varying working speeds because of their intent for industrial applications. Over the years, the carburetor slowly evolved into a complex and expensive fuel delivery system.

3.2 Basic Operation

The basic operation of a carburetor can be broken down into several stages. The first stage is providing and regulating the fuel from jets for vaporization into the incoming flow of air. Atomizing the fuel into small droplets to induce evaporation. Lastly, providing an uniform flow of the fuel mixture to the intake manifold, leading to the cylinders for combustion.

The modern day carburetor, shown in Fig. 3.1, is primarily comprised of a venturi tube, a tube which forms a throat to increase the velocity of the incoming air as it passes into the narrowest section and then decreases the velocity once the throat ends. The venturi is mounted with a fuel capillary tube and throttle plate. It also employs a fuel reservoir, idle speed adjustment, idle valve, main metering needle valve, and choke.

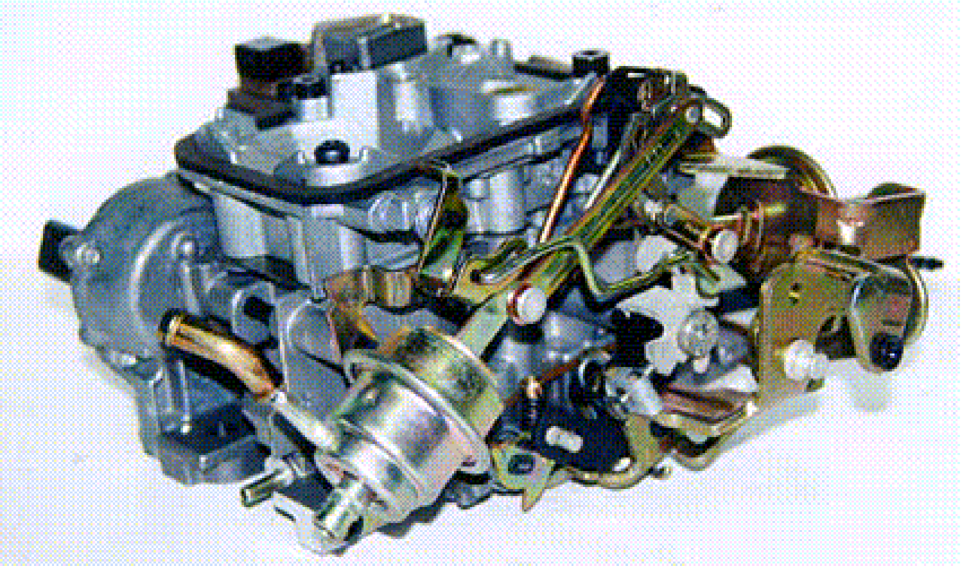

Figure 3.1: Modern Carburetor

Air enters the carburetor due to a pressure differential from a depression caused by the movement of the pistons in the cylinders. As the air travels through the venturi, it is accelerated and absorbs fuel droplets through Bernoulli's principle. Bernoulli's principle states that as the air is accelerated through the venturi, there is a subsequent drop in pressure. The fuel which is at atmospheric pressure then is pushed through the capillary tube and forces droplets of fuel into the air stream. These fuel droplets then evaporate into the air stream producing an air and fuel mixture. And if the engine reaches higher speeds, a higher pressure differential will increase the fuel mixture through the same principles, and conversely at slower speeds.

A fuel reservoir is maintained through a float shut off, which meters the entering fuel from the fuel line. The fuel line is fed from the gas tank through either an electric or mechanical fuel pump.

The air flow rate and engine speed is controlled though a throttle butterfly valve, which has a throttle stop acting as the idle speed adjustment allowing for air to enter during idle operation. To deal with the problems from the small pressure differential and subsequent low fuel flow, an idle valve is used to provide better fuel flow control during idle operation.

A choke, a butterfly valve position upstream of the venturi, is implemented during cold engine starts. It works by closing during cold engine starts, which creates a restriction in the air flow, thereby creating a vacuum downstream of the choke in the intake system. The large pressure differential across the fuel capillary tube and idle valve allows for a richer fuel mixture, created by combining the larger quantity of fuel with the reduced air flow. This allows for a greater quantity of fuel to vaporize, thereby allowing for the ignition for combustion even in cold environments.

As time and technology progressed, other feature were added to the carburetor such as the accelerator pump. The accelerator pump provided greater performance during operation by fulfilling the parameters for efficient carburation.

3.3 Air and Fuel Flow

The modern day four-stroke engine's carburetor must overcome several obstacles in order to perform at an optimal level.

The first obstacle to be overcome is that of the flow of the air stream into the venturi. Adverse effects in the mixing of the fuel and air can be cause by turbulent flow through the venturi. To combat this problem, there needs to be little to no interference between the outside air and the venturi besides the air cleaner; subsequently, carburetors were designed so the throttle valve is always down stream of the venturi.

Another obstacles is the need for complete combustion of the fuel mixture in the cylinders. To comply, a stoichiometric mixture is used. This is a mixture with precise proportions of fuel to air. For gasoline, this proportion of air to fuel weight is approximately 14.7:1. [2] This mixture must meet parameters such as ignition under any circumstance. The fuel must be completely oxidized to avoid the production of carbon monoxide. And the maximum amount of chemical energy must be taken from the fuel mixture to be turned into mechanical energy.

The mixture quality is the most important job of the modern carburetor. During the starting process, a rich mixture is needed, especially during cold conditions because the vaporized fuel tends to condense on the walls of the intake manifold. During idling, an enriched mixture is needed because of condensing of the already small amount of fuel injected during this operation. For cruising, a weaker mixture is needed to ensure complete combustion and highest efficiency. During acceleration, more fuel is needed to combat the condensation of the fuel mixture caused by the sudden opening of the throttle and rise in pressure.

To control the flow of fuel appropriately, many modern carburetor manufacturers use fuel and air metering devices such as the hydrostatic pressure of fuel to force the fuel through the jets in the appropriate proportions. Less complex models may use a needle valve actuated by a float to maintain a constant fuel level.

3.4 Starting and Enriching Devices

When a four-stroke engine is at idle or running slowly, there is only enough air flow moving through the carburetor to provide fuel to overcome the resistance of its part. Consequently, during this operation, there must be an enrichment from the fuel source allowing for instant acceleration, yet also not effect the engines efficiency or decibel level at these low engine speeds.

In order to meet these conditions, an additional jet and air inlet must be added for fixed choke carburetors. The first mechanism used to accomplish this goal was a manual actuated strangler. This was a system comprised of a cable controlled valve up stream of the venturi, which when partially closed, increases the depression above the jets, thereby enriching the fuel mixture. Unfortunately, if the driver forgot to open the valve, the engine would run with an enrich mixture, wasting valuable gasoline. More problems arose during cold weather when the extra fuel wetted the sparkplugs. Eventually, manufacturers developed automatic stranglers which were actuated with thermostatic devices such as bimetal strips.

Similarly to the idling fuel deficiency, another problem exists when there is a sudden acceleration after engine use at low speeds. This is caused by the sudden rush of incoming air flow, which is too short to overcome the drag and inertia of the fuel from the jets. To combat this problem, most carburetors have an added acceleration pump, which is a single diaphragm or plunger type pump with a linkage connected to the throttle. When the throttle is depressed, the linkage opens the pump, which results in a direct injection of fuel into the induction system just above the venturi, where the evaporation process is aided by the low pressure. This spraying process is further prolonged by a compression spring pushing down a piston which then progressively injects the fuel through an acceleration jet. Over-enrichment is avoided through a small clearance between the piston and the cylinder walls, where the consequential leak back is adequate to avoid supplying any excess fuel.

Chapter 4

Fuel Injection

4.1 Introduction to Fuel Injection

Edward Butler, from Erith, Kent, and Henri Tenting, from Paris, were the first two men to develop a fuel injection system for the internal combustion engine in 1883 and 1891, respectively. [2] During the early stages of production, most of these units were built for application to the aircraft, such as Wilbur and Orville Wright's unit for their infamous flight in 1903. [2]

Fuel injection was first introduced to the automotive world in the form of a spline driven, rotary injection pump in the Gobron Brille car. [2] But, it was not until 1940, when Mercedes developed an electric injection system for the Alfa Romeo car, that fuel injection was seriously considered for production vehicles. [2] Further development of fuel injection later took place for racing applications as well as other production vehicles.

In 1970, Bendix implemented the use of the Lambda sensor in the automobile system. [2] This device had one of the most major impacts of the fuel injection industry because it made possible for control on the principle of a closed-loop system. Without this development, it might have been impossible to have met the emissions regulations of today.

Today's fuel injection systems work similarly to a carburetor, by delivering a metered air and fuel mixture to the engine for combustion. The incoming air is controlled through a throttle body, usually controlled with butterfly valves. The incoming air is then metered through a sensing device and an appropriate mass of fuel is added to the air stream through an electrically controlled injector. The whole sequence is monitored and controlled by a small engine management computer, which will be discussed in a further chapter.

4.2 Fuel Delivery Requirements

Similarly to the carburetor, the most important task of the modern fuel injection system is to deliver a stoichiometric mixture of fuel and air to the engine for combustion, no matter the driving conditions; cold starting, idling, economy, or sudden acceleration. This stoichiometric mixture is achieved by electronically controlling the timing of the injectors from the start to the end of fuel injection, which combat the various needs of the engine operation under varying conditions.

To achieve the necessary symmetry in the electronic fuel injection system, the fuel must be delivered to the system continuously and reliably without pulsation at a controlled constant pressure with a fuel pump. The fuel must be closely metered and delivered in an atomized form into the engine manifold through injectors without liquid fuel entering the manifold. And lastly, a multitude of sensors for monitoring the environmental and engine conditions must be able to send accurate information to an engine management computer which must accurately run the whole fuel injection system.

4.3 Types of Fuel Injection Systems

The first method for fuel injection is the direct injection into the cylinders, but unfortunately it suffers from an extraordinarily high back-pressure due to its placement, as well as other severe disadvantages. Because of the close proximity of the injectors to the pistons in the cylinder chamber, fuel must be injected progressively to allow for atomization of the fuel and mix with the air before the spark. The fuel must also be able to enter the cylinder chamber flowing against the rising back pressure. Because of the exposure of the injector tips to the combustion process, a carbon build-ups easily clog the injector tips. Lastly, a complete atomization and mixing of a homogeneous air and fuel mixture are almost impossible because of the short time frame. With all of these potential problems, this method of injection is avoided for more efficient systems.

Throttle body injection, also known as single-point injection or central fuel injection, has been a favorite of manufacturers because of its simplicity and low cost compared to its major competitor, the multi-point injection systems. This system relies on a single jet fuel injector down stream of the throttle valve, which reduces the effects of the air flow, or a dual jet fuel injector setup, upstream on each side of the butterfly valves. However, there are several disadvantages to the single-point injection system. In a single-point injection system, the fuel has the tendency to condense on the walls of the intake manifold, and then vaporize again in an uncontrolled fashion, partially taking away control of the system. Similarly to the carburetor, the single-point injection has difficulty distributing the fuel mixture accurately to the different cylinders. Lastly, there must be a hot spot in the throttle body to aid in the atomization of the injected fuel as well as preventing icing during cold conditions.

Multi-point fuel injection is the most widely used fuel injection system employed in today's automobiles. This system works by injecting fuel into the intake manifold directly into the cylinder head ports. Implementing this direct injection to the cylinder head ports, the multi-port system avoids the previously mentioned disadvantages of the single-point system. The fuel injector is directed to spray onto the hot inlet valves, preventing condensation of the fuel in the port as well as decreasing the likeliness of the fuel mixture being drawn into an adjacent cylinder due to the effects of back pressure. The only real disadvantage of this system is the extra cost from specialized intake manifolds and extra components such as fuel rails, which are outweighed by the better performance achieved.

4.4 Flow Types in Fuel Injection Systems

Continuous injection is the simplest and least costly method of injecting fuel from injectors. Continuous injection works by injecting a fuel mixture spray into the intake manifold, where it is ready to flow into the individual cylinders when the inlet valves open. The fuel mixture is controlled through variation in the pressure of the fuel sent to the injectors from the fuel pump. In multi-point injection, the fuel is made into a homogeneous mixture through the turbulence in the cylinders.

The more favored method of fuel injection is through sequential or timed injection, which injects the fuel for limited time periods, usually once for every revolution of the crankshaft. Fuel is maintained at a constant pressure combating the difficulty related to the small time lag in the electronic control between receiving and sending signals between sensors, the computer, and then the fuel pump.

Generally, the timing of the opening of the fuel injectors is fixed and changes are produced from varying durations of time before the closing of the injectors. With almost instant responses from the electronic control computer, the air to fuel mixture can be closely controlled.

Further development produced the simultaneous double-fire injection, or phased injection system which allows for extremely accurate regulation of the air to fuel mixture. This is accomplished by an injection of fuel into the ports as the inlet valves open, consequently only once every two revolutions of the crankshaft.

The numerous advantages of sequential and phased injection arise from the accurate monitoring from the engine management computer system which help avoid numerous problems of engine operations, through the implementation of the multitude of sensors such as the detonation sensor and crankshaft angle sensor.

4.5 Flow Sensors

There are four types of flow sensors implemented in electronic fuel injection systems: the suspended-plate type flow sensor, the swinging-gate type flow sensor, the manifold absolute pressure (MAP) sensor, and the mass-flow sensor. The suspended-plate type flow sensor is comprised from a circular plate pivoting on the opposite end of an arm, balanced by a small weight, which suspends the plate in the horizontal plane within a circular throat. When the engine is turned off, the plate then returns to its equilibrium position in the narrowest section of the complex tapered throat. The entering air then pushes the plate against the resistance produced from a hydraulically actuated control plunger, which depresses a roller on a small level arm thereby controlling the idle setting for the engine with a screw

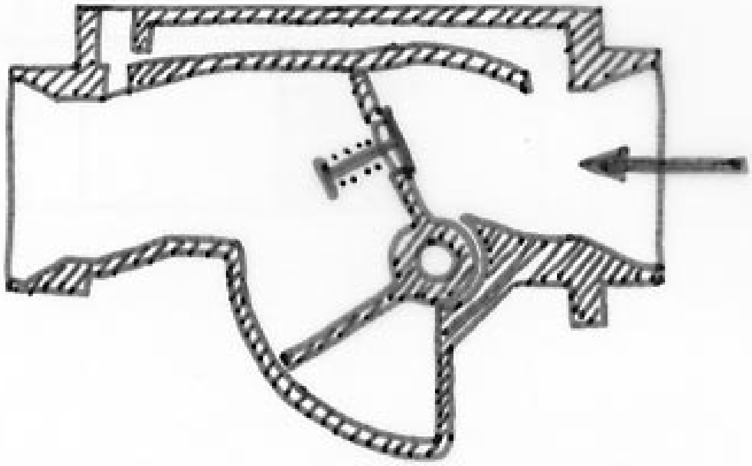

Figure 4.1: Swing Gate Volume Flow Sensor

stop. During sudden acceleration, the plate momentarily over swings, increasing the supplied mixture, and then returns to the equilibrium position.

The second type of flow sensor, the swinging-gate sensor, or air vane sensor, illustrated in Fig. 4.1, is comprised of a housing and internal vane which is deflected by the incoming air into the engine. The vane is spring loaded lightly and pivots from the force of the incoming air. The sensor incorporates a damper which pivots with the vane to negate the effects of pulsing air distorting the reading of the actual air flow through the sensor.

The third flow sensor, the MAP sensor works by theoretically calculating the mass of the air entering the intake system. The manifold absolute pressure sensor sense the absolute pressure in the intake manifold, and then through calculations in the engine management system, finds out the air mass traveling through the intake. The disadvantage to this type of sensor is that it has general calculations which rely on standard conditions, such as temperature, which fluctuate in real world conditions.

The forth flow sensor, the mass-flow sensor is perhaps the best method in measuring the incoming air flow because it senses the incoming air mass where as the other sensors measure the incoming air volume and must have additional sensors to compute the mass due to varying conditions such as cold weather. This sensor operates on the principle that the temperature loss in a heated element is a function to the density and velocity of the air passing it. The engine management system then calculates the mass flow from the flow density and velocity as well as the known diameter of the passage of the sensor.

There are two types of mass-flow sensors: hot wire and hot film, illustrated in Fig. 4.2. The simplest is the hot wire, but due to accumulated deposits on the wire, it must be cleaned off by momentarily raising the temperature each time the engine is turned off. The hot film elements are placed on a ceramic plate parallel to the air flow, which is shaped to shead any deposits, keeping the film clean. Both types are subsequently controlled through a wheatstone bridge circuit.

4.6 Miscellaneous Sensors

The lambda sensor, whose name came from the Greek letter lambda, used represents the air to fuel ratio, is implemented to detect differences in the air ratio by measuring the oxygen content in the exhaust gases. This is accomplished by

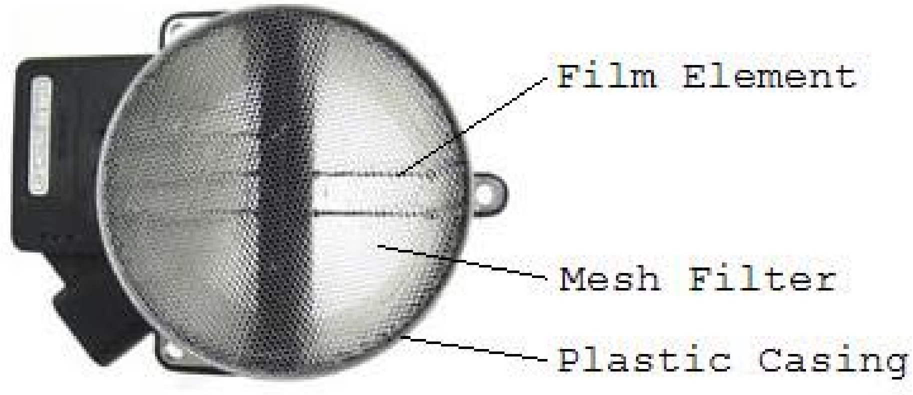

Figure 4.2: Hot Film Mass Flow Sensor

using a thimble shaped oxygen sensitive component made of zinconium oxide, which then is coated in a thin layer of platinum. The thimble acts like an electric cell. When a oxygen concentration inside is different from the outside, an electric potential between the platinum coatings relays a measurement of the difference between the two oxygen concentrations.

The engine temperature sensor and the air temperature sensor both operate on a similar principle. They are composed of thermistors, semi-conductor resistors. They are frequently referred to as NTC I or II because they operate on a negative temperature coefficient, meaning, as the temperature goes down in the sensor, the actual temperature of the environment is increasing. [3]

4.7 Air and Fuel System

The fuel injector, illustrated in Fig. 4.3, is the most important component of the fuel injection system because it delivers the atomized fuel to the cylinders for combus-

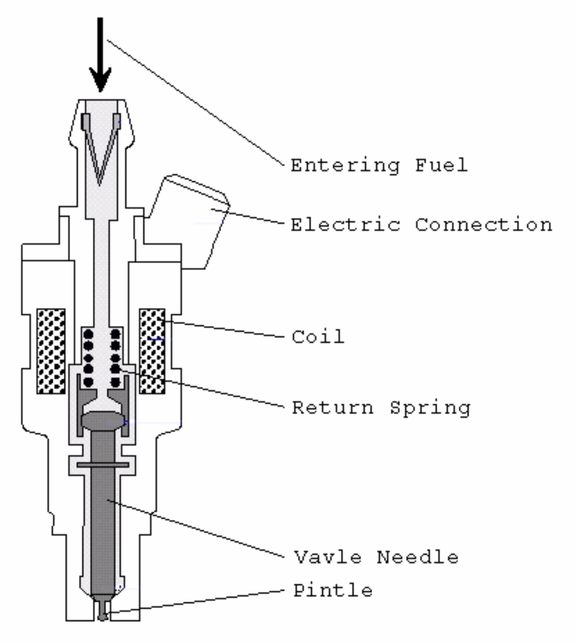

Figure 4.3: Fuel Injector

tion. All injectors are electronically controlled by the engine management system by sending an electric signal which energizes a solenoid. The resulting magnetic force then over comes the force of a spring and hydraulic pressure, which then opens an armature or pintle, allowing the fuel to flow from the injector. The end of the injector is shaped into a nozzle to atomize the out-flowing fuel.

To deliver the fuel to the injection system, an electric fuel pump is employed, usually near the tank allowing for pressurization of the majority of the fuel line, which prevents vapor lock. The high pressure fuel then flows through a check valve keeping the pressure even when the pump is turned off. The fuel pump is also used in conjunction with a fuel filter composed of a paper element, containing pore sizes of roughly 10 micrometers, which is then backed with a strainer to catch any loose particles. [3]

To control the high pressured fuel delivered from the fuel pump, a pressure regulator may be implemented. The regulator holds the fuel in the injection system at a constant pressure. A spring normally keeps the regulator valve closed except when excess fuel pressure builds up, resulting in the opening of the valve, which leads the fuel back to the tank.

Fuel rails are used to distribute the pressurized fuel from the pump and regulator to the individual injectors in a multi-port injection system. While it distributes the fuel to the injectors, it also stabilizes fuel pressure fluctuates at the injectors, caused from the rapid opening and closing of the injectors, which could affect the amount of fuel injected. This problem is elevated by increasing the size of the fuel rails, thereby storing more fuel and stabilizing the system.

To overcome the problems associated with the mechanical drag of a cold engine, additional air flow is produced with an auxiliary air valve. The valve bypasses the throttle, but not the air flow sensor, so that the required fuel still is delivered to the engine. The resulting extra air and fuel allows the engine to overcome the extra resistance forces. They work by either being electrically or coolant heated. A blocking plate opens to allow the flow of air when the valve is cold, and then closes once the valve become warm.

Chapter 5

Engine Management

5.1 Overview

This chapter describes the main types of engine management used today. It also explains the advantages and the appropriate applications for each type of engine management system. The majority of this information was found in the Holden Gen III service manual distributed by General Motors [4].

5.2 Types of Engine Management

There are mainly two predominant types of engine management that exist today. The first of these two types is Speed Density; the other is Mass Air Flow. Both systems have their advantages and disadvantages, and each are better suited for different types of applications.

5.3 Speed Density

Speed density calculates the injector pulse width by first calculating the mass air flow from the following inputs: engine displacement, RPM, manifold pressure, manifold air temperature, and volumetric efficiency. Once the mass airflow has been calculated, the engine control unit (ECU) uses it along with RPM, injector flow rating (usually given in lbs.), and the target air/fuel ratio to find the desired injector pulse width. The injector pulse width is simply the time taken in between each firing of the injector.

5.4 Mass Air Flow

Mass air flow uses a different technique to calculate the injector pulse width. The mass air flow type of engine management uses a sensing device such as a pivoting vane or headed wire to calculate the mass air flow into the engine. This mass air flow value is then used in conjunction with similar variables as in speed density to calculate the injector pulse width.

5.5 Open and Closed Loop Operation

Note that the target air fuel ratio is used as a factor in calculating the injector pulse width. This is only a factor when the system is operating in a closed loop manner. In closed loop, the ECU compares the actual air fuel ratio to the desired value. Therefore, the output of the O2 sensor is used in the determination of the final calculation of the injector pulse width.

There are many instances where the closed loop mode is desirable. One of the most important uses of closed loop is to meet emissions laws. Simply put, the leaner (high air fuel ratio) fuel mixtures provide the best possible emissions output due to the fact that the intake charge will burn hotter than a rich mixture. The hot burning ensures that no unburned fuel gets emitted from the exhaust system and into the atmosphere.

There are, times, however, where closed loop is not desirable. During cold start up, open loop is usually disabled in order to let the engine temperature rise to its normal operating value. In addition, at cold temperatures the O2 sensors usually do not produce accurate readings as they can sometimes become lazy when not up to normal operating temperature. At temperatures under operating temperature, the O2 sensor has a very high internal resistance. The ECU usually supplies a constant voltage to the O2 sensor. With the high internal resistance, the ECU only receives a very low, constant voltage value from the sensor itself. Once it warms, the O2 sensor outputs a very rapidly changing voltage reading that the ECU can use accordingly. The O2 sensors used by General Motors engine platforms range from 100mV (lean mixture) to 900mV (rich mixture).

Open loop is sometimes preferred in engines where there is little reason to have a target O2 value. This can be in high performance applications where attention to emissions is rather unnecessary. Sometimes it is necessary to disable closed loop from a ECU designed in such a way that that it only works with O2 sensors that are not compatible with leaded fuel if a leaded fuel is to be used. In the author's 2002 LS1 based Pontiac Trans Am, it was necessary to disable closed loop operation in order to run a 120 octane high lead nitrous blend fuel.

5.6 Sensors

Each type of ECU uses different methods to calculate the desired injector pulse width. However, they do use similar sensors to determine the inputs needed to make the necessary calculations. The following is a list of the sensors used (note that the O2 sensor has already been discussed previously). Depending on the particular system used, some of these sensors might not have any specific input into the final injector pulse width calculation. This is to be treated as a survey of the variety of sensors used by the ECU itself.

5.7 Crankshaft Position Sensor

This sensor is used to determine crankshaft position. Usually, there will be a reluctor wheel on the crankshaft itself and a sensor which reads off of each tooth on the reluctor wheel itself. As such, the position of the crankshaft may be determined by the teeth on the reluctor wheel which interrupt the magnetic field produced by the magnet located within the sensor itself. For the GM LS1 crankshaft position sensor, cylinder position identification may be made within around 90 degrees of crankshaft rotation.

5.8 Manifold Absolute Pressure Monitor

This sensor measures changes in the pressure exhibited within the intake manifold of the engine. When the manifold pressure changes, there is a corresponding change in the output voltage of the MAP sensor. The ECU uses this output voltage in a transfer function to calculate the manifold air pressure. When the engine is at wide open throttle, the intake manifold pressure is the same as the outside air since the throttle blade is completely open. On a GM system, this would measure as 100 percent of the barometric pressure. The MAP sensor is also used in some applications to measure the barometric pressure which helps better determine the operating conditions in which the automobile is operating.

5.9 Engine Coolant Temperature Sensor

The engine coolant temperature sensor has a relatively simple operation. It consists of a sensor mounted in a location that allows contact with the engine coolant and its resistance changes as a function of temperature. When the temperature of the coolant increases, the resistance of the temperature sensor decreases which therefore increases the voltage value supplied back to the ECU (the ECU supplies the required voltage for normal sensor operation).

5.10 Intake Air Temperature Sensor

This sensor is usually a thermistor. The resistance is a function of temperature. This is usually mounted before the throttle body in fuel injected engines. Just as the coolant temperature sensor, the air temperature sensor receives an input voltage from the ECU. The output voltage is dependant on the resistance level of the thermistor itself. As the temperature increases, the resistance increases.

As such, it is possible to fool the ECU into thinking that the ambient air is at a higher temperature than the actual value. Some performace applications use this trick in order force the ECU to pull timing out of the spark advance table in the spark map. The author has used trick in order to manually pull timing for a nitrous oxide assisted application.

5.11 Throttle Position Sensor

This is another very important sensor which is used to determine the throttle position (the position of the throttle blade within the throttle body). It is a variable resistor which receives its input voltage from the ECU and outputs a voltage back to the ECU which is a function of the current resistance value of the throttle position sensor. It is important to note that some very important values are displayed as a function of throttle position, especially in some other types of engine management other than MAF and Speed Density.

5.12 Mass Airflow Sensor For Mass Airflow Type Engine Management Systems

More recent mass airflow sensors involve a heated element which is placed in the flow stream of the incoming intake air. This type of mass airflow sensor uses a voltage value from the ECU that will vary to keep the element at a constant temperature. The voltage required to maintain the element at the constant temperature is a direct function of the mass air flow into the engine.

The airflow past the heated elements reduces their temperature through convection. The convection process transfers the heat from the surface of the heated element to the entering airflow.

Note that sometimes there are applications where the use of a mass airflow style of engine management is not desirable. This is sometimes the case in a forced induction car. Forced induction cars can utilize such a large amount of boost that they actually max out the mass airflow sensor. That is, the ECU cannot produce a high enough voltage to maintain the heated MAF elements at their proper temperature. In cases such as these, a Speed Density system with a capability to measure a large difference between ambient and intake manifold pressure is preferable.

Some engine types utilize a mass airflow engine management system with a

Speed Density backup. Therefore, the engine will not cease to run if the mass airflow sensor fails (this is a type of redundant system). Some of today's tuners are disabling the mass airflow sensor and simply using the speed density backup system through the use of computer programs which allow the user to alter the programming within the ECU. This method of tuning for forced induction cars has proven to be very useful.

There are some important power adding systems as well which require the use of a mass airflow sensor. One of these power adders is a dry nitrous oxide system. This type of system sprays the nitrous oxide into the intake tract right before the mass airflow sensor. As such, the cooling properties of the nitrous oxide cool the heating element of the mass airflow sensor to such an extent that the ECU commands the injector pulse width to widen. This widening of the injector pulse width is rather important, because it provides the necessary extra fuel that must be supplied with the nitrous oxide to make more power. Due to the simplicity of the system, the dry nitrous kits have had much success in the aftermarket industry.

Chapter 6

Turbocharging

6.1 Overview

When matched properly to an appropriate internal combustion engine, turbochargers provide a great means to efficiently increase the power output of any engine. Naturally aspirated engines are limited to the amount of air/fuel charge that can be combusted efficiently. The amount of air that makes its way to the combustion chamber can be greatly increased through turbocharging. By effectively increasing the mass flow rate of air into the cylinder and simultaneously increasing the amount of fuel supplied (through engine management techniques), substantial power gains may be realized. One advantage of turbocharging is that it increases the efficiency of a properly matched engine by converting previously wasted by-products into useful sources of energy.

6.2 Theory of Operation

There are two main types of turbochargers: radial flow turbines and axial flow turbines. The most commonly used turbochargers in automobile applications are the radial flow turbines. The radial flow turbine has a compressor and a turbine wheel. The exhaust gas propels the rotor (turbine wheel) which is mounted on the same shaft as the compressor (impeller) wheel. The impeller wheel draws air from the intake tract of the engine and accelerates it towards the compressor housing. Once the air is compressed, it then enters the diffuser section of the housing. The compressed air then slows and the pressure increases. Note that with the pressure increase, the temperature also increases.

Note that in the radial flow turbine, there is some loss associated with the gap between the turbine blades and the turbine and compressor housings. Note that this gap becomes less of a factor when larger turbines are used. This particular loss becomes less relevant with larger turbines; therefore, larger turbines are deemed to be more efficient. However, this does not imply that a larger turbine will always make the most power as the turbine must be carefully selected to match the particular engine in question.

Note that for this discussion, the operation of the turbocharger will be treated as adiabatic. That is, there is no heat transfer in or out of the system. While real world applications prove otherwise, the amount of heat dissipated by the turbine is insignificant as compared to the amount of heat energy within the system. The approximation remains rather suitable for very short time periods as well. Since the compressor is assumed to be reversible as well, it can also be assumed that it is isentropic (the entropy of the system remains constant).

The T-s plot above remains a good method to better understand the turbocharger. The irreversible processes are associated with an increase in entropy. The isentropic processes are represented by vertical lines.

Eq. (6.1) provides an expression for the work per unit mass flow of the turbine [5]:

$$h_{in} + Q = h_{out} + W \tag{6.1}$$

Eq. (6.2) shows the adiabatic assumption used in this analysis [5].

$$W = h_{in} - h_{out} \tag{6.2}$$

These equations can be used to determine the work associated with a specific turbine.

6.3 Turbocharger Efficiency

The isentropic efficiencies of the compressor and the turbine can be found using the following equations from Richard Stone [5]:

Eq. (6.3) shows the efficiency of the compressor:

$$\eta_c = \frac{(T_{2s} - T_1)}{(T_{2s} - T_1)} \tag{6.3}$$

Eq. (6.4) shows the efficiency of the turbine:

$$\eta_c = \frac{(T_{3s} - T_4)}{(T_3 - T_{4s})} \tag{6.4}$$

Note that the isentropic efficiency of a turbocharger is usually a good method to compare the real work of the turbine to the actual work produced from the system. The isentropic efficiency of a radial flow turbocharger is usually 75 percent for the compressor and 70-85 percent for the radial flow system.

A useful equation to determine the output temperature of the turbine is given below as Eq. (6.5)

$$T_2 = T_1[1 + \frac{\frac{p_2}{p_1}^{(\frac{\gamma-1}{\gamma})} - 1}{\eta_c}] \tag{6.5}$$

Note that the temperature of compressed air that leaves the system is rather important for it plays a large role in the density of the exiting pressurized air. As temperature increases, the density of the pressurized air decreases and thus the system becomes less efficient.

In addition, the mechanical efficiency of the turbine can be defined as the following:

Eq. (6.6) shows the efficiency of the turbine:

$$\eta_m = \frac{W_c}{W_t} = \frac{m_{12}C_{p12}(T_2 - T_1)}{m_{34}c_{p34}(T_3 - T_4)} \tag{6.6}$$

6.4 Performance

The performance of a particular turbocharger can be determined by looking at a turbocharger compressor map. The compressor flow map gives the amount of air compression as a function of the mass (or volume) flow of the uncompressed air entering the turbo itself. At first glance, these charts may seem quite difficult to read.

The curved lines on the map with numbers ranging from 46,050 and 125,650 represent the rotational speed of the turbine in RPM. The isentropic efficiency of the compressor is represented by the elliptical curved lines which range from 50 percent to 73 percent for this particular turbocharger. The pressure ratio on the vertical axis is the ratio of the exiting air pressure to the incoming ambient air pressure. The air flow rating on the horizontal axis gives an output of $\frac{lb}{min}$.

An interesting side note concerning the wheel speed of the compressor is that at certain high wheel speed values, it becomes very difficult to raise the output pressure of the turbine. At these speeds (which are faster than the speed of sound), the diffuser in the housing becomes choked and does not permit notable increases in flow. At this point, the turbine has become inefficient and a larger unit may be required. In addition, when the turbine is spun to a very high speed, engine damage may occur. This danger is usually overcome through the use of a wastegate valve. Wastegate operation may vary depending on its design. One of the simple and common mechanical wastegate designs involves the use of a calibrated spring which regulates manifold pressure by directing flow around the turbine wheel and directly into the exhaust system.

6.5 Turbocharger-related Sources of Engine Failure

The damage that may occur from a turbocharger usually concerns pre-ignition or ″engine knock.″ This sometimes occurs from setting the timing of the spark ignition system at a value which is too far advanced. The combonation of increased cylinder pressure and early ignition causes combustion substantially before the piston has reached TDC. This early ignition produces a knocking sound and is accompanied by very high pressures. This high pressure causes high stress on the piston and ring assembly as well, and has been known to crack ringlands and severely damage piston assemblies, along with other internal parts. In addition to advanced spark timing, a high compression engine will be less effective at making power than a lower compression engine if a turbocharger is applied. This stems from pre-ignition due excessively high cylinder pressures. A lower compression motor will accept a larger amount of the highly dense intake charge produced by the turbocharger. It is important to also note that an engine running lean will also be susceptible to knock and pre-ignition.

Besides reducing the compression ratio and retarding the timing, it is also effective to reduce the probability of knock and increase performance through the use of an intercooler to reduce the temperature of the incoming intake charge. The power level of the engine may be increased with an intercooler since the density of the incoming charge may be increased substantially. If the inlet temperature is reduced, there will be less thermal loading on the engine. The equation showing the efficiency associated with an intercooler is shown below as Eq. (6.7) from Richard Stone [5].

$$\epsilon = \frac{\text{actual heat transfer}}{\text{maximum possible heat transfer}} \tag{6.7}$$

The cooling medium used in intercoolers is usually air or water. Sometimes water in the form of ice for high performance applications such as drag racing where the car will travel short distances. In some cases, engine coolant is used; however, due to its high temperature, it is not the best choice as a cooling medium.

Note that with an intercooler, some losses in flow might be present through the intercooler. As such, it is sometimes necessary to increase the output pressue of the turbocharger itself to compensate. Also, due to the increased mass flow rate of air into the engine, the fueling system must be altered to provide more fuel to the engine.

6.6 Turbocharger Sizing

Richard Stone notes that large turbochargers provide a poor transient response. However, as previously noted, a larger turbocharger will be more efficient at high operating speeds. Conversely, a smaller turbocharger has less inertia and will provide a better transient response and low speed efficiency. As such, it is very important that the operating conditions be taken into consideration when selecting a turbocharger.

It should also be noted that while internal combustion engines operate over a large range of speeds, turbines are very sensitive to operating speed. This high sensitivity is due to the fact that the angle of the gas flow and angle of the blades themselves must be matched for a specific operating speed/range. Stone notes that a flow rate provided by a manufacturer corresponds to one operating speed. Therefore, it is very important that care is taken in selecting a turbocharger for a specific application.

In order to select a turbocharger, one must first calculate the volume air flow of the engine. The equation from Lucius [6] expressing this value is shown below as a function of engine displacement (in cubic inches), volumetric efficiency, and engine speed:

$$\mathrm{VAF} = \frac{\mathrm{CI}}{1728} * \frac{\mathrm{RPM}}{2} * \mathrm{VE} \tag{6.8}$$

It is sometimes useful to use the mass flow rate of the air:

$$\dot{m}_a = \rho * N * V_s * \mathrm{VE} \tag{6.9}$$

The volume air flow and the mass flow rate of the air may be used to choose a turbocharger based on its workable range. Based on the engine load chararcteristics and operating environment, the compressor will be chosen. Of course, the most obvious choice will be a compressor which will operate in its most efficient region as much as possible. For the times that the compressor is not operating near its efficient range of operation, it must be operating at a location on the compressor map substantially distant from the surge line. Finally, a turbine will be chosen to match the compressor. Note that the output of the turbine is a function of effective flow area.

Chapter 7

Fundamentals of Supercharging

7.1 Introduction

The supercharger's origins do not lye in the automotive industry, but rather primarily in the airplane industry. During WWII, airplanes started to push their physical limits, especially in their engines because of the reduction in atmosphere at higher altitudes, which adversely effected the combustion process of the internal combustion engine. The supercharger assisted aircraft engines by compensating for the reduced atmosphere by forcing the extra needed air into the cylinders.

After the success of the supercharger in the airplane industry, hot rodder's could not resist the extra power implications that the supercharger offered. The automotive industry first used a fixed displacement Roots supercharger and later, the screw compressor and centrifugal supercharger.

Today there are three major types of superchargers: the Roots, centrifugal, and screw compressor superchargers. These can then be reduced into two categories, the fixed displacement and the variable displacement types. The Roots and crew compressor both fit into the fixed displacement category, because they pump a specific volume per revolution and block any reverse flow. The centrifugal supercharger lies in the variable displacement category, which forces a unspecified amount of air, meaning there is the possibility of a reverse flow.

These three types of superchargers can further be divided into one's with or without internal compression ratios. The Roots does not have an internal compression ratio, while the centrifugal and screw compressor both possess one.

7.2 Fundamentals

What is it about superchargers that add power? The power output from an engine is limited by the amount of fuel that can be combusted in the cylinders, which is dependent on the amount of air present to complete the combustion chemical reaction. In natural aspirated engines, the air is forced into the cylinders through atmospheric pressure forces. Unfortunately, due to viscous drag in the intake system, not all the potential air that theoretically could enter the cylinders actually does, resulting in a pressure in the cylinders below atmospheric, on the induction stroke. As a result of the lower air pressure in the cylinders, the mass consequently is lower.

The supercharger is able to increase the power output of an engine because of the forcing of *extra* air into the induction system. With the addition of the extra air mass, more fuel can undergo the combustion process. With this device, not only can atmospheric pressure and density be reached, but for more power, high pressure and densities can be attained.

Unfortunately, the supercharger is less than perfect, because they obey the laws of thermodynamics. At closer observation, it is seen that as a result of the added boost, rise in pressure and density, there is also a rise in the temperature of the air forced into the cylinders. As a result, the ratio between the forced pressure and density becomes skewed due to the ideal gas law. This law leads to the reality that as the pressure rises in a constant volume with an increasing temperature, the resulting gas's density will decrease proportionally. What this means is that supercharger's have certain efficiencies which relates the theoretical mass of air to the actual air forced into the cylinder. The efficiencies can be estimated for Roots, centrifugal, and screw superchargers as 55, 75, and 70 percent respectively. [7]

Another draw back to superchargers is that they also require power to run. The power is taken from the engine usually through the means of a belt connecting the supercharger to the crankshaft. Further losses occur in the actual belt movement because of the overcoming of friction in the system, which is needed to turn the supercharger's compressing mechanism.

Some superchargers may also need additional equipment for better performance, such as bypass valves. These allow for any extra buildup of pressure in the induction system to be alleviated. But these devices can hamper the advantages of superchargers with internal compression ratios because they keep the boost at a specified value.

7.3 Roots Supercharger

The Roots type of supercharger, illustrated in Fig. 7.1, is constructed of two lobes which mesh together, revolving in opposite directions. Reducing the need for lubrication, there is a small, but precise clearance between the outer shell and the lobes, as well as between the two lobes themselves.

This particular design results in its best performance at low to medium pres-

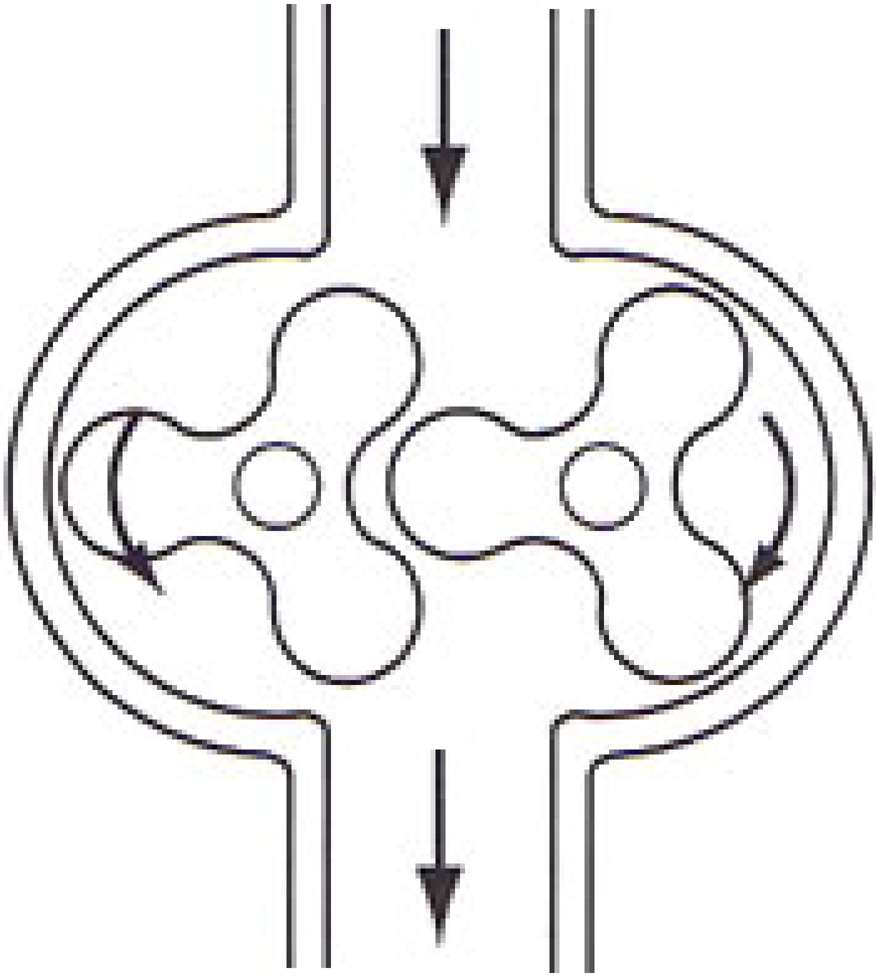

Figure 7.1: Roots Supercharger Design

sure boost where thermal inefficiencies do not have as great an effect on the power output. Since it does not compress the incoming air, but rather delivers it at atmospheric pressure at a constant pumping capability, it can deliver large amounts of power and torque at low engine speeds. However, speeds too low may also hamper the efficiency of the blower because air can escape through the clearances of the lobes. This is not a problem at speeds generally higher than 1000rpm because the air leakage is a function of time, which decreases with faster revolutions. [7] Further disadvantages from the design include a small carry back of air from the induction system, from trapped air in the clearance space of the lobes. The trapped, now heated air then heats up the incoming air which then is forced into the induction system.

The roots type supercharger generally is not used in today's modern vehicles because generally they limit the vehicles emissions through addition needs of fuel mixture to flow through the lobes for cooling characteristics, stopping thermal expansion. Secondly, they also tend to produce large amounts of noise from the gears and the movement of the air into the intake.

7.4 Centrifugal Supercharger

The centrifugal type of supercharger, illustrated in Fig. 7.2, is constructed similarly to a turbocharger. The outside air forced is into the engine intake through a rotating impeller which takes air molecules and forces them from the center of a impeller to the outside, collecting into a snail-shell shaped collector, which directs the compressed air into the intake system. The inner impeller is driven by a shaft connected to a pulley, which ultimately is driven by a belt between it and the

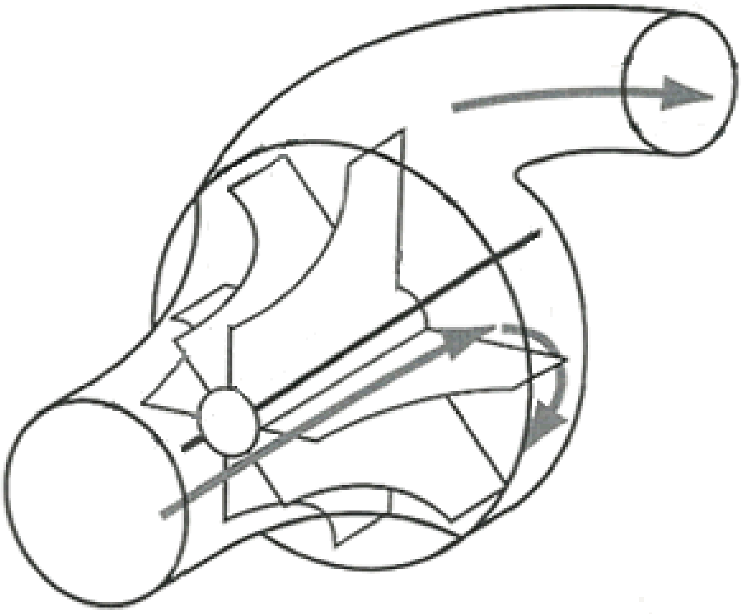

Figure 7.2: Centrifugal Supercharger Design

crankshaft.

Because the speed of the impeller depends on the speed of the engine, low boost is produced at low speeds and high boost is produced at high engine speeds. As a result, the engine receives extra boost at high revolutions and speeds.

This type of supercharger enjoys many advantages. The first is the greater thermal efficiency due to its internal compression of the air. It also can be easily installed on engines because it has no need to be directly mounted to the engine, but rather can be remotely mounted as an engine accessory and connected with pipes and a drive belt. Lastly, the drive powers tend to be lower than those of Roots or screw superchargers. [7]

The centrifugal supercharger also has several disadvantages. The first is the

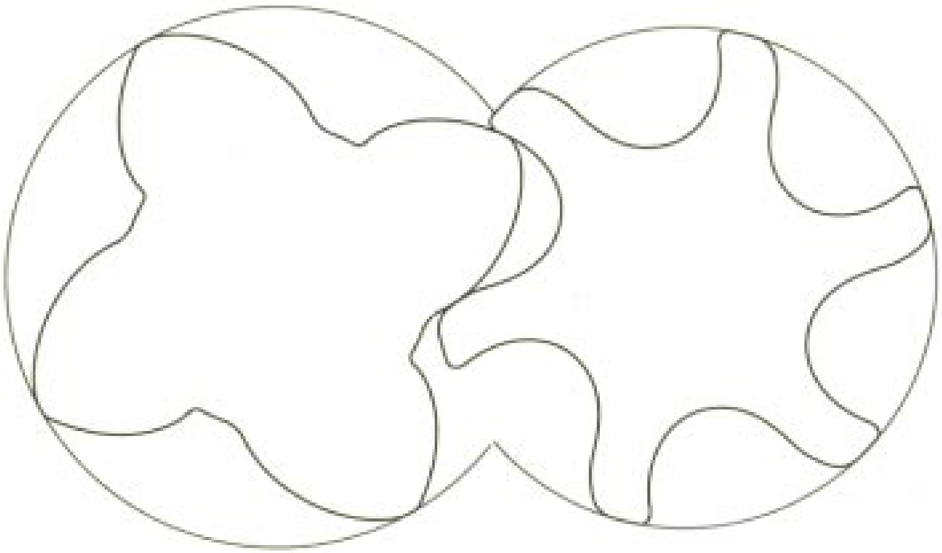

Figure 7.3: Twin Screw Supercharger Design

noise produced by the unit's gear drive. Secondly, this type does not provide high power outputs at low speeds, thus only being effected at mid/high speeds.

7.5 Screw Supercharger

The screw type of supercharger, illustrated in Fig. 7.3, is constructed similarly to the Roots supercharger. The difference is that the internal rooters are spiraled; one having female indentions, the other male lobes. The two rooters are geared and positioned to never tough each other, but have tight clearances, thereby eliminating the need for special lubrication.

The screw has many advantages from its design. The first is it has a high thermal efficiency, close to those of centrifugal superchargers or turbochargers, which is largely due to its internal compression ratio. It also has the unique characteristic, in that it produces more heat when it is off boast, rather than when it is under boost. This is partially due to the heating of the outer casing when no boost is produced through the lobe's movement. It also enjoys a high volumetric efficiency, especially at low pressures where it approaches 95 percent. [7] Lastly, similar to the Roots supercharger, the screw compressor can produce high pressures at low engine speeds.

The disadvantages of the screw type is that, like the Roots supercharger, it also has problems with leakage at engine speeds lower that 1000rpm. [7] Another disadvantage is the noise produced by the unit due to its fixed displacement and internal compression ratio characteristics, which produced a popping sound when the compressed air is released into the induction system.

7.6 Miller Cycle

The Miller Cycle is an interesting cycle which can be employed through the use of a supercharger, especially the twin screw. It revolves around the premise that the expansion ratio and compression ratio can be **different**. The expansion ratio can be defined as the ratio of volumes, independent of other factors, which is also the same for the compression ratio. But if the intake valve is held open for a longer period of time, the piston can not compress the air in the cylinder until the intake valve closes. Consequently, the volume above the cylinder remaining after the intake valve closes becomes the new cylinder volume. Through the high density of air mass produced from the supercharger, the greater density will make up for the lost compression, resulting in a compression ratio substantially smaller than that allowed by standard valve timing. This reduces further the heat of compression, which in turn allows for a much high boost level. This principle allows for a naturally aspirated engine with 10:1 compression to have the power generated from high boost pressure, but have the anti-knock characteristics of a 7:1 compression engine. [7]

Part III

Internal Air Flow

Chapter 8

Intake Manifold Design

8.1 Basic Operation and Design

An intake manifold, is comprised of a main trunk which diverges into separate passages leading to the individual intake valves for each cylinder, which routes the incoming air from the throttle body or carburetor to the cylinder head.

The basic intake manifold will be designed for minimum resistance to air flow, light weight, and ease to manufacture at a relatively low cost. Minimum resistance is achieved through relatively straight runners, the individual ducts leading to the cylinders. If turns must be present in the ducts of the manifold, they should be generally designed with big radii, unless a right angle is desired to promote fuel vaporization by shattering fuel droplets against the interior walls.

The manifold design should distribute the incoming air equally to each of the cylinders for optimal performance and incorporate smooth inner surfaces to aid in laminar flow. Smooth walls reduce the viscous friction, but some designs may use a slightly rough wall to assist in evaporation of the fuel from the accompanying turbulence. Roughness may also be desired to reduce the speed of flow near the inner radius of bends in the ducts.

8.2 Air Distribution

A main design constraint for a carbureted or throttle body fuel injected system is for equal distribution of air and fuel to each of the cylinders, which is not necessary in multi-port injection because the alternative fuel delivery method. Distribution is further complicated through the use of multiple carburetors. To combat the problem of some cylinders receiving a lean or rich mixture, a mixing box may be designed to assist in more equal distribution.

Another potential problem arises from the suction created by the opening of the intake valves, which may rob neighboring tubes of their fuel mixture. To combat this problem, manifolds may be divided into two subsections separating the runners for opposing cylinder induction strokes.

Another important design consideration is to avoid depositing of liquid gas on the walls of the manifold. For example, at idle, the manifold walls are dry and the air is virtually saturated with vapor. If the throttle is suddenly depressed, the density of the air suddenly rises which effectively squeezes the fuel vapor from the air leading to condensation on the manifold walls.

In a cold starting engine, the fuel may not fully evaporate because of the lower temperatures causing for pools of fuel to form in the manifold. The liquid fuel can not be allowed to drip into the cylinders in order to prevent misfiring and dilution of the lubrication. To prevent these conditions, a well beneath the riser can be designed to capture the liquid fuel as well as assist in the re-evaporation of the fuel. Some runners may also be slightly sloped down from the cylinder head to prevent entering liquid fuel into the cylinder. Buffered ends also assist in straight rake type manifolds to lead the condensed fuel into the well. Lastly, to ensure fuel is not deposited on the walls of the manifold, in general the runners should be sized so the velocity of the incoming air is no less than 70 m/s. [2]

8.3 Manifold Heating

Manifold heating is important to intake manifold design to assist in the vaporization of the fuel. To accomplish this, a hot spot is designed beneath the fuel well in the manifold. These hot spots are attained through various means, either water, exhaust, or electrical heating or a combination of them.

One problem with water heating is that it may be difficult to deflect the water flow from the hot spot after the engine is warm, which could lead to variations in the volumetric efficiency. To achieve a more stable temperature, a thermostat can be used. The thermostat will allow the hot water to heat the manifold until the liquid reaches a set temperature, when it will open and allow the water to flow to a radiator for cooling.

An effective way to heat the manifold quickly is by using exhaust fumes. This will produce heat quickly because of the high temperatures of the gases which have been recently combusted in the cylinders.

The biggest leap in technology for manifold heating came after the development of the engine management system. Now electrical heaters could be implemented and kept at a constant temperature through the feedback received by the computer from temperature sensors. This system can be even more effectively implemented when combined with a thermostat regulated water heating system.

8.4 Effects of Resonance and Waves

There are four basic phenomena which can be taken advantage of or avoided in the manifold design: Inter-cylinder charge robbery, inertia of flow, resonance, and the Helmholtz effect. [2] The first phenomena is perhaps the most important of the four because failure to take its effects into consideration can lead to low power output from the engine.

To explore inter-cylinder charge robbery, valve timing and cylinder layouts needs to be explored. The depression in the cylinders alternates similarly to that of the motion of the piston in the cylinder. As a result, the opening of the intake valve creates a suction wave, and when it closes, it creates a pressure wave to form in the runners. When the intake valve is closed, the fuel mixture in the runner tends to stagnate.

Because of a possible over lap time or period of different cylinders in a multiple cylinder engine, overlapped induction phases can cause charge robbery between the cylinders. This is cause by one cylinder running rich while the other runs lean due to the suction of the newly opening intake valve. This phenomena decreases with increasing engine speeds because there is less time for flow reversal to occur between different runners. The adverse effect can partially be solve by designing a plenum chamber, which would connect all of the runners. Another partial solution is to arrange runner orientation into the plenum in a fashion that cylinders with overlapping induction strokes are not next to each other.

As discussed above, it is important to have the correct placement of runners for cylinders with overlapping induction strokes. Fig. 8.1 to Fig. 8.3 illustrates the firing order and overlap for inline three, four, and six cylinder engines. Acknowl-

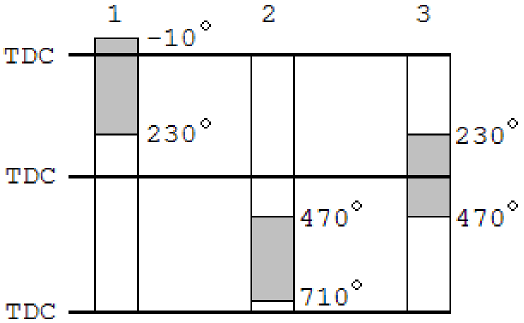

Figure 8.1: Inline Three Cylinder Firing Order

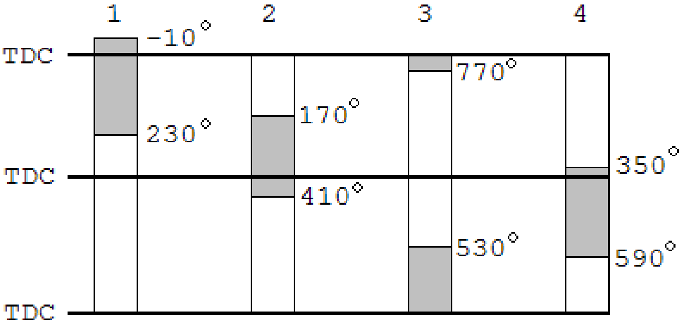

Figure 8.2: Inline Four Cylinder Firing Order

edgement of these factors are important in the design to prevent charge robbery from the overlapping strokes. An example of a manifold design to solve this problem is shown in Fig. 8.4. These overlaps can also be incorporated into V-engines because they are treated as two side by side inline engines, although there may be some variations in individual cylinder positioning. A solution for the intake manifold layout for a V6 engine is illustrated in Fig. 8.5.

The pressure wave inside the runners can be broken into several stages. The

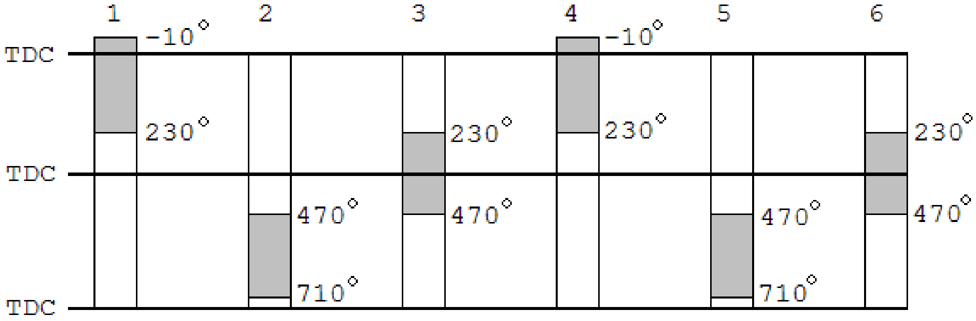

Figure 8.3: Inline Six Cylinder Firing Order

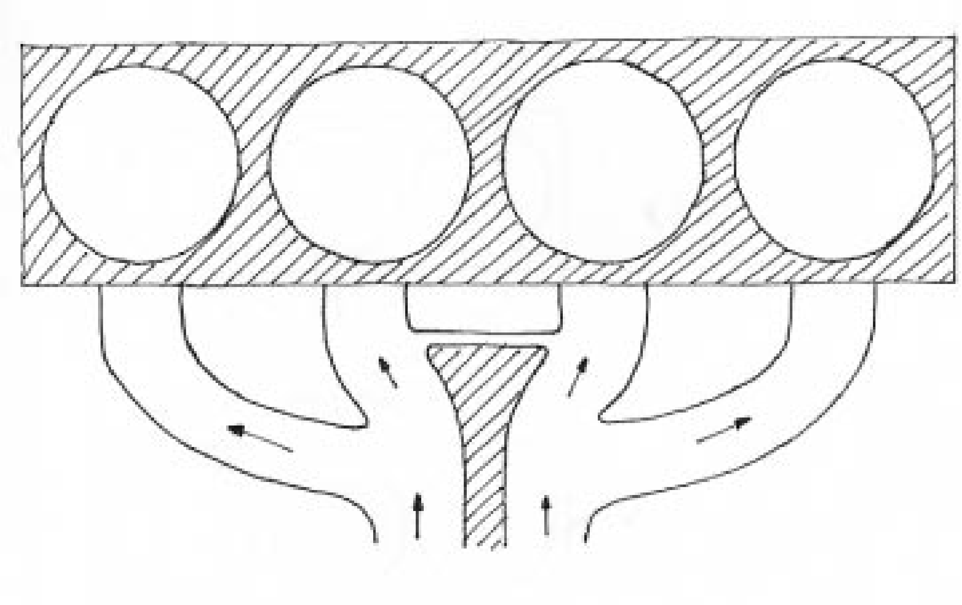

Figure 8.4: Manifold Design

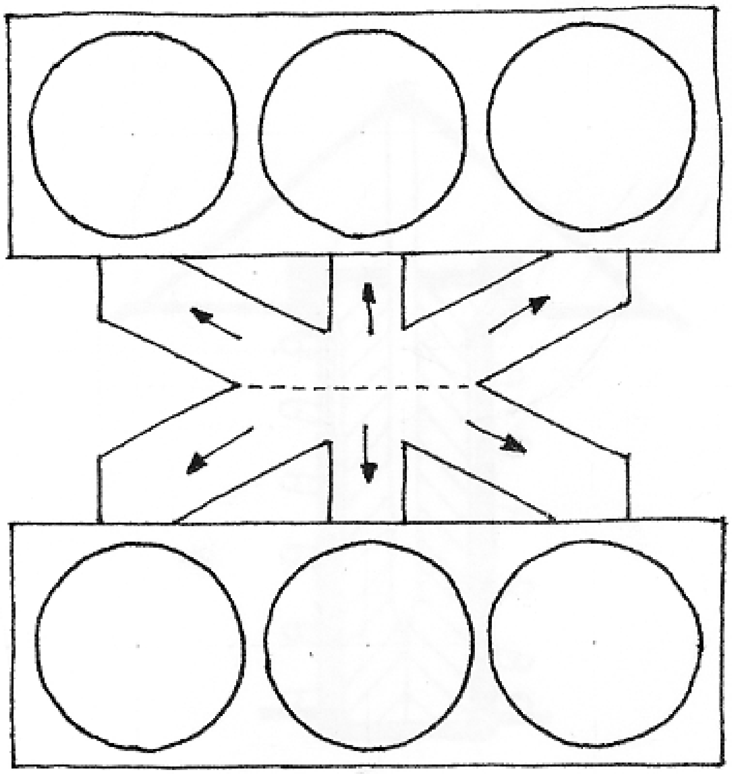

Figure 8.5: V6 Manifold

first is when the fuel mixture is drawn into the cylinder causing a depression in the runners. When the intake valve closes at the end of the stroke, the depression wave is reflected against the valve sending it back up the runner, where it is then reflected again back towards the intake valve. The amplitude of the pulse increases as the engine speed gets higher. The larger the area of the runner, the greater the effect of the depression from the greater effects of inertia. As a result, it is important to take advantage of these properties so that the returning wave reaches the intake valve again when the new stroke starts. There is also an important ratio of the runner volume to the piston-swept volume which needs to be considered in the design of the manifold.

Because of the natural changing characteristics of the internal combustion engine, certain compromises must be made to make the engine as powerful and efficient at certain engine speeds. This is particularly true for the intake manifold characteristics, like the length of the runners being dependent on the engine speed. Compromises must also be made to add features, such as a reducing taper of the runners from the plenum to the cylinder heads; but care must also be given not to disturb the laminar flow.

As previously discussed, it is important to design a runner length which will cause the depression wave to return to the valves when the valve opens again. More to the point, the wave should return to the end of the runner when the intake valve opening period is about half way through for optimum performance. If the wave arrives too early, the pressure might fall before the intake valve closes again, which could cause a reverse flow. But if the wave arrives too late, it will fill the cylinder at the end of the stroke and cause turbulence when the valve closes, reflecting the new depression wave.

At low speed operation, the depression waves move at a slower velocity comparatively to that of high speed operation. As a result, for lower speed operation, a shorter pipe is more beneficial for creating optimal influx of fuel mixture, where as with the high velocity waves at high speeds, runner lengths should be increased to yield the optimum setting.

The runner endings need to also be considered in the design because of the effects on the incoming and out going air flow. Because of the influx of air and the variations in the depression waves, the ends of the runners have increased turbulence, which adversely effects the efficiency of the engine. If the ends of the runners are flared out like the end of a trumpet, it guides the air in a smoother fashion into the runners and increases the coefficient of inflow by as much as 2 percent. And as mentioned before, a tapered runner will also reduce the end turbulence effects.

A good example of an efficiently designed intake manifold is the GM Dual Ram. This system works by using variable runner lengths through the implementation of a dividable plenum. When the plenum is divided into two separate chambers, it effectively make the runners long which is good for the high speed operation. But when the plenum is not separated, the runners are then turned into short lengths which optimizes efficiency at low speed. The valve in the plenum is usually controlled by the engine management system for optimal operation.

Chapter 9

Cylinder Heads

9.1 Overview

In order to delve into the topic of cylinder heads, it is important that one have some background information concerning the different configurations. Since some engines have overhead cams and others have the cams placed in the engine block itself, there are fundamental differences in their corresponding cylinder heads. In overhead cam applications, the cylinder head itself has a provision to mount a camshaft (or two, if it is a dual overhead cam engine).

In applications where the camshaft is mounted in the cylinder block itself, the cylinder head has provisions for pushrods and rocker arms to actuate their corresponding valves. The figure below shows an example of the overhead valve engine from Richard Stone [5]:

Note that some cylinder heads have more than two valves per cylinder. In fact, some cylinder heads have been known to have 2, 3, 4, or in rare occasions 5 valves per cylinder (this is more common in motorcycle applications).

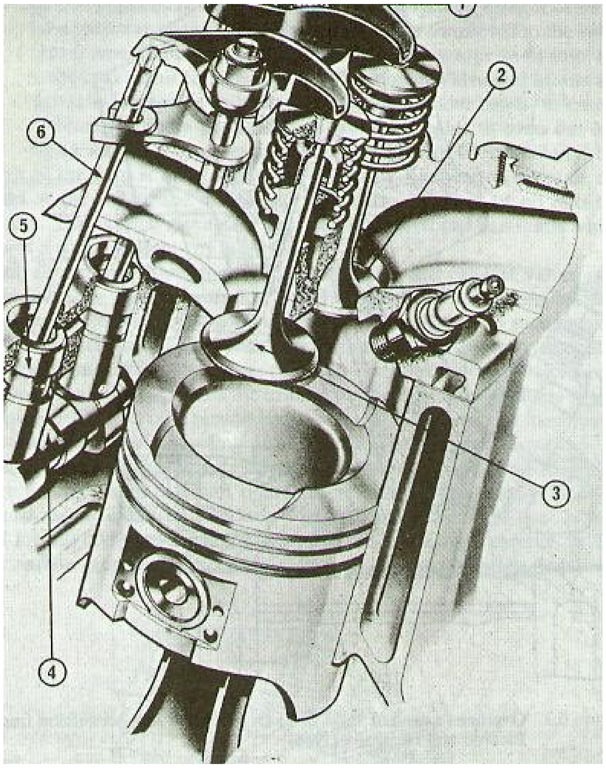

Figure 9.1: Overhead Valve Cylinder Head Configuration

9.2 Valves

There are many types of valves for a cylinder head; however, the most common one is the poppet valve which is common in most overhead valve engines. The poppet valve is rather cheap to manufacture (for most applications) and offers a good seat due to its shape and construction. The poppet valve also has great flow characteristics and provides a good means to direct fluid flow into the combustion chamber. The stem of the valve usually rides up and down a provision incorporated into the head itself that is machined called a valve guide. Valve guides can be made from steel, aluminum, or other materials which have good wear properties.

It is important to note that most valve design is empirical. Experiments are carried out with flow meters and other equipment to ensure that the flow rate meets the desired value.

The best valve designs have the least pressure drop (and therefore, the lowest losses) across the flow path. The figure below shows a typical poppet valve from Richard Stone Stone.

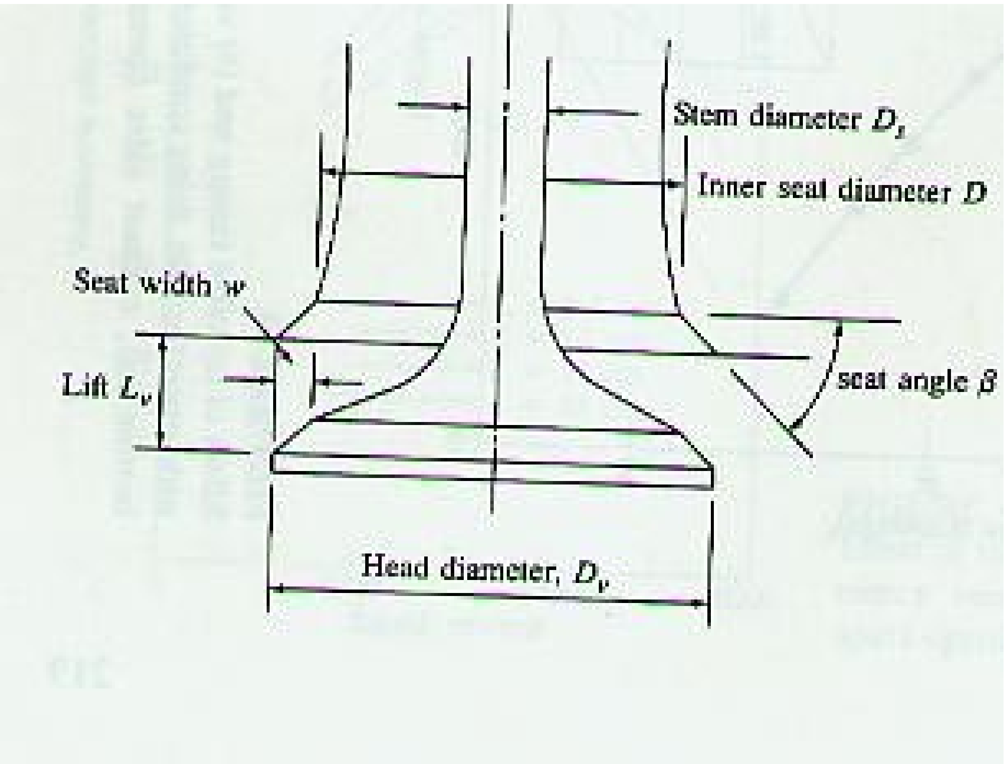

Figure 9.2: Typical Designs of Poppet Valves

In order to measure the instantaneous flow of the charge as it passes the valve, the minimum flow area must be calculated. The minimum flow area corresponds to the lift and shape of the valve head. The minimum flow area has three stages which correspond to the different levels of valve lift. For very low levels of lift, the minimum flow area corresponds to an area that is perpendicular to the seat. The area has the appearance of a frustum whose shape is determined by the interface between the valve itself and the valve seat. This area value can be defined by the Eq. (9.1) [5]:

$$A_m = \pi * L_v * (cos(\beta)(D_v - 2w + (L_v/2)sin(2 * \beta))) \tag{9.1}$$

The second stage of minimum area has a cross section which still resembles a right frustum. However, this frustum no longer has an angle defined by the valve seat. Rather, the frustum has an angle which is increasing to a maximum value of 90 degrees. This minimum valve flow area is represented by Eq. (9.2) [5]:

$$A_m = \pi * D_m[(L_v - wtan\beta)^2 + w^2]^{(1/2)} \tag{9.2}$$

The final minimum valve area is no longer defined by the shape of the valve head. This valve area is simply the cross sectional area of the valve stem subtracted from port flow area. Therefore, the only element blocking the fluid flow is the valve stem itself. At large valve lift values, the valve head is removed far enough from the port such that it has minimal effect on fluid flow. Equation Eq. (9.3) may be used to find the minimum flow area corresponding to high lift values [5]:

$$A_m = \pi/4(D_p^2 - D_s^2) \tag{9.3}$$

Finally, the pseudo flow velocity for the valve may be found using Eq. (9.4) [5]:

$$v = \frac{1}{A_m}\frac{dV}{d\theta} \tag{9.4}$$

The pseudo velocity is measured in units of meters per degree of crankshaft revolution since it is easiest to reference everything to the crankshaft angle when describing the fundamentals of engine operation.

An important difference between intake and exhaust valves is in the direction of fluid flow: fluid passes by the intake valve into the combustion chamber, and fluid exits the combustion chamber via the exhaust valve. The opposite directions of flow mandate different fundamental designs of each type of valve.

Intake valves usually have seats with very pointed edges. There are 3 main fluid flow stages of the intake valve which correspond to different lift intervals (and the three main minimum flow areas previously mentioned). In the first, low lift, stage, the incoming fluid tends to adhere to the walls of the valve seat and the valve itself. In the second, mid-lift, stage, the fluid will only adhere to only the valve or the seat and break away on the other side. Finally, at high lift intervals, the fluid has broken away from the valve seat and the valve head and remains unobstructed as it flows into the combustion chamber.

Note that the seat and valve head width, seat angle, and radii (on the edges of the valve head and seat) play a major role in determining the flow rates at these three stages of lift. In addition, the port design and cylinder head shape plat a role in determining the flow characteristics of a poppet valve. Richard Stone [5] uses a study done by Annand and Roe (1974) which showed that the ideal intake valve has a seat angle of 30 degrees with a 10 degree angle upstream from the seat itself. The study also showed that flow may be improved by rounding the corners on the valve seat itself.

For exhaust valves, the amount of lift has less of an impact on flow. This is due to the fact that the pressure gradient across the exhaust valve is greater than that of the intake valve. Due to this higher pressure gradient, the design of the exhaust valve is less critical than the intake valve. Stone points out that the exhaust valve usually takes up 40-44 percent of the bore diameter while the intake valve takes up about 44-48 percent of the bore diameter. These values are for a flat two-valve cylinder head. For a hemispherical head, these values can be larger; however, the ratios are still very similar. For a four valve engine, Stone notes that the intake valves should compose about 39 percent of the bore size, and the exhaust valve should be around 35 percent of the bore diameter. The higher pressure gradient on the exhaust side is why the intake valve is usually larger in diameter than the exhaust valve.

There are two major flow stages of the exhaust valve. In the first, at low lift values, the flow adheres to the seat and the valve itself. As with the intake valve, at high lift values, the flow separates from the valve seat and the valve. For the exhaust valve design, it has been shown that a poppet valve with very sharp corners provides the best flow characteristics for an internal combustion engine.

9.3 Port Design

Most port design today is empirical. The figure below shows two types of port designs typical to intake and exhaust valves [5].

Note that from empirical designing, it has been concluded that a circular intake port suits the four stroke internal combustion engine the best. Note that the cross sectional area is set such that it is just large enough to achieve the desired power output for the particular engine. For exhaust valves, an oval or rectangular shape is

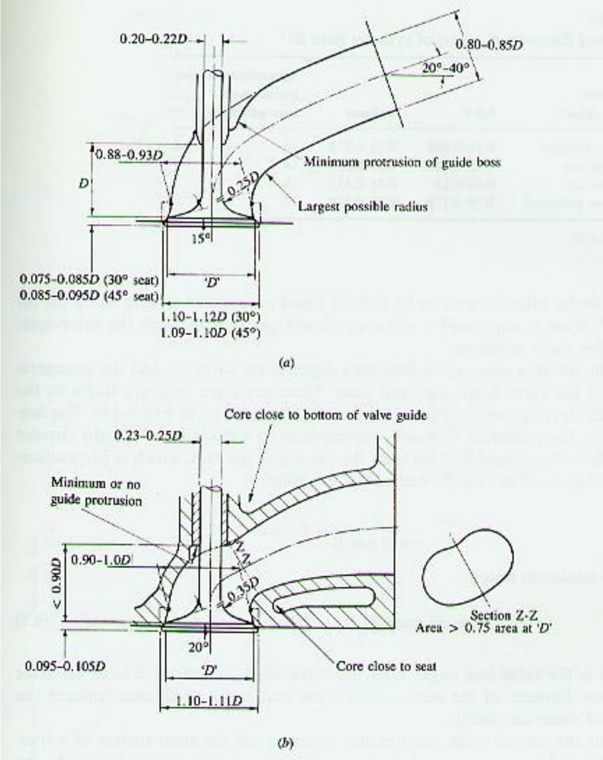

Figure 9.3: Intake and Exhaust Port Designs

usually incorporated even though a circular cross section is desirable. The oval or rectangular shape is usually used out of necessity from space constraints to guide the fluid flow around the valve guide boss area. In addition, the exhaust port should have provisions for proper cooling of the valve seat and the valve stem.

Chapter 10

Camshaft Profiles

10.1 Overview

In order to discuss the theory behind camshaft profiles, one should first have some understanding of the different types of cams that exist. The major types of cams are roller and flat tappet cams. Flat tappet cams incorporate a lifter which has a flat face which rides on the cam lobe. Roller cams have a rolling element lifter which rides on the cam lobes. Note that both flat tappet and roller lifters can be broken down into two types, hydraulic (which uses oil to pump up a spring loaded lifter, this type requires little to no adjustment) and solid (which requires periodic adjustment to ensure that the tolerance between the valve and rocker or cam follower is met). Solid lifters are used widely in racing applications where very aggressive camshaft profiles are required. A hydraulic lifter will collapse under high stress due to the fact the oil pressure required to keep the lifter pumped up is inadequate. Camshafts may be placed in the engine block (for overhead valve engines) or in the heads (for overhead cam engines). In overhead valve engines, the camshaft actuates the valves via a lifter, rocker, and pushrod assembly as shown below. In overhead cam engines, the valves are actuated via a lifter which rests on the valve stem as shown below. The theory of operation and lobe profile are similar for the two types of engines regardless of the type of engine in question. Camshaft profiles may be governed by a polynomial function. Such lobe profile is called the polydyne cam which was introduced by (Dudley 1948). Due to the fact that the cam is rotating on an axis and the valve lift is determined by the location on the cam lobe, the lift is given as a function of angular displacement as in Eq. (10.1). Note that Eq. (**??**) [5] can be differentiated to find the velocity, acceleration, jerk, and quirk of the valve.

$$L_v = f(\theta) = a + a_1\theta + a_2\theta^2 + a_3\theta^3 + \ldots + a_i\theta^i \tag{10.1}$$

This may be differentiated to find the velocity of the valve as shown in Eq. (10.1):

$$L_v = f'(\theta) = \omega(a_1 + 2a_2\theta + 3a_3\theta^2 + 4a_4\theta^3 + \ldots + ia_i\theta^{i-1}) \tag{10.2}$$

For acceleration:

$$L_v = f''(\theta) = \omega^2(2a_2 + 6a_3\theta + \ldots + i(i-1)a_i\theta^{i-2}) \tag{10.3}$$

For jerk:

$$L_v = f^3(\theta) = \omega^3(6a_3 + \ldots + i(i-1)(i-2)a_i\theta^{i-3}) \tag{10.4}$$

For quirk, Eq. (10.4) may be differentiated to finally give:

$$L_v = f^4(\theta) = \omega^4(24a_4 + \ldots + i(i-1)(i-2)(i-3)a_i\theta^{i-4}) \tag{10.5}$$

Note that by integrating the valve lift equation with respect to angular position, one may obtain the equation for the valve lift area. Eq. (10.6) [5].

$$A_\theta = \int_{-p}^{p} L_v dv = 2bph \tag{10.6}$$

Valve lift area is a useful quantity because it may be used to compare the performance characteristics of two different camshaft grinds. In general, the greater the valve lift area, the more performance oriented a camshaft profile is. Note that the length of time that the valve is open (duration) remains a very important element to determining the lift area. There is much discussion regarding the actual point at which this lift is measured, but the SAE standard for hydraulic and solid lifters is defined as follows:

1) Hydraulic Lifters: 0.006 in (0.15 mm) valve lift positions are considered to be the opening and closing positions. 2) Solid Lifters: 0.006 in (0.15 mm) in addition to the valve lash is considered to be the position at which the valve is considered in the open or closed position.

In order to take into consideration the design of a camshaft, one must first decide what the requirements of the engine are. In his article Valve Events and Engine Operation, T.W. Asmus [8] specifies four important characteristics of an IC engine that are affected by valve timing events: 1) Engine power output 2) Engine low speed torque 3) Engine fuel consumption at idle 4) Engine idle quality. In order for an IC engine to operate at a high speed, it is important that the durations of both the intake and exhaust valves are longer than the duration of the corresponding piston stroke. Closing the intake valve after the intake stroke ensures increased cylinder filling. According to Asmus, volumetric efficiency of the engine is increased by a later closing of the intake valve due to the fact that the measured pressure within the cylinder is less than that of the charge within the intake at bottom dead center (BDC). For a performance oriented street engine, this could be as much as 70 degrees after BDC. In addition, opening the intake valve before TDC will accelerate the flow of the intake charge into the combustion chamber. For a performance oriented street engine, the camshaft should open about 10 degrees before TDC. Furthermore opening the exhaust valve before BDC (around 60-66 degrees for performance oriented street engines) reduces the amount of work required to push the exhaust out of the combustion chamber. This early opening of the exhaust valve uses blowdown to accelerate the exhaust out of the combustion chamber. Note that as the IVC (intake valve closure) is moved to a later point, some of the spent exhaust gasses may return into the intake, especially at lower speeds. The early EVO (exhaust valve opening) decreases the value of the expansion ratio, once again especially at lower engine rpm. Both of these occurrences have the effect of lowering engine torque at lower rpm values. In high performance applications where engine speed is kept high, the duration values of the intake and exhaust lobes are kept high to increase volumetric efficiency and thus high engine speed power output.

It is very interesting to note that valve lift does not have a large impact on the maximum effective flow area. In fact, duration plays the key role in the determination of flow area. This stems from a quick study of Eq. (10.7) which shows that as the volume flowrate and the flow area are proportional to each other [5].

$$A_C C_D = \frac{\dot{V}}{(\dot{V}_O / A_C)} \tag{10.7}$$

Since duration affects the volume flowrate more than lift, it is thus logical to conclude that duration plays a larger role in maximum flow area than lift.

10.2 Valve Events

In order to understand the cam theories provided by different camshaft manufacturers, it is essential to obtain a good grasp of the valve event fundamentals. These are outlined by Elgin [9] and Asmus [8] in their respective papers on camshaft theory:

EVO: Exhaust Valve Opening

Elgin considers this particular valve timing event to be of least importance. This event should occur before BDC in order to ensure that the combustion chamber pressure is equal to that of the exhaust system in order to reduce the loss associated with pumping the exhaust out of the combustion chamber. Note that the expansion ratio is greatly reduced if the engine EVO occurs too early which reduces power output. In his case study of the Chrysler 2.2 L engine that the volumetric efficiency is reduced by 0.07-0.12

EVC: Exhaust Valve Closing

This valve timing event significantly affects the valve overlap in an IC engine. Note that valve overlap is a very important quality in the production of an engine that has a smooth idle operation. At low engine speeds a late EVC event will cause some exhaust gas to enter the combustion chamber and dilute the fresh intake charge. However, at high engine speeds, the timing of this event is very critical in the discharge of exhaust gasses and ultimately determines how much of the exhaust is allowed to exit the combustion chamber. In general, if two similar engines are compared and the first has a later EVC event than the second, the first will produce more power at high engine speeds while the second will have a better idle quality and more torque at lower engine speeds. Asmus also points out in his case study of the Chrysler 2.2 L engine that the effect of EVC on the volumetric efficiency is about half that of the IVC (0.15-0.35percent/deg) at lower engine speeds.

IVO: Intake Valve Opening

It must be first noted that the volumetric efficiency of an engine is a function of piston speed Eq. (10.8) [5].

$$\eta_v = \frac{(2\dot{m}_a)}{\rho_{a,o} dN)} \tag{10.8}$$

Where $\rho_{a,o}$ is the air density and η is the volumetric efficiency. Note that the volumetric efficiency may be affected by valve lift and effective compression ratio, both of which are affected by camshaft profiles. Volumetric efficenty is also affected by port shape and size, valve geometry, mixture temperature, and fuel type (among other elements).

This is highly important in the filling of the cylinder since the effectiveness of the engine to fill the combustion chamber with charge is directly related to piston speed and thus volumetric efficiency. Eq. (10.9) below gives the piston velocity as a function of engine speed, crankshaft position, and the linear piston displacement given in Eq. (10.10) [5].

$$V = \frac{dl}{\beta} d(\beta)(360 frac\text{degrev})N \tag{10.9}$$

Where the instantaneous linear piston displacement is defined as [5]

$$l(\beta) = R + r - rcos(\beta)\sqrt{(}R^2 - r^2(sin\beta)^2) \tag{10.10}$$

Note the following:

$$N = engine\, speed \tag{10.11}$$

$$\beta = \text{crankshaft displacement from TDC} \tag{10.12}$$

Elgin points out that while the intake charge starts to enter the cylinder as soon as the intake valve opens, the charge does not rapidly enter until the pressure differential between the intake manifold and the combustion chamber is at a maximum (which occurs around 70 to 80 degrees after TDC). The momentum of the incoming charge is increased by opening the intake valve before TDC as previously stated. Of course, this early opening of the intake valve results in the flow of some of the exhaust gases to flow into the intake due to the existing pressure gradient. Once the pressure of the intake exceeds that of the combustion chamber, the exhaust diluted-intake charge then flows into the combustion chamber. Asmus notes that the intake valve opening is not the most important contribution to engine performance.

IVC: Intake Valve Closing

Elgin points out that the IVC is the most important valve timing event for it ultimately determines the engine rpm and the effective compression ratio (which is a function of valve overlap). While timing the intake valve to close after BDC is important and leads to an increase in performance, Elgin notes that extending the valve closing event too long (such as 75 degrees after bottom dead center) will decrease performance by reducing the effective compression ratio and limiting the horsepower output of the engine.

It was previously stated that the volumetric efficiency of the engine is decreased at lower engine speeds when the IVC occurs after BDC. This is the result of the fact that the pressure gradient between the intake and the combustion chamber is equal to zero at lower engine speeds. This results in the intake charge being pushed from the combustion chamber back into the manifold. An equation quantifying the loss of volumetric efficiency is given by Asmus as Eq. (10.13) [5].

$$\%Loss = \frac{dV(\beta}{d\beta}\frac{100}{V_s} \tag{10.13}$$

Note that the increase in performance at higher speeds is attributed to the momentum of the incoming charge in addition to the fact that even after BDC the pressure inside the intake is greater than the pressure inside the combustion chamber. Asmus notes in his case study of a Chrysler 2.2 L engine that as ICV is delayed one degree at lower engine speeds, the engine loses 0.42-0.65 percent of volumetric efficiency.

10.3 Selection

There are many variables that must be considered when chosing a camshaft, the first being the purpose of the engine. The difference in camshaft profiles for a performance-oriented sports car engine and a longevity-oriented delivery truck engine is rather significant, as both Asmus and Elgin point out. It is important to note that the recycling of exhaust gasses created by valve overlap is one way to reduce emmisions, yet this will be discussed further in a later chapter.

The amount of valve overlap in an engine also determines the burned gas fraction (BGF). The BGF is simply the ratio of burned gas to the unburned gas that exits the combustion chamber. This ratio is especially important at lower engine speeds where a large amount of unburned fuel can exit the combustion chamber. Asmus notes that exhaust gas recirculation systems (EGR) can aid in recycling the unburned fuel to decrease NOx output. If the EGR system recycles the unburned fuel in such a manner that each cylinder receives and equal amount of recycled exhaust, it remains of little consequence if exhaust gasses are recycled via valve overlap or an EGR system.

While valve overlap may be used to control emissions, it is important to note that this will sacrifice idle quality. Asmus notes at idle, it is not uncommon for the exhaust manifold pressure to be double that of the intake manifold. As such, exhaust gas is pushed from the exhaust manifold to the intake manifold due to the pressure gradient. This dilutes the fresh intake charge and hampers idle quality. By reducing the valve overlap and thus increasing the lobe separation angle (LSA) of the camshaft, it is possible to improve idle quality.

Note that improved idle quality has more importance than simply letting the engine freewheel at low engine speeds in a smooth manner. In fact, improved idle quality guards against surging and results in a smooth operation when the engine is under load at low engine speeds. This is similar to an automobile traveling up a slight incline with a locked torque converter (TCC lockup) in overdrive. An engine with a widened LSA has an audible difference in idle quality than one with a tighter LSA as well. The tight LSA has a choppy sounding idle which is harder to muffle. The wider LSA also produces a motor with a higher vacuum at idle as well, thus providing a source from which accessories may be run, such as a power brake booster on an automobile.

While lowering valve overlap produces an improved idle quality, it does however reduce WOT performance. As such, there is somewhat of a trade between improved idle and good WOT performance. Asmus feels that WOT performance can be salvaged by setting a late EVC and delaying the IVO, however, in high performance naturally aspirated applications, a tight LSA is deemed acceptable.

For WOT performance, it is rather important to time the IVC perfectly. Elgin and Asmus both note that this is the most important valve timing event, and in a performance application it is best follow the guidelines listed above for chosing the LSA and duration for this event. This one event can determine if an engine is performance oriented or not.

Part IV

Combustion

Chapter 11

Gasoline

11.1 Overview

Because this book only deals with gasoline 4-stroke internal combustion engines, it is only logical that some information be included on the fuel that powers these engines. Gasoline is widely used today as the predominant fuel in the United States for automobile engines. It is rather interesting to note that in the United States, more than 50 percent of the gasoline used annually is consumed on short trips according to Richard Stone. This is most likely due to the fact that many of the short trips do not involve freeways but rather stop and go traffic. As such, the fuel consumption associated with gasoline engines is increases with the number of short trips taken by Americans annually. Much of this information was referenced from books by Arcoumanis [10] and Ferguson [11].

11.2 Properties of Gasoline

At each gas station pump, the octane rating of the gasoline blend is displayed. The octane rating is simply a relative scale on which the fuel's resistance to knock is determined. Note that knock associated with pre-ignition was discussed in the Turbocharging chapter of this book. For this discussion, it will be assumed the reader has already studied that particular chapter.

Some very important properties of gasoline that one should consider when making an educated decision on the type of fuel needed are listed as follows:

- Heating Value
- Specific Gravity
- Gum
- Motor Octane
- Reaserch Octane
- Benzene

The chemical breakdown of most gasolines is given below:

- Aromatics 28.6 percent
- Olefins 10.8 percent
- Reid vapor pressure, kPa 60-79
- Sulfur, mass ppm 338
- MTBE 0 percent
- Ethanol 0 percent

The next section deals with a more specific, highly important aspect of gasoline: octane.

11.3 An in Depth Look into Octane Ratings

The octane rating is developed on a scale which ranges from 0 to 100. The 0 value is associated with the knock resistance of n-heptane abd the 100 value is associated with iso-octane. The low knock resistance of n-heptane and the high resistance of iso-octane make them appropriate fuels to set the scaling of octance ratings. It is important to note that some fuels have an octane rating greater than 100. For instance, some leaded racing fuels have octane ratings above 120. These fuels are used in applications where combustion pressure is very high and the engine is highly prone to knock. Applications such as these include high-boost supercharger and turbocharger engines, and engines which make the use of large amounts of nitrous oxide.

Note that an octane rating of 80 indicates a fuel that is equivilant to a mixture of 20 percent n-heptane and 80 percent iso-octane. Another way of quantifying the resistance to knock is the motor octane rating of gasoline. The motor octane involves a fairly strenuous test and usually carries with it more significance than the octane rating found at the pump at a gas station, especially in performance applications where the test conditions are very severe. Compared to the research octane number (the octane number shown at the pump), the motor octane number has harsher test condtions. While both tests involve a variable compression ratio engine, the motor octane test involves conditions at high temperatures (the incoming mixture temperature is about 300 degrees farenheit), higher engine speeds (about 300 rpm higher), increased spark advance (from 14-26 degrees for motor octane, compared to 13 degrees for the research test).

11.4 Case Study: The Effect of Fuel Octane on a Nitrous Oxide Assisted GM LS1 Engine

One specific instance where a very high octane fuel was used is in the authors 2002 Pontiac Trans Am street/drag car. This particular car involves an untouched, stock shortblock (stock crankshaft, connecting rods, cast pistons, and rings) with a high performance camshaft and a set of ported and milled cylinder heads which bump the static compression ratio to around 10.5:1. The engine relies on a rather radical and somewhat unconventional nitrous oxide system which utilizes its own low pressure fuel source to increase the tuning parameters availible. The nitrous oxide system raises power output at the rear wheels from 390 hp to 653 hp. The cast pistons in the engine are prone to failure from detonation, so close watch is kept on the amount of knock produced during the intervals in which the nitrous system is activated. When a fuel with an octane rating of 100 was utilized in both the nitrous stand alone fuel system and the car's engine fuel system, some knock was detected in the form of timing retard controlled by the engine's management system. Since the total timing at wide open throttle was only set at 19 degrees, it was determined that in order to keep power levels at their current levels it would be necessary to find a fuel more suitable to the engine parameters and characteristincs.

A high lead 120 octane fuel with a low specific gravity was chosen. Even when the nitrous system was "leaned out" (that is, the amount of extra fuel injected under nitrous activation was decreased in an effort to find more power), there was no sign of knock under activation of the nitrous oxide system. The air fuel ratio hovered at around 10-10.5:1 throughout the dyno session. However, due to the relative weakness of the cast pistons, it was opted to leave the car at its relatively

”safe” horsepower level of 653 rwhp (rear wheel horsepower).

From this case study, it can be seen that sometimes high octane fuels can be substituted for pricey strong internal engine parts in engines where performance is the highest priority. This is not implying, however, that an engine with weak internal parts can produce the same power as an engine with stronger internal parts (all else being equal). This is because engines with strong internal parts can withstand higher stress, temperatures, and have a higher resistance to knock. In addition, the use of high octane fuels can be rather expensive. For instance, the 120 octane, low specific gravity nitrous use fuel listed above costs over 8 dollars per gallon when even purchased in bulk from the manufacturer, Torco Race Fuels.

Chapter 12

Nitrous Oxide

12.1 Overview

This chapter will cover the fundamentals of nitrous oxide use on an automobile engine.

12.2 Nitrous as a Power Adder

Nitrous oxide can sometimes be utilized to increase the performance characteristics of any gasoline engine. The gas itself is highly misunderstood by the general public, and many people have even more questions about how to actually utilize it.

12.3 History of Nitrous Oxide

Nitrous oxide use began in the 1960s and 1970s as a highly experimental way to increase the performance characteristics of automobile engines. Due to the largely primitive ways of monitoring engine performance and along with the air/fuel ratio, dialing the systems in proved to be extremely difficult without ruining an engines internal parts. Most individuals who actually used nitrous oxide were limited to only reading spark plugs as the method by which they determined if the engine was running well. A drag racer would make a quarter mile pass, immediately shut off the engine to ensure that the plugs were close to the condition that they were in while operating at wide open throttle, and start pulling plugs are reading them. A white or blue spark plug meant that the fuel mixture was burning too lean, and a tan or dark brown color meant that the engine was operating at a fairly safe air fuel ratio.

12.4 Requirements of Nitrous Oxide

Through much experimentation and many broken motors, there were several things learned about nitrous oxide itself:

- Nitrous oxide runs best with elevated octane ratings as to prevent any form of detonation.

- When run too lean, nitrous oxide can cause catastrophic engine damage.

- Nitrous oxide, when used in heavy amounts, requires strong internal engine components.

- Careful tuning is needed in setting up a nitrous oxide system. Care must be taken to not run lean.

- Nitrous oxide performs best if the total timing in the engine is reduced.

12.5 Setting Up a Nitrous Oxide System

Setting up a nitrous oxide system can be relatively difficult or easy, depending on the complexity of the system and the desired operation of the system. Most nitrous oxide systems contain two solenoids: one for fuel and the other for nitrous. Lines that run from each solenoid then converge into the nozzle which is plumbed into the intake. At the nozzle and line meeting point, there are a set of jets (one for nitrous, one for fuel). The jets can be adjusted to increase the horsepower levels of the shot, as well as adjust the air fuel ratio accordingly. The fuel solenoid obtains its fuel from the automobile fuel system itself or a stand alone fuel system dedicated to the nitrous oxide system itself. The nitrous solenoid is connected to a bottle containing nitrous oxide at high pressure (a pressure value exceeding 1000 psi is not uncommon). Some systems only require the use of a nitrous solenoid. This is called a dry system and is only used for fuel injected cars. The nitrous is sprayed before the MAF and it adds the necessary fuel. Some dry systems for speed density cars use engine vacuum as a reference to add fuel to the engine.

There are more complicated systems besides these simple single nozzle systems. Direct port systems offer superior nitrous distribution by having a nozzle for each individual intake runner. These systems can usually be jetted much higher than their single nozzle counterparts because there is less of a chance of one cylinder running lean due to unequal nitrous oxide distribution. As such, more nitrous can be used in order to create more power.

Nitrous systems are sometimes set up on a dual or even triple stage (sometimes, in rare cases, more) configurations. These configurations either use separate solenoids and nozzles for each stage, or it uses a computer to control the voltage seen by the solenoid to adjust the amount it is open. This technique of using several nitrous stages has proven to be very useful for drag racers as they often are traction limited. Therefore, a drag racer can set up his system such that once the car has left the line and has full traction; a second stage can hit and produce more power. A third stage might be useful on the big end of the track as well.

There are many ways to activate the nitrous oxide system. One is by a simple button or switch, but others prefer a safer approach as nitrous oxide can backfire at low rpms and also cause severe engine damage if the engine is over revved. One way to activate the nitrous system is by using a wide open throttle switch in conjunction with a window switch. The wide open throttle switch makes a contact which powers the positive side of the electrical connection on each solenoid, both fuel and nitrous. However, the system is still not grounded and therefore is not activated. The window switch provides the ground with which the solenoids will receive a current and therefore open. However, the window switch only completes that ground when the engine is in a certain RPM window. The window switch reads RPM through the use of a crank trigger, distributor trigger, or another mechanism that can actually read the engine RPM. Most racers set their window switches high enough so as to not cause a backfires. Nitrous backfires have been known to blow the intake manifold completely off the car and sometimes cause fires that put the driver in danger. However, todays nitrous technology has allowed racers to make use of the power adder in a highly productive way.

Nitrous oxide by itself does not make power. In order to make power, fuel must be burned in an efficient manner. As such, nitrous oxide supplies the extra oxygen needed to burn the extra fuel. Nitrous oxide will not burn on its own, it needs another chemical to actually become combustible. The general public is highly uninformed about this, and as such many think nitrous oxide is an explosive gas, which is untrue. There is much misunderstanding about the gas itself, and this is why many people damage the internal components of their motors. If only nitrous is sprayed into the intake tract of the engine, then the engine will no undoubtedly run lean and hurt the internals of the engine. Usually, a piston will burn up and will have to be replaced. However, sometimes major engine damage can occur and render an entire motor totally useless if nitrous oxide is not utilized correctly.

Chapter 13

Emissions

13.1 Introduction

Los Angeles, in 1947, was the first place to call attention to atmospheric pollution problems, which in 1952, Dr. Arie J. Haagen-Smit blamed the rise on the automobile, which was backed by his research. [2]

In a complete combustion process, for every kg of hydrocarbon fuel burnt, 1.3 kg of H2O and 3.1 kg of CO2 is produced. The undesirable exhaust emissions, NOx, HC, CO, CO2, polyaromatics, soots, lead salts, nitro-olefines, and aldehydes ketones, are produced in very small quantities. And of these toxins, only NOx, HC, and CO are produced in large enough quantities to cause environmental problems.

CO2 caused concerns because it was suspected of allowing ultra-violet rays to penetrate the atmosphere. CO causes problems by being absorbed into red corpescles of the blood, preventing the absorbtion of oxygen. Lastly, Nitric acids and nitrogen dioxide along with HC caused smog.

13.2 Controlling Emissions

The first method used for controlling emissions produced by the automobile was to have precise control over the carburetor or fuel injection system, which provided accurate mixtures of fuel and air for complete combustion. During idling, the fuel mixture was either made to be completely combustible, or was cut off. Devices that were sensitive to manifold pressure, tapped immediately downstream of the throttle, were employed to retard the ignition during slow engine speeds. Gulp valves were produced to compensate for the lack of air when the throttle is suddenly closed, allowing for the fuel to be completely combusted. High temperature thermostats were employed to improve cold whether combustion. PCV, positive crankcase ventilation, was employed to eliminate the crankcase fumes.

To combat the problems with NOx, ERG, exhaust gas recirculation, was used to lower the temperature of combustion. This was needed because to production of NOx took place generally above 1350 degrees Celsius.

13.3 Catalytic Conversion

General Motors was the first automotive company to employ the catalytic converter as a standard feature on their automobiles to meet the rising emissions regulations during the early 70's. They chose this approach to comply with regulations, while keeping the durability of their engines. In addition to this change, they also argued the benefits of unleaded gasoline, which would eliminate lead oxyhalide salts, reduce the combustion chamber deposits, further reducing HC due to additional oxidation with the lack of lead. Basic maintenance on the vehicle was reduced, and it assisted in the use of the catalytic converter and overlooked the alleged toxic effects of leaded salts in the environment from leaded gas going through the converter. [2]

The two way catalytic converter is made up from a container, constructed of stainless steal, and the catalysts and supporting features inside the container. Around the converter, a aluminum heat shield protects nearby parts of the automobile from potential damaging heat. The two catalysts usually used are platinum and palladium, or in some cases, just platinum. In the two way converter, HC and H2O are oxidated and converted to form H2O and CO2.

The support piece for the catalysts were developed into a one piece honey comb structure, which had large surface areas on which the catalysts were deposited. They operated at 550 degrees Celsius under normal working conditions. This type has the advantage over pellet type converters because of their more compact form. Later improvements lead to the use of metals instead of ceramics for use as the monoliths, support pieces, to meet the needs of durability and very high, changing temperatures. The new accepted metal was Emicat, which met all the necessary conditions for the support of the catalyst in the converter.

In 1978, General Motors developed the three way catalytic converter, which now dealt with the NOx part of the emissions. The three way converter now employed two stages opposed to the one stage in the two way converter. An additional chamber now used Rhodium for the reduction of NOx. With this advance, 95 percent of NOx in a 0.1 percent rich mixture could be removed. [2] This additional step had to be placed before the oxidation of HC and CO because of the needs to reduce atmosphere call for a rich mixture. For this, a closed loop system must be employed to regulate the supply of fuel accurately according to the incoming air mass, which can be accomplished with the lambda sensor.

13.4 Engine Management

When an engine is cold starting, it must be switched from a closed to an open loop system, which will then provide the necessary rich mixture for ignition. During this operation, the air supplied to the second chamber in the three way converter is diverted to the exhaust manifold, which then avoids a rapid rise in temperature and overloading in the second stage of the converter. And because of the low temperature in the cylinders, there is minimal NOx produced, so it is not necessary to worry about the first stage of the converter during the starting sequence.

13.5 Evaporative Emissions

The evaporative emissions is mostly composed of HC, generally from 4 sources: fuel tank venting system, carburetor venting system, permeation through plastic tanks, and through the crankcase vent. [2] To combat the fuel tank vent problems, a carbon canister is employed to catch the exiting fumes, which periodically needs to be cleaned. The permeation through the tank walls can be solved with one of several methods: sulphur trioxide treatment, fuel system lamination, fluorine treatment, or the Du Pont one-shot injection molding. [2] All of these methods act as barriers which successfully block the emissions.

From the total HC pollution, the crankcase used to account for 25 percent of the total. To prevent this source of toxins, the crankcase fume are vented into the induction manifold through a close circuit by a positive ventilation system. Then the excess HC is burnt in the combustion process in the cylinder. The positive flow is provided through a venting system into the cylinder heads, which is capped off with an air filter. In order to prevent the back flow of the HC fumes, a valve is employed to stop back flow, limit suction in the crankcase, and lastly to avoid upsetting the flow at slow engine speeds.

Additional parts have been employed to reduce emissions, such as the gulp valve. The gulp valve is used to account for conditions such as a sudden release of the throttle. In a situation like this, the fuel mixture momentarily is still delivered to the engine, but the air needed for complete combustion is taken away. The gulp valve is used to provide the necessary additional air to allow for the complete combustion of the fuel, thereby reducing emissions.

Part V

Auxiliary Systems

Chapter 14

Cooling

14.1 Basics

Engine cooling is an intricate part of the automotive four-stroke engine. The four-stroke engine produces large amounts of heat during the combustion process. This heat is discharged in two manners, through the exhaust gases and through heat transfer through the engine itself.

Because of the potential for large heat buildups in the engine block and related components, it is important to discharge the heat through a safe manner. Without a cooling system, the heat build up could reach the melting points of the materials that make up the engine, or reach a critical temperature for a given material where it will loose its structural integrity, such as in the cylinder chamber, in the piston, and in the valves.

While it can be seen that cooling is a major part of the engine, it is also important to consider how much the engine is actually cooled. With too little cooling, the volumetric efficiency could be reduced which would reduce the effective power of the engine. But with too much cooling, vaporization of the fuel mixture could be hindered, which again reduces the power of the engine as well as leak fuel into the oil pan. It can be seen that finding a medium in cooling needs to be reached for a properly running engine.

The cooling system must also be adaptive because of different driving conditions a car might encounter. So there must be a way to increase and reduce the cooling for these different conditions. It also must be taken into consideration that at different altitudes, the water in water cooled engines will boil at different temperatures. Today's vehicles meet all of these requirements in order to develop and produce the most effect combination possible.

There are two basic types of cooling systems for the automobile engine: Air Cooled and Liquid Cooled. In today's vehicles, air cooling is rarely found anymore because of the overwhelming advantages of liquid cooled engines for street application.

14.2 Air Cooling

In air cooled engines, the heat of the engine is transferred out of the engine block through the exchange between the metal and the ambient air. Because the natural flow of air is difficult to control, artificially controlled air cooling was introduced. This is accomplished by using a large high speed fan to force an air flow over the engine thereby increasing the exchange between the engine and the air. Some engines had built in fins to increase the effective cooling area which assisted in the cooling process. But these air cooled system would only economically work on smaller engines. And with the use of the cooling fan, air cooled engines earned the reputation of being known as very noisy. One of the last air cooled engines was used on the mid nineties Porsche 911.

14.3 Liquid Cooling

Liquid cooling has practically become universal for almost all automotive applications. The beneficial characteristics of the liquid cooling process over the air cooling process came from the greater efficiency of heat transfer between metal and a water based liquid and then between the liquid and the atmosphere. In the liquid cooled engine, the liquid can also be recycled after the cooling process.

In a liquid cooled engine, the cooling takes place by a liquid, usually water or a mixture of water and chemical agent, circulating through the engine block. The water takes the heat of combustion and carries it out through hosing to a radiator which releases the heat from the liquid into the atmosphere. The liquid is then recirculated from the radiator back into the engine to again restart the process. Through this recycling process, eventually, a steady state temperature will be reached in the engine.

14.3.1 Fluid Flow

There are two basic types of fluid flow in the liquid cooling cycle: Thermosyphon System and Pump System. Today's vehicles primarily use the pump type system because of its numerous advantages over the thermosyphon process, which works off of a pressure difference in the liquid between the heated liquid inside the engine block and the cooled liquid in the radiator. [2]

There are two basic types of cooling pumps: the radial flow centrifugal pump and the simpler axial flow impeller pump. The radial pumping operation begins with cooled liquid entering the pump casting. The liquid is then forced out of the pump through a radial motion which uses the principal of centrifugal acceleration to propel the liquid out of the opposite end of the pump casting. These pumps are either driven by an electric pump, or more commonly, through a serpentine belt connected to a main crankshaft pulley.

14.3.2 Temperature Control

Today's liquid cooled engines rely on a thermostat to control the temperature of the engine through balancing the opening and closing of a passage way for the liquid to go to the radiator. This thermostat regulates the amount, if any, of liquid that will be diverted from the engine coolant loop to the radiator loop by measuring the temperature of the liquid in the engine.

The thermostat operates by utilizing a wax-copper element. The added copper increases the thermal conductivity of the wax element which further increases its sensitivity. The thermostat, illustrated in Fig. 14.1, works by employing a small tapered rod which is enveloped in the wax copper material element. The opposite end of the tapered rod is connected to a seated plate. When the heated water reaches a certain temperature, the wax element will expand and push the tapered end of the rod out, thereby unseating the plate and allowing the fluid to flow to the radiator.

14.3.3 Pressurization

Today's liquid cooled engines employ pressurized cooling systems because of their added benefits over the thermosyphon pumping system. In a thermosyphon or depressurized system, there is the possibility of the formation of steam pockets, which arise from the liquid's temperature rising above its boiling point. The prob-

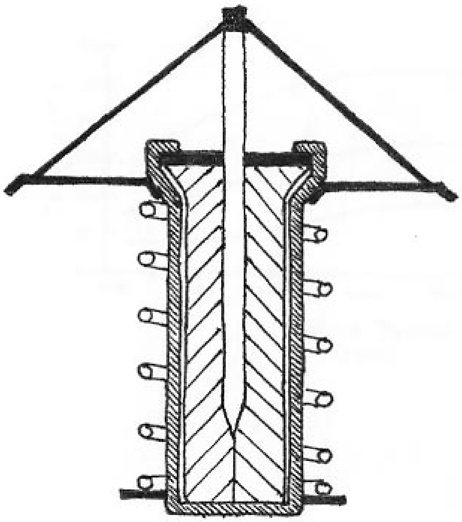

Figure 14.1: Wax-Element Thermostat

lem with these steam pockets is that they can cause a vapor lock, which means that the liquid has a difficult time pushing past the gas.

In a pressurized system, it magnifies the best characteristics of the liquid cooling system. The liquid can be sustained at a higher temperature, which increases the efficiency of the combustion process, while sustaining the liquid phase because of the elevated pressure. This allows for a cooling system to be operated at the necessary pressure to ensure the coolant will not change phase during the heat transfer process.

14.3.4 Radiator

Modern radiators have rapidly evolved over time, which has given us very effective units. Today's radiators look for a high ratio of metal:air to liquid:metal, which gives favorable cooling.

The basic radiator is composed of several rows of metal tubes, usually copper, placed next to each other vertically. Each of the tubes is connected at the top end to the inflow of liquid from the engine, and connected at the bottom to the outflow to the engine with the cooled water. Thin metal fins are then placed on the metal tubes which allows the heat to be dissipated over a greater area, increasing the heat transfer ability into the air. Further modifications have been made to the simple radiator design which use flattened tubes instead of round ones, increasing the heat transfer into the air.

Chapter 15

Intercooling

15.1 Introduction

Intercooler systems are used primarily in conjunction with a forced induction system, such as a supercharger or a turbocharger. The main purpose of an intercooler is to take the turbulent out going air from the forced induction device and cool down the air molecules before they enter the manifold. This adds to the power of the engine by allowing more air to enter the cylinder chamber, which also allows for more fuel, and therefore a greater force of expansion exserted on the piston.

15.2 Potential Gains

An intercooler has the ability to add significant amounts of power when used properly, while robbing the engine of power when used in an improper application. An intercooler in itself probably will not increase the power output of an engine for several reasons.

The first element to realize is that an intercooler is nothing but a simple heat exchanger, and as such has certain defined attributes. It **cannot** cool down the incoming air to a temperature lower than ambient temperatures, unless used in specific circumstances which will be discussed later in this chapter. This means that the air coming out of an intercooler will be no cooler than the ambient air that an engine could breath under regular induction circumstances. And because most intercoolers are actually mounted in or near the engine compartment, the ambient air around the intercooler will actually heat up the incoming air, and reduce the efficiency and power output of the engine.

The second element that needs to be understood, is that with any process, something cannot be gained at no expense. In other words, even though an intercooler has the potential to cool down the air going into an engine, it also restricts the air flow to the engine because the air must travel through a indirect path to get through the heat exchanger.

As a result of the two above mentioned characteristics, if an intercooler is applied improperly to an induction system, it can actually reduce the power out put of the engine. Even if the incoming air is not actually heated by the intercooler from its placement, there will be an inherent loss due to its restrictions in flow.

Conversely, when an intercooler is used properly and designed correctly for the intended application, it has the ability to drastically improve the power output of the engine.

From the following two equations, it will be illustrated how the power output increases or decreases can be simply calculated. [7]

$$\text{Density ratio} = \frac{\text{original absolute temperature}}{\text{final absolute temperature}} \tag{15.1}$$

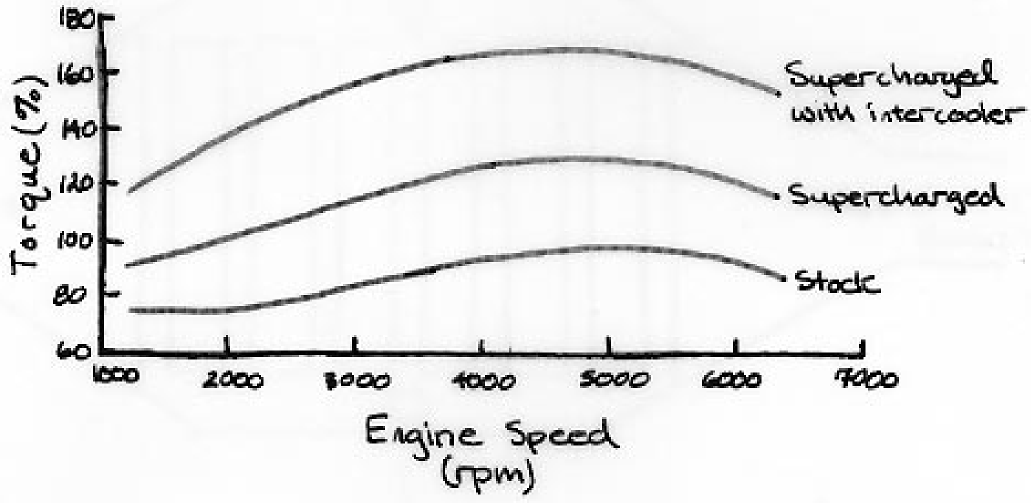

Figure 15.1: Intercooler Potential Power Gains

$$\text{Flow loss} = 1 - \frac{\text{pressure with intercooler}}{\text{pressure without intercooler}} \tag{15.2}$$

If the intercooler is employed in addition to a forced induction system, eqn. 15.1 will usually produce a number between 1 and 2. If you subtract 1 and multiply by 100, it will give you the percentage power increase from the density ratio. Unfortunately, because of the flow losses in the intercooler, this power output must be corrected with eqn. 15.2 by subtracting the output from the second equation after multiplying it by 100. Fig. 15.1 illustrates the potential power gains that can be acquired from a properly implemented intercooler.

15.3 Air-to-air vs. Air-to-water

There are two basic types of intercoolers applied currently on today's automobiles, the air-to-air and air-to-water intercoolers. As implied by the names, an air-to-air intercooler cools the air flowing to the engine by transferring the heat from the incoming air to the outside ambient air; whereas the air-to-water transfers the heat from the incoming air to coolant, and then from the coolant to the outside ambient air. Both when used properly can be advantageous, but in general, the air-to-air is the most common and best choice for the job.

15.3.1 Air-to-air

The air-to-air intercooler is the most common type of intercooler because it is the least expensive and simplest unit, as well as most power efficient system. It works by taking the exiting boost from either a supercharger or turbocharger and directing it into the intercooler where it flows through small tubes attached to fins and turbulators where the heat transfer takes place. The heat transfer occurs by the transfer of heat from the internal air flow to the outside flow of air through the mesh of the intercooler, illustrated in Fig. 15.2. Finally the cooled air exits from the intercooler and enters the induction manifold.

15.3.2 Water-to-air

There is one major disadvantage to the air-to-air intercooler, and that is that it takes up substantially more room than the water-to-air type, which can be a huge difference in today's small compact automobiles where space is at a premium. This is accomplished because of heat transfer ratio between water and air is 14 to 1,

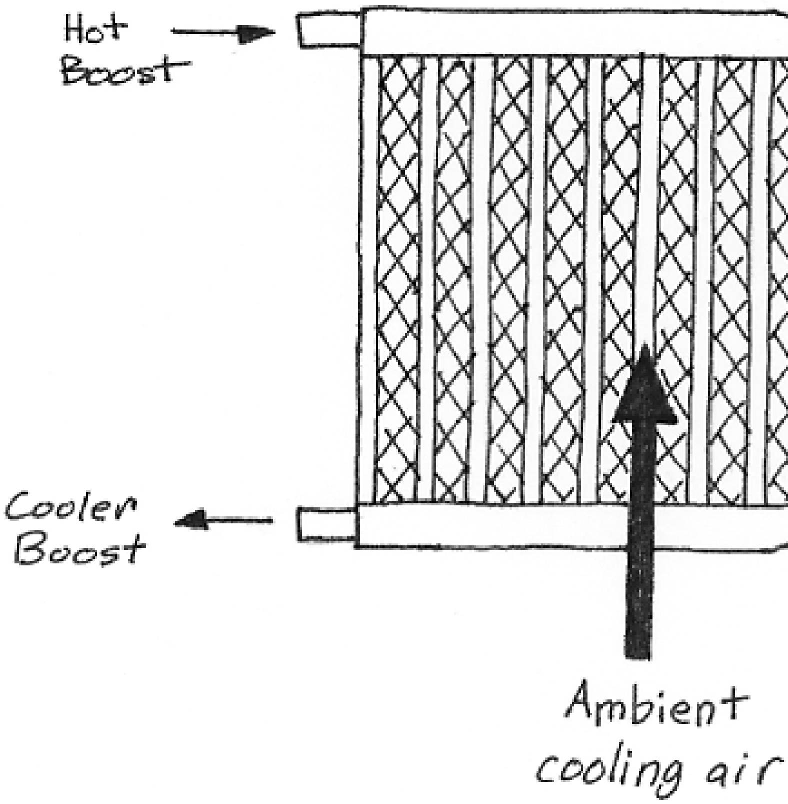

Figure 15.2: Flow of air through an Air-to-air intercooler

dramatically higher than the 1 to 1 in an air-to-air intercooler. The water-to-air has an additional advantage in drag racing applications over the air-to-air, in that if the coolant reservoir is filled with chilled water, the intercooler has the potential to become over 100 percent efficient, which will produce substantial gains in power.

A water-to-air intercooler, illustrated in Fig. 15.3, works similarly to an air-to-air intercooler, except the heat transfer flow is reversed. This flow reversal is due to the water coolant actually running through the tubes making up the intercooler, where as the air to be cooled was run through the internal tubes. In the water-to-air intercooler, the boost runs through the fins of the intercooler, where the heat transfer occurs between the water and the air. The water then takes the absorbed heat to a radiator to release the heat into the atmosphere.

Unfortunately, with the added systems needed in the water-to-air intercooler system, there is an additional power loss in the system besides the previously mentioned air flow losses, the loss from pumping the water through the system, which is a direct loss from the crankshaft of the engine.

15.4 Positioning

The positioning of an intercooler is a critical part of the designing of the system. If the system is not properly orientated in the automobile, the true gains will never be realized. The intercooler needs to be positioned outside of the engine compartment in order to be positioned to have a flow of the outside ambient air, rather than the heated engine compartment air.

In many applications, the intercooler is placed in the front grill area along with the radiator. In this type of placement, the intercooler must be positioned in front

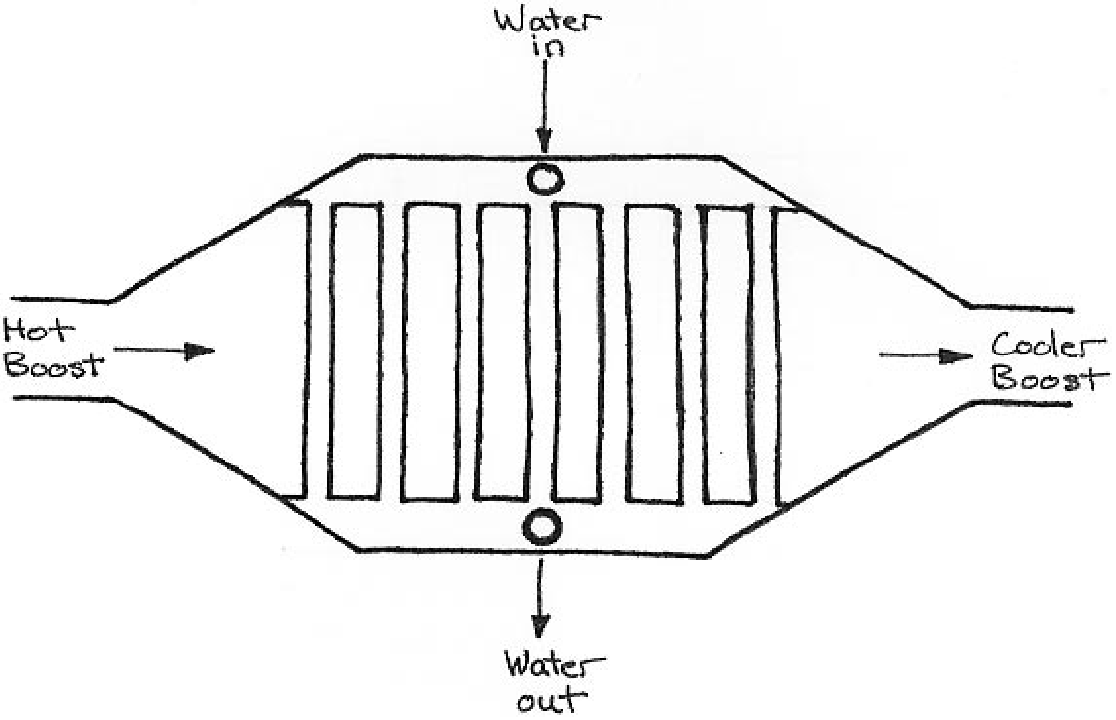

Figure 15.3: Flow of air through a Water-to-air intercooler

of the radiator so it has access to the outside air, opposed to the highly heated outflow of air from the radiator. With this proper placement, the addition of an intercooler to a forced induction system is in valuable to the power output of the engine.

Chapter 16

Lubrication

16.1 Introduction

The lubrication system in an engine serves four major purposes:(1) to prevent seizure in the components, (2) to remove the heat generated by friction, (3) reduce the friction between components, and (4) to reduce the wear of the internal components. [2] These four byproducts of the lubrication system are achieved by effectively separating the internal components to varying degrees with a layer of oil lubricant.

16.2 Types of Lubrication

Lubrication can be further be broken down into three major types: (1) no lubrication, (2) boundary layer lubrication, and (3) full lubrication.

When there is no lubrication, the surfaces of the interacting components physically interact with each other, most commonly in sliding friction when there is dynamic movement. Under these circumstances, friction is the greatest under static loads, and lowers during dynamic movement. It is also important to notice that as the speed of interaction between the two surfaces increases, the generated heat also increases because of the energy released from the surface reactions.

Boundary layer lubrication occurs when there is provided a layer of lubricant to partially separate the interaction components. Under these conditions, the lubricant can significantly reduce the sliding friction between the components, as well as have the added benefit of cooling the components by absorbing the heat generated from the partial interaction as well as the shear force in the lubricant. Components such as cams operate under this type of lubrication.

Full lubrication occurs when there is no interaction between the machine elements because of a think layer of lubrication. The advantage of this type of lubrication is that it effectively stops wear between the machine elements because there is only an interaction between the lubricant and the element, but unfortunately, wear still occurs. This type of lubrication takes place in mechanisms such as the valves in the cylinder heads. In applications such as the valves and cylinders, it is also important to take into consideration the prominent effect of viscosity, because as the lubricant's temperature increases, the viscosity of the lubrication decreases. So it must be taken into consideration that the lubricant is viscous enough under operating conditions, but also not be too viscous that the engine can not turn over in the ignition sequence.

16.3 Common Lubricants

The most common types of oils used in the engine lubrication system is either vegetable oil or mineral oil. Vegetable oil was used in the past for racing applications because of its high film strength, and excellent protection against wear from its high lubricity. [2] But was not widely used in other applications because of its rapid rate of deterioration, which produces gums and lacquers on the machine elements. [2] So mineral oils are more commonly used because they are much more cost effective, readily responsive to additives, can be produced in a wide range of viscosities, as well as deteriorate much less rapidly than vegetable oils.

Today, lubricants such as synthetic oils replace natural oils as lubrication for the engine. Besides the higher cost, synthetic oils are much more effective lubricants than mineral oils because they can be chemically developed to have whatever the particular engines specifications require for proper operation. A brief comparison is illustrated in table 16.3.

Based-oil type	**Light volatile components**	**Waxy thickening components**	**Range of chemical types**	**Precision of chemical structure**	**Purity**
(1) Mineral	Yes	Yes	Very Wide	Very low	Very low
(2) XHVI	Some	Some	Wide	Low/medium	Medium
(3) PAO	None	None	Narrow	Very narrow	High
(4) Ester	None	None	Very narrow	Very high	Pure

16.4 Pressurized Lubrication System

Today's engine lubrication systems revolve around the oil pump, which provides the pressure to deliver oil to every part of the engine. The oil pump is driven by the camshaft in most cases. The pump has a strainer attached to it to strain the incoming oil from the sump in the oil pan beneath the engine. The actual oil pressure varies depending on the requirements of the engine, as well as the speed of the engine.

Before leaving the pump, the oil passes through a relief valve and fine filter, and is then distributed into the ″main oil gallery,″ which is drilled in parallel to the crankshaft. [2] The oil is then distributed from this main tube to smaller subsidiary pipes which direct the oil flow to the crankshaft, camshaft, and other vital parts such as the valve train. From there, the individual components receive the lubricant through various methods.

The oil being directed to the main bearings travels through the crankshaft and is separately distributed to each bearing through small holes in the shaft. The cylinder heads are also supplied with oil to lubricate the valves and rockers. After each of the internal components is properly lubricated, the oil then returns to the main sump in the oil pan by a combination of pressure and gravitational forces, working its way from top to bottom.

In the pressurized lubrication system, it is very important to regulate the amount of oil being delivered to each of the components, because either too little or too much lubrication may effect the engine adversely in multiple ways. The oil is regulated through restrictions, and intermittent devices, which are controlled by the position of the machine element. It is also very important to have enough oil in the oil pan to give a steady supply of lubricant to the oil pump, while not too much where it will actually produce a drag force on the crankshaft.

16.4.1 Lubrication of Bearings

In some applications, the roller element bearings may be sealed with a previously applied grease. But for most cases, they are provided with lubrication from the main oil source of the engine, which is limited to prevent drag on the components. As mentioned previously, the oil for these bearings is supplied from the shaft revolving in them through a machined hole. As the oil moves radially outwards and to the side, the oil takes the heat from revolving. The lubrication is most needed at the center of the bearing's surface because of the nature of the pressure distribution.

When a shaft has eccentricity in its alignment, it undergoes hydrodynamic lubrication. The lubrication is dragged around the shaft while the element revolves which then provides added lubrication to the wedge sections created by the eccentricity.

16.4.2 Gear Driven Oil Pumps

The gear driven oil pump is the most commonly used type of oil pump in the automotive engine. It is basically comprised of a cast casing which contains the pump. The actual pumping mechanism is comprised of two intermeshing gears which create a pressure differential sucking the oil in through the strainer and pushing it through the exiting tube of the pump. The delivery chamber in the pump is also fitted with a relief valve, which returns excess oil to the sump when the additional lubrication is not required and would adversely effect performance.

The oil pump is also designed to be self priming and closing to ensure there is always oil captured in the system. This is a needed characteristic because the engine needs the most amount of lubrication during the start up cycle because it is the cycle in which the most wear will occur in the engine.

16.4.3 Oil Filters

The oil filter takes up where the strainer on the oil pump leaves off. The strainer on the oil pump is relatively large because it is necessary to have a complete unobstructed flow of lubrication, otherwise the engine could break. This way, the oil filter strains the very small impurities, which guarantees that the oil pump will always flow free. The oil filter is made similarly to the thermostat in that it will be bypassed when a certain limit is reached. In other words, the oil flow will actually bypass the filter paper, or composite filament if the pressure rises to a certain level within the filter. This guarantees that the system will continuously deliver the needed lubrication. The filter has also been manufactured into a small self contained package for easy removal and replacement to ensure the filament is clean after so much use of the engine.

Part VI

Engine Components

Chapter 17

Engine Materials

17.1 Introduction

Today, with the advances in material science, the options of materials available to designers has become quite numerous. This chapter will briefly delve into the the material characteristics of some of the most commonly used materials on the engine, which can be seen in table 17.1. Further detailed information on material properties with regards to the internal combustion engine have been classified and standardized in a SAE, Society of Automobile Engineers, handbook. [12]

Part	Material Type	Remarks	Reasons
Cylinder Heads	Gray cast iron J431a*	Usual	4,7
	Cast aluminum J465	Aircraft (some others)	1,4
	Forged aluminum J454c	Usual	2
Cylinder Barrels	Gray cast iron J431a	Usual	4,5,7
	Steel	Aircraft Engines, often nitrided	2
	Cast aluminum J465	Small engines, plated bore	1,4
Pistons	Sand-cast aluminum or Die-cast aluminum	Usual for engines of less than 10-in. bore	1,4
	Forged aluminum J454c	Aircraft and some Diesel	1,3
	Gray iron J431a	Small engines and most engines of more than 10-in. bore	4,7
Piston Pins	Steel	Usual	2
	Steel, c.h.	Hard-surfaced	1,10
Piston Rings	Special cast iron	Usual material	5,10
	Steel, chrome plated	Heavy-duty	1,10
Connecting Rods	Steel	Small rods	1
		Large rods	2,13
	m- or *n*-Iron	Small engines	4,7
Bolts, Studs, Nuts	Steel	Highly stressed	2
		Minor fastenings	1,7
Crankshafts	Steel	Usual	1,2,13
	Cast steel J435a	Frequent	1,4,7
	n-Iron J433	Rare	1,4,7
	m-Iron J434	Rare	4,7
Crank-Cases	Gray iron J431a	Automobile engines	4,7
	Cast aluminum J465	Aircraft and some automotive engines	1,4
	Forged aluminum J454c	Aircraft Engines	2
	Welded steel J410b	Many large engines	1
Main and Rod Bearings	Tin-base babbit Lead-base babbit	Light-duty non-automotive	5,7,10
	Lead-tin overlay Copper-lead Aluminum	Heavy duty	5,10,11

Part	Material Type	Remarks	Reasons
Camshafts	Special cast iron	Automotive practice	7,10
	Steel, c.h.	Heavy-duty	10
Push Rods	Steel tubing	Usual	1,7
Rocker	Steel	Usual	1
	n-Iron J433	Rare	4,7
	Sintered steel		
	m-Iron		
Valves and valve seats	Special steels		8,9,10
Valve Springs	Alloy steel	Often shot peened	11
Gears	Steel, c.h.	Heavy duty	2,10
	Steel	Medium duty	1,7
	Carbon steel	Light duty	7
	Bronze		
	Sintered		
Gear Case	Cast iron	Usual	4,7
	Cast aluminum J452	Common	4,1
	Cast magnesium J465	Aircraft	

Reasons

1. High strength/weight ratio
2. Very high strength/weight ratio
3. High heat conductivity
4. Can be cast in intricate shapes
5. Good bearing properties
6. Best bearing properties
7. Low cost, adequate
8. High hot strength
9. Resistance to corrosion
10. Resistance to wear
11. Strength to resilience
12. Water-tightness and durability
13. Good heat treatability

When choosing a material for any machine part, several considerations must be looked at: (1) General function of the part: bearing, sealing, structural, heat conducting, or space filling, (2) Life expectancy, (3) Cost of the finished part and of its maintenance and replacement, (4) Environmental conditions: loading, exposure to corrosive conditions or abrasion, temperature range, or wear, (5) Space and weight limitations, and (6) Considerations such as appearance, etc. [12]

It is also important to realize the relative importance of each of these characteristics. For example, for a high performance vehicle, elements 2, 3 and 6 may not be as important as 1, 4 and 5. Where as for a economical vehicle, elements 1, 2, 3 and 4 are the most important.

17.2 Structural Properties

Structural materials can in general be classified as ones which will carry relatively high stresses, which include ones which transmit or carry torques and forces. For these types of applications, a designer must take into consideration fatigue failure in order to guarantee structural success. Fatigue failure is most dependant on: Frequency, temperature effects, stress-cycle effects, combined stresses, effects of shape, stress concentration, notch sensitivity, sharpness of notches, surface finish, effects of corrosion, effects of size, surface treatments, effects of grain direction, creep failure. [12]

17.3 Non-Structural Properties

The are several other important properties in the materials of machine elements besides structural properties. Properties such as cost of materials, cost of fabrication, availability, density, heat conductivity, hardness, bearing properties, thermal expansion, and resistance to corrosion are just a few of the important factors which must be considered. Factors for several materials are illustrated in table 17.3.

	Carbon Steel	Alloy Steel	Stainless Steel	Aluminum Alloys
UTS, kis	45-120	75-300	100-170	15-77
BHN	85-250	100-600	160-180	23-135
Endurance ratio EL/UTS	0.35-0.60	0.4-0.6	0.3-0.6	0.35-0.50
Elongation, percent	0-50	0-50	10-55	1-30
Specific gravity	7.6-7.85	7.6-7.85	7.1-8.1	2.2-3.0
Heat conductivity cal/cm C hr	0.108-0.115	0.11	0.06-0.10	0.37-0.53
Relative machinability	good	good to impossible	poor	excellent

17.3.1 Steels

Steel is the most commonly used material in the internal combustion engine because of its overwhelming advantages: Relatively low cost, highest endurance strength of available materials, naturally hard surfaces, and strength and hardness controlled through a wide range of heat treatments. [12] Although, steel does have several disadvantages: Subject to rapid corrosion, relatively low thermal conductivity, and not easily cast. [12]

With steel's given properties, it is the preferred material for the composition of moving parts like crankshafts, gears, connecting rods, and auxiliary shafts as well as fasteners. [12]

In general, steels can be classified into 6 categories: Cast steels, stainless steels, low carbon steels (Carbon = 0.10 to 0.20 percent), medium carbon steels (Carbon = 0.30 to 0.50 percent), high carbon steels (Carbon = 1.0 percent), and special steels. [12] The major types of steels are illustrated in table 17.3.1.

Types of Steel	SAE Identifying Numbers
Carbon steels	
- Plain carbon	10xx
- Free cutting	11xx
Magnesium steels	
- Mn 1.75	13xx
Nickel steels	
- Ni 3.50	23xx
- Ni 5.00	25xx
Nickel-chromium steels	
- Ni 1.25; Cr 0.65	31xx
- Ni 3.50; Cr 1.57	33xx
- Corrosion and heat resisting	302xx, 303xx
Molybdenum steels	
- Mo 0.25	40xx
Chromium-molybdenum steels	
- Cr 0.50 and 0.95; Mo 0.25, 0.20, and 0.12	41xx
Nickel-chromium-molybdenum steels	
- Ni 1.82; Cr 0.50 and 0.80; Mo 0.25	43xx
- Ni 1.05; Cr 0.45; Mo 0.20	47xx
- Ni 0.55; Cr 0.50 and 0.65; Mo 0.20	86xx
- Ni 0.55; Cr 0.50; Mo 0.25	87xx
- Ni 3.25; Cr 1.20; Mo 0.12	93xx
- Ni 1.00; Cr 0.80; Mo 0.25	98xx
Nickel-molybdenum steels	
- Ni 1.57 and 1.82; Mo 0.20 and 0.25	46xx
- Ni 3.50; Mo 0.25	48xx
Chromium steels	
- Low Cr-Cr 0.27, 0.40, and 0.50	50xx
- Low Cr-Cr 0.80, 0.87, 0.92, 1.00, and 1.05	51xx
- Low Cr (bearing) Cr 0.50	501xx
- Medium Cr (bearing) Cr 1.02	511xx
- High Cr (bearing) Cr 1.45	521xx
- Corrosion and Heat Resisting	514xx, 515xx
Chromium-vanadium steels	
- Cr 0.80 and 0.95; V 0.10 and 0.15 min.	61xx
Silicon-manganese steels	
- Mn 0.65, 0.82; Si 1.40, 2.00; Cr None, 0.17	92xx
Low ally, high tensile steel	950

Carbon steels are generally used in machine elements which are small and in which stresses are low. Some common uses are for the screw fasteners not under heavy loads, oils pans, small case hardened parts, and covers. Carbon steel is also used when weldability is necessary.

Alloy steels have the advantage over carbon steels of being able to have a slower cooling rate, which can result in more uniformity of physical properties and has less residual stresses, deformations, or cracks. This allows alloyed steel to be treated for significantly higher strengths and hardness. These properties are especially important as the machine elements increase in size and have more complex shapes. Its only major disadvantage is that it is more costly than carbon steel.

Stainless steel are characterized by their high chromium content, giving them an almost corrosion proof characteristic. They are limited to the amount of heat treatment, which make them undesirable for application where a hard surface is necessary. In general, stainless steels are only used for exhaust valves and pipes and rarely for combustion chamber inserts.

Special alloys are mostly used in highly stressed parts that need to be tolerant of high temperatures such as exhaust turbine nozzles, rotors, and blades as well as valves. These steel must have the non-oxidizing characteristics of stainless steel while also having high endurance and creep strength for the working temperatures.

17.3.2 Surface Hardening

Surface hardening can be employed in the manufacturing of the machine elements to increase their strengths and other properties. Casehardening is used on steels with low carbon contents, which increases the outer shell hardness, while not adversely effecting the inner micro-structure of the material. Surface heat treatments may be employed on medium carbon steels. Elements such as crankshafts and camshaft bearing surfaces use the heat treatment method to meet design requirements. Nitriding can be used to produce an extremely hard, wear resistant surface. Plating is used to reduce wear of elements such as piston rings and cylinder bores using chromium.

17.3.3 Cast Iron

In general, the main engine block is made from gray cast iron, except for application which need light weight components, such as race cars. Gray cast iron has the exceptional characteristic that it can be cast into intricate shapes with relative ease. And while the endurance limit is lower than steel, its notch sensitivity is very low. [12] Gray cast iron also makes an excellent bearing material.

Chilled cast iron is used to obtain very hard surfaces from gray cast iron. With its added beneficial characteristics, it is used for camshafts and tappets and other low cost automobile parts.

Malleable iron, or ”white” iron, is annealed after casting which gives it great strength and ductility characteristics. It is advantageous because it can be used in some cases where perviously, parts had to be forged, which saves money in the production of the part.

Nodular steel has a very high tensile and endurance strength compared with normal gray iron. This is achieved through a casting method which makes free-carbon granules spherical opposed to stringy. [12] Nodular steel is used for crankshafts to achieve cost savings.

17.3.4 Aluminum

Aluminum has become very popular for producing pistons, bearing surfaces, cylinder heads because of its numerous advantages: Low density, high heat conductivity, good resistance to corrosion, ease of casting, and good bearing characteristics against steel and iron. [12] But it does have several disadvantages which also must be taken into consideration in the design process: Low hardness, high thermal expansion coefficient, cost of material, and adverse effects of high temperatures. [12] Aluminum pistons are generally used for pistons under 6in bore because they aluminum tends to reduce the working temperature of the piston. [12]

17.3.5 Magnesium

Magnesium is generally used for covers and other parts which are lightly loaded for application in which weight is a significant factor. It is lighter than aluminum, but also more expensive and softer.

Chapter 18

Piston and Rings, Connecting Rod, and Crankshaft Design

18.1 Overview

This chapter will delve into mechanical design considerations for the piston and rings, connecting rod, and crankshaft design. This will mostly be a ”qualitative discussion” as very few equations will be introduced to avoid complexity.

18.2 Piston and Ring Design

There are two main metals from which a piston is formed. The first is cast iron, which is used in heavy duty diesel applications. The second is an aluminum alloy which is used for the majorty of pistons in automobiles. These aluminum alloy pistons may be produced through forging or casting. Forged pistons are considered stronger than cast pistons, however the dimensional tolerances needed to allow for forged piston expansion in an IC engine can lead to severe piston slap during cold startup. While the piston slap does cease as soon as the engine is up to operating temperature, it can be rather annoying to the driver. As such, most automobiles produced today utilize a cast piston. This is also done out of econimical concerns. While they are not as strong, the dimensional tolerances of a cast piston are not very large to accomodate for the thermal expansion.

It is important to note that a piston is not of a uniform construction. As such, parts of the piston expand at very different rates. The difference in thermal expansion can create an ”oval shaped” piston, which makes it very difficult to allow for dimensional accuracy while setting the tolerances between the piston and the cylinder walls. There are several ways to accomodate for this. Most pistons are made with an aluminum alloy with a very low coefficient of thermal expansion of around 0.0000195 K (this involves the use of silicon in the alluminum alloy). In addition, the piston may be constructed into a non-circular shape. This non-circular shape will have a circular cross section once the piston is up to operating temperature. Sometimes, machined slots and steel inserts are used in a piston made from aluminum alloy in order to keep the thermal expansion in check.

Pistons must also have provisions for oil flow as well. The oil control ring keeps a lubricating layer of oil between the piston itself and the cylinder wall. There is also provisions for oil galleys to keep the piston pin lubricated. The piston pin is held in place by a set of circlips.

There are usually 3 rings placed on the piston. The first two rings are compression rings which remain in place to decrease blowby between the piston walls and the cylinder walls. Note that ring gap plays a very important role in the compression rings. If there is too much gap, then the static compression ratio will be affected. If the ring gap is too small, when the ring expands the gap will decrease to 0 and the ring will begin to expand outward and close the gap between the cylinder bore and the ring itself. This is not acceptible because it will cause ring to cylinder bore contact without any form of lubrication. This will cause premature wear and might even break a ringland on the piston. The piston ring gap is very important in power adder applications as the increased heat sometimes requires a larger ring gap to allow for greater ring expansion.

The third ring is an oil control ring. These rings, along with the compression rings, are usually made from an alloy cast iron wish good wear and heat resistance. These rings simply control the flow of oil up and down the combustion chamber walls.

The thickness of each ring is determined by the amount of pressure desired on the cylinder walls. Simply put, the thicker the ring, the increased stiffness.

18.3 Connecting Rod Design

The design of the connecting rod requires very little discussion. Most connecting rods are stamped or forged. There are several materials used such as cast iron, titanium, and aluminum. Aluminum rods are usually strictly reserved for high performance applications as they tend to stretch and deform after long periods of usage, such as daily street driving. Performance connecting rods are usually offered in an ”H beam” configuration, although several other types exist.

18.4 Crankshaft Design

Crankshafts are offered in two main types: forged steel and cast iron. Cast iron crankshafts are usually found in the majority of automobiles produced today as the strength characteristics of these cranks are usually more than adequate for a daily driven automobile. However, cast cranks are of a lower stiffness and therefore are prone to deflect under stress. Cast cranks have great wear properties and are relatively inexpensive to manufacture in comparison to forged steel cranks. In fact, in some applications forged crankshafts may cost several times more than a cast crankshaft. Cast iron crankshafts also have good internal damping qualities to reduce torsional vibrations.

The main bearing journals on each crankshaft have passages drilled for lubrication purposes. The oil is supplied via the oil pump through the block's oil passages. In addition to the main bearing journals, the connecting rod journals also have provisions drilled for oil passages as well.

A torsional damper is pushed onto the machined end of the crankshaft. This is made to reduce the torsional vibrations associated with the engine operation. The annulus of the torsional damper is bonded to a machined hub which fits on the crank snout. The annulus changes the vibrational characteristics of the engine by absorbing the vibrations produced by the engine itself. The bonding material is usually rubber and its properties are determined by an experimental analysis of the engine dynamics themselves. The torsional vibration energy is released as heat. The heat release is caused by the hysteresis losses which are made possible by the rubber bonding material itself.

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