Text and Reference Book No. 54
August 1990

I.C. ENGINES FUNDAMENTALS
(II)
(Applications)

compiled by
Shinzo Yamamoto

Training Department
Southeast Asian Fisheries Development Center

PREFACE

This text book has been compiled for the Marine Engineering Course trainees on the subject of Internal Combustion Engine for fishing boat during October 1990 to March 1991. Firstly it is intended as an introduction to the principles and applications of Internal Combustion Engine in terms of I.C. Engine fundamentals. However, it was found that the compilation of the principles and applications of I.C. Engines will become massive volume. Therefore, the division of the volume is considered as stated in the text of I.C. Engine Fundamentals (I). In I.C. Fundamentals (I), we have studied about the relationships between heat and work, which represent the basic principles of I.C. Engines.

In this text I.C. Engine Fundamentals (II), we mainly deal with their applications in which our lives are increasingly dependent upon great prime movers, such as reciprocating piston engine, rotary combustion engine, gas turbine engines, and jetpropulsion engines.

It is hoped that the learner should be encouraged to survey a broad study of energy transformation, transmission and control in the various fields not only limited in the marine engineering.

Shinzo YAMAMOTO
Instructor
August 1990.

CONTENTS

Page

2. Kinds of Internal Combustion Engines

Heat engines which burn fuel inside the engine to create a high-temperature, high-pressure gas, and make use of this gas to obtain mechanical work are called internal combustion engines. Because internal combustion engines are relatively small and yet provide large output, they are in wide use today in automobiles, airplanes, and other vehicles.

Internal combustion engines can be categorized as shown below.

1) Piston engines
   - Reciprocating piston engines
   - Rotating piston engines
2) Gas turbines
3) Jet engines
4) Rocket engines

2.1 Piston Engines

Piston engines can be classified according to ignition method and fuel, as shown below.

- Piston engines
  - Spark ignition engines
    - Gas engines
    - Gasoline engines
    - Kerosene engines
  - Compression ignition engines — Diesel engines

(1) Spark ignition engines

In these engines, a mixed gas consisting of fuel and air is sucked into the cylinder where it is compressed and ignited by an electrical spark.

1) Gas engines

Gas engines, which use a gas as the fuel, were the first internal combustion engines developed. Some of the fuels used in gas engines include natural gas and blast furnace gas, but today liquefied petroleum gas (LPG) is also used. The atmospheric pollution rate of LPG is extremely low, however, it is not in abundant supply and is difficult to handle.

2) Gasoline engines

Gasoline engines are the most widely used engines today. These engines use a spark ignition system which is virtually the same as that used at the end of the 19th century when these engines were first built, but rapid improvements have been made in many other aspects.

3) Kerosene engines

These engines run on kerosene or light oil. Compared to gasoline engines, their fuel costs are less and they are easier to handle. Small versions of these engines are widely used in automatic cultivators and threshing machines.

(2) Compression ignition engines

When air is sucked into a cylinder and compressed, its temperature increases. In a compression ignition engine, spontaneous combustion occurs and the fuel is burnt when injected into this compressed air. These engines were developed by R. Diesel, thus are referred to as diesel engines. Since they use low-cost fuels and have a high thermal efficiency, they are widely used as the engines in ships, vehicles, passenger cars, and construction machinery.

2.2 Gas Turbines

Gas turbines make use of an air compressor which compresses air, and burns the fuel after it has been injected into the compressed air. The expansion of the high-temperature, high-pressure gas causes the turbine to rotate.

Since gas turbines provide direct rotary motion, they do not need a crank mechanism, which on piston engines works to convert reciprocating into rotary motion. These engines are used on helicopters and generators.

2.3 Jet Engines

Jet engines inhale air into the engine and compress it, inject fuel into the compressed gas to make a high-pressure combustion gas, and blow the combustion gas out at the rear. The engine's thrust is generated by the force of the exhausted gas.

Inside the jet engines, as on a turbo jet engine, a gas turbine is used to make a jet-flow of gas.

2.4 Rocket Engines

As in jet engines, rockets make use of a reaction force to propel objects forward, and since the fuel and oxygen needed for combustion are carried on board, these engines make it possible for objects to fly in space where there is no air. For that reason, they are used to launch satellites and as the jet thrust engines of spaceships.

3. Gasoline Engines

Gasoline engines are the internal combustion engines which are most familiar to us, since they are used as the prime movers in automobiles and motorcycles.

In the following sections we will study the basic principles and structure of internal combustion engines.

3.1 Principles of Action of Gasoline Engines

Gasoline engines convert heat energy into mechanical energy by causing an explosion of a mixture of evaporated gasoline and air in cylinders and using the expansion force associated with that explosion to move the pistons.

The structure of an automobile gasoline engine is shown in Fig. 4-12.

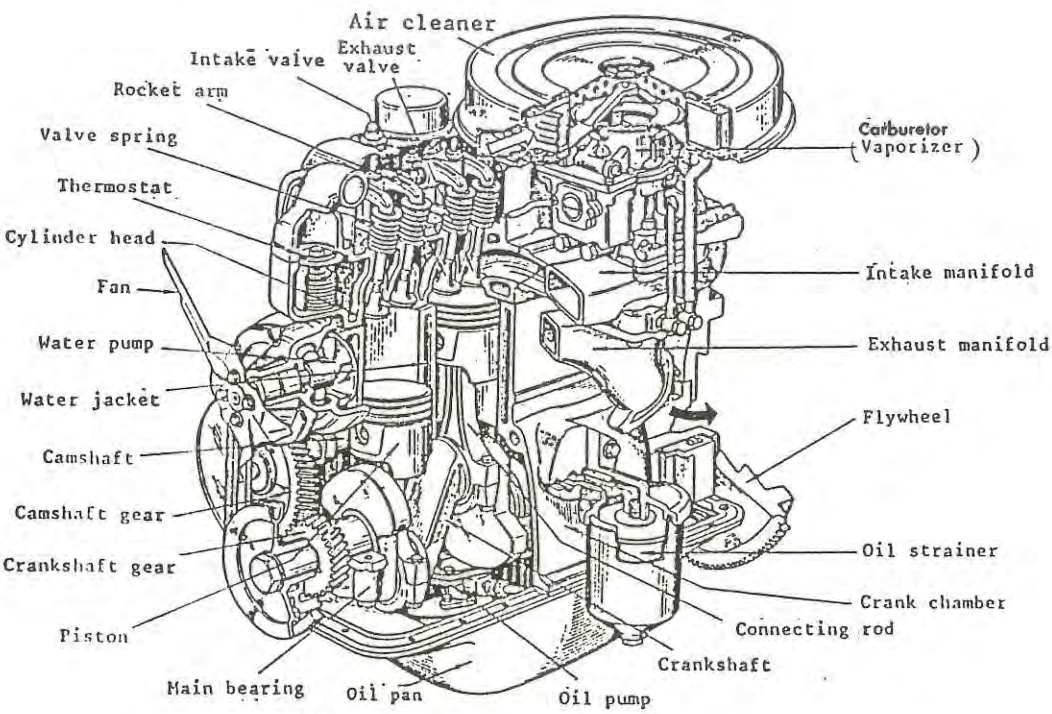
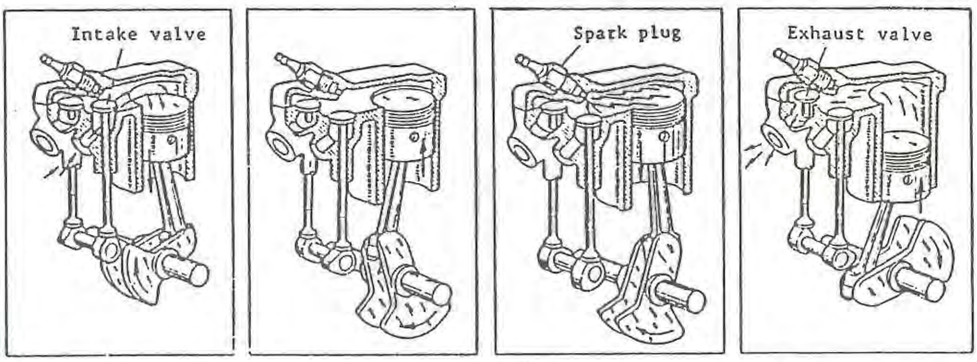


Fig. 4-12 Structure of Automobile Gasoline Engine

Depending on the form of action, gasoline engines are divided into two types: the four-cycle type in which four strokes make up one cycle and the two-cycle type in which two strokes make up one cycle.

(1) Four-cycle gasoline engines

As shown in Fig. 4-13, four-cycle gasoline engines are engines in which power is generated by carrying out the processes from tne intake of a fuel-air mixture to the ejection (exhaust) of combusted gas within the time that the piston makes two complete-strokes. (Two complete turns)



(1) Suction Stroke (2)Compression stroke (3)Expansion Stroke (4)Exhaust Stroke

(1) Suction stroke : The exhaust valve is closed and the intake valve is opened, and as the piston travels from the top of the cylinder to the bottom, the fuel-air mixture is inhaled into the cylinder.

(2) Compression stroke: The intake valve closes, and as the piston rises, the inhaled fuel-air mixture is compressed.

(3) Expansion stroke : At the end of the compression stroke, the pressure and temperature rise because of the compression and the fuel-air mixture becomes easier to burn. When the mixture ignites as a result of an electric spark released by the spark plug, that combustion causes a further increase in temperature and pressure, and the gas pushes down the piston. The expansion stroke is also called the working stroke.

(4) Exhaust stroke : When expansion is completed, the exhaust valve opens, the combusted gas is exhausted outside the cylinder, and the pressure inside the cylinder drops. Next, the piston starts rising and pushes out the combusted. When the piston reaches the top of the cylinder, the original condition is obtained again.

Fig. 4-13 Sequence of Action in a Four-Cycle Casoline Engine

Fig. 4-14 is a pV curve which shows the relationship between the theoretical changes in pressure p inside the cylinder and cylinder volume V as they change with the displacement of the cylinder.

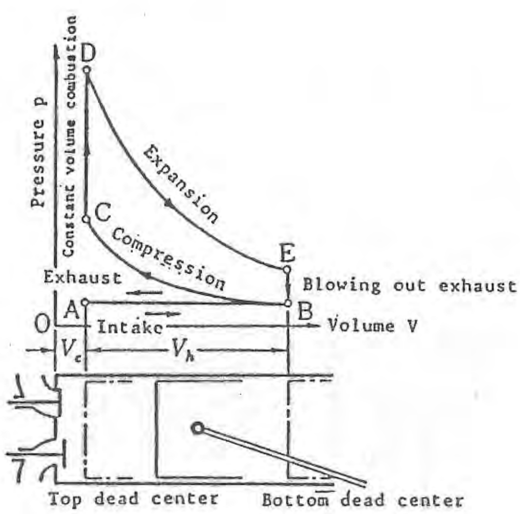


Fig. 4-14 pV Curve for Four-Cycle Gasoline Engine

Piston stroke

As shown in Fig. 4-15, when the piston is at the uppermost end of the cylinder, the position is called top dead center, and when it is at the bottom end of the cylinder, it is called bottom dead center. The distance that the piston moves from top dead center to bottom dead center is called the stroke.

The volume opened up in the cylinder as the piston moves one stroke is called the stroke volume, and this is the value of what is usually called displacement. When the piston is at top dead center, the volume remaining at the top of the cylinder is called the clearance volume, and the sum of the clearance volume and stroke volume is called the total cylinder volume. In addition, the ratio between the cylinder total volume and clearance volume is called the compression ratio.

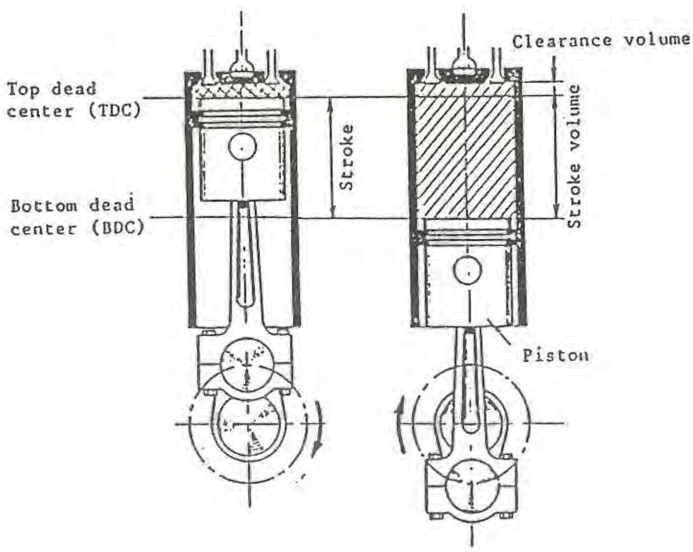
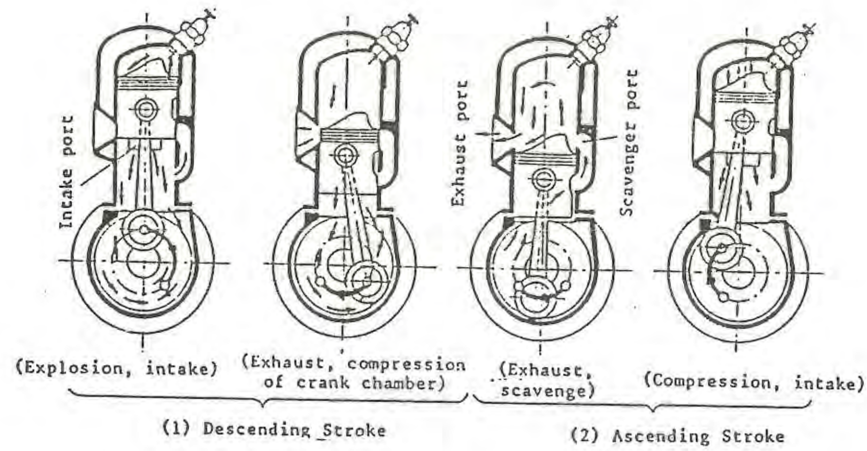
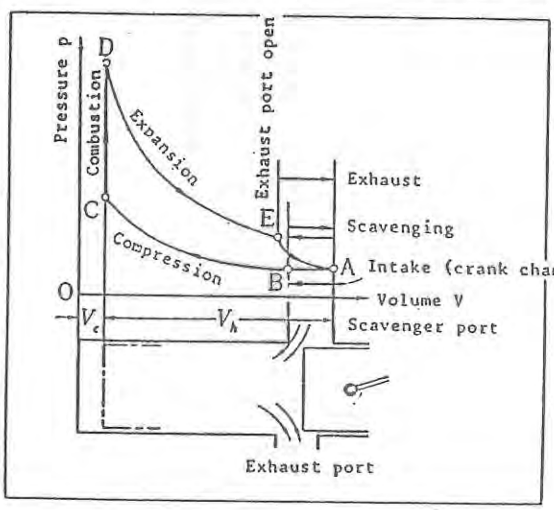


Fig. 4-15 Piston Stroke

(2) Two-cycle gasoline engines

A two-cycle engine, as shown in Fig. 4-16, generates power by carrying out all processes from the intake of fuel-gas mixture to the exhaustion of combusted gas for each round trip of the piston.





(1) Descending stroke : When the compressed fuel-air mixture is injected with the piston at TDC, an explosion occurs, the gas expands, and the piston is pushed down. Before the piston reaches BDC, the exhaust port opens and the combusted gas begins to be forced out. Shortly after the exhaust port opens, the scavenger port opens, the previously compressed fuel-gas mixture is pushed into the cylinder, and this gas forces out the combusted gas and cleans the inside of the cylinder. This process is called scavenging, a special type of action found only in two cycle engines.

(2) Ascending stroke : The piston begins rising from BDC and first the scavenger port, then the exhaust port, closes. As the piston rises, the fuel-air mixture in the cylinder is compressed until the piston reaches TDC, at which time the stroke is completed.

Fig. 4-16 Principles of Action of Two-cycle Engine

3.2 Structure of Major Components of Gasoline Engines

The major components of gasoline engines have the structure shown in Fig. 4-17.

(1) Cylinder head, cylinder block, and crank chamber

The cylinder head is a component for covering the top of the cylinders, and together with the cylinders and pistons, it forms the combustion chamber.

The cylinder head is provided with holes for mounting the intake valves, exhaust valves, and spark plugs of each cylinder.

The cylinder block consists of several cylinder heads and water jackets, and is cast into an integral part with the crank chamber.

The inside walls of the cylinders are exposed to the high temperatures and high pressures of the combustion gas, and are subject to friction from the pistons. Therefore, cylinder liners made of high wear-resistant nickel-chromium castings are press-fitted into the cylinder blocks, which are made of aluminum alloy castings.

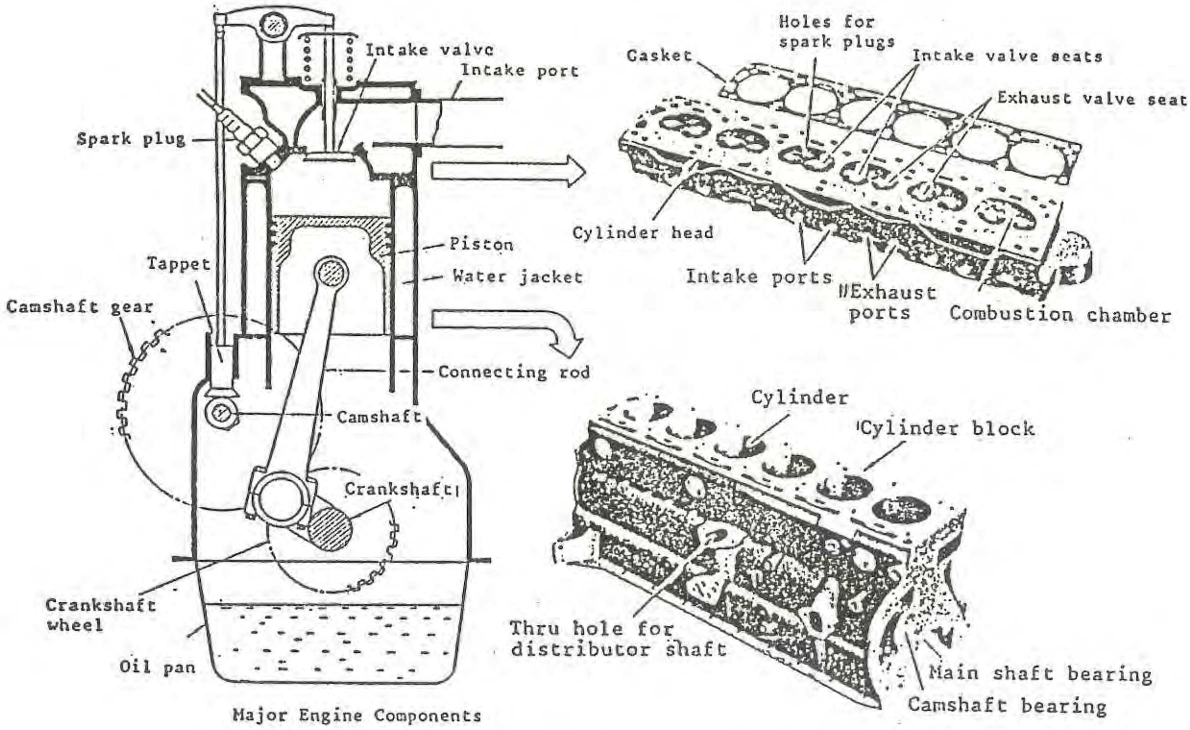


Fig. 4-17 Structure of Major Components of Gasoline Engines

(2) Pistons and connecting rods

The pistons, powered by the high-temperature, high-pressure combustion gas, reciprocate inside the cylinders at an average speed of 10 m/s. Consequently, pistons should have minimal thermal expansion and conductivity and their diameters should become gradually smaller at the top.

The connecting rods transmit the motion of the piston to the crankshaft, and are linked to the pistons by means of piston pins.

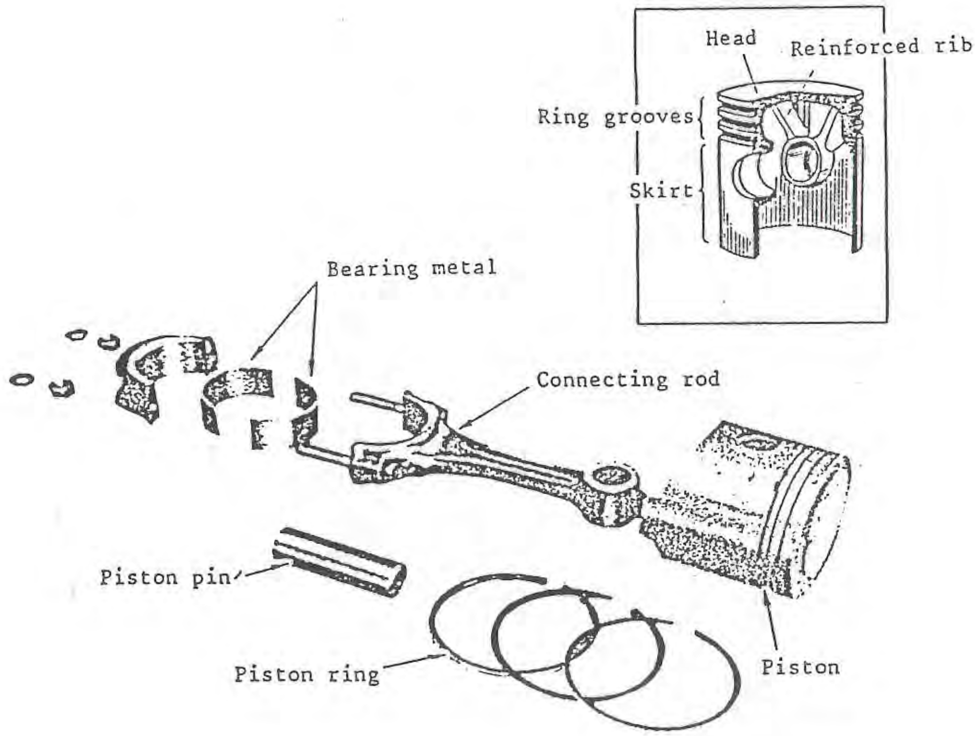


Fig. 4-18 Piston and Connecting Rod

o The pistons are fitted with three to four piston rings. The two or three rings at the top are called compression rings, and they serve to keep the gases sealed inside the cylinder and to let the heat of the pistons escape into the cylinder. The one or two rings at the bottom are called oil scraping rings, and they serve to keep an oil film on the cylinder walls and to scrape off any excess lubricant.

(3) Crankshaft

As shown in Fig. 4-19, the crankshaft is the main shaft of the engine. It converts the reciprocaling motion of the pistons into rotary motion or, in the opposite way, moves the pistons to inhale fuel-air mixture and compress it, and then exhaust the combusted gas.

In multi-cylinder engines, the layout of the crank arm or used and the firing order are determined considering following items; Beep the ignition or combustion at equal intervals and keep the rotary power as uniform as possible, (2) prevent consecutive explosions in the neighboring cylinders so that the load on the main bearing can be kept in balance, and (3) maintain the dynamic balance. Table 4-2 shows various arrangements of crank arms and firing orders.

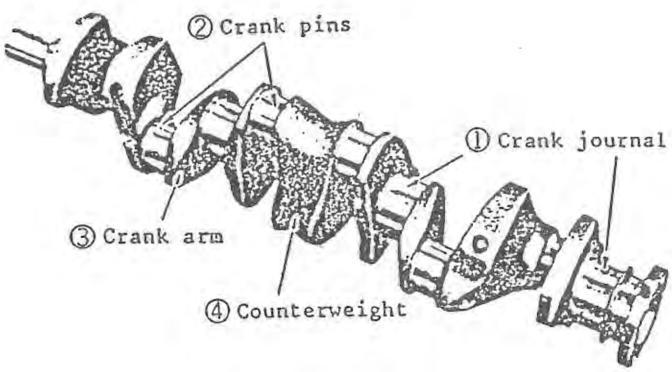
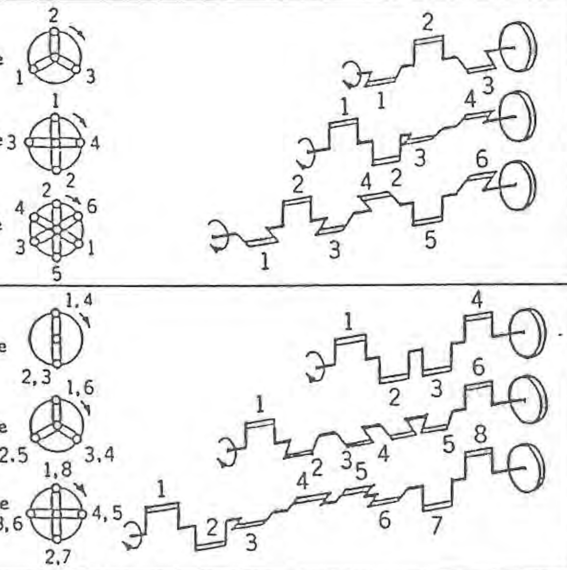


Fig. 4-19 Crank Arm

o A flywheel, which has a large moment of inertia, is installed at the rear end of the crankshaft. It stores some of the energy from the expansion stroke and releases it in the other strokes to prevent periodic fluctuations in the rotating force. Gears are fitted to the circumference of the flywheel, and serve to transmit the rotating force of the starting motor to the main shaft.

Table 4-2 Arrangement of Crank Arms and Firing Order

	No. of cylinders	Cylinder arrangement	Firing order
2 cycle	3	In-line	1 3 2
	4	In-line	1 3 2 4
	6	In-line	1 6 2 4 3 5
4 cycle	4	In-line	1 2 4 3
	6	In-line	1 5 3 6 2 4
	8	In-line	1 6 2 5 8 3 7 4



(4) Valve train

Valve trains are usually used on 4-cycle engines. The rotating speed of the crankshaft is reduced to half by a gear or chain, and then transmitted to the crankshaft. As a result, for every two revolutions of the crankshaft, the intake valve and exhaust valve each open and close one time.

The cams for the intake and exhaust valves are made into a single unit with the camshaft and, as shown in Fig. 4-20, the valves are pushed open by the rotation of the camshaft transmitted via the tappets, push rods, and rocker arms, and are closed by the force of a valve spring.

To make the valve train lighter, an overhead camshaft system, (OHC) in which the push rods are eliminated, is widely used. Poppet valves are used for the valves.

o Since both the intake and exhaust valves are exposed to high temperatures while the engine is in operation, they will expand slightly. To ensure that the valves can be adjusted so that they close completely, a small clearance is provided between the rocket arms and valve rods or between the tappets and valve rods. This is called the valve clearance.

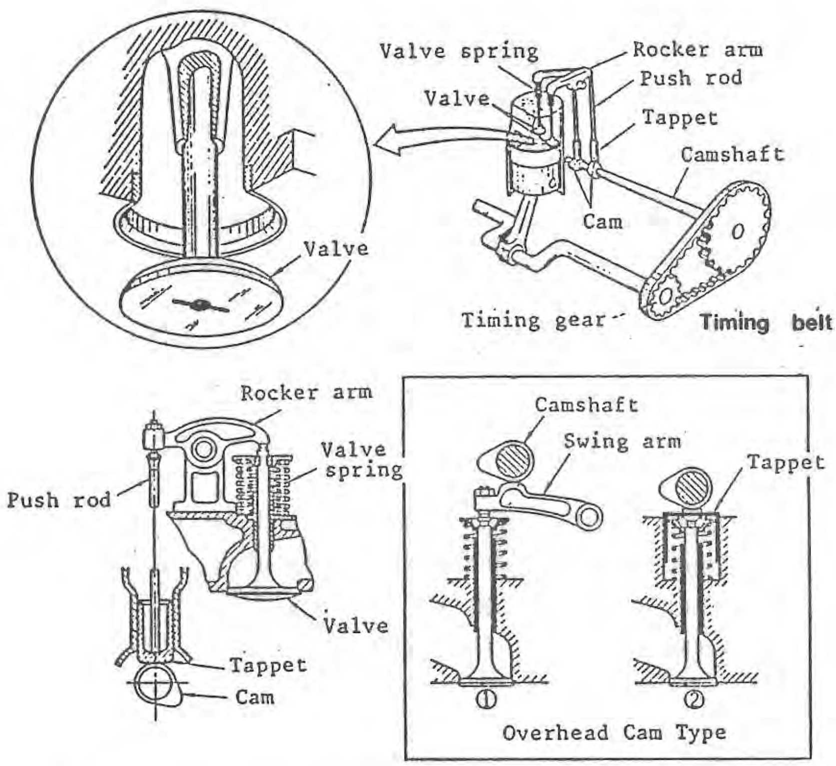


Fig. 4-20 Valve Train (Example of Head Valve Type)

As shown in Fig. 4-21, the intake valve and exhaust valve open and close at a position just a little before TDC and BDC. The main purpose of this is to carry out intake and exhaust more efficiently in order to overcome the inertia in the flow of the fuel-air mixture and combusted gas. For this reason, in the vicinity of TDC, both the exhaust valve and intake valve are opened at the same time for a brief period, and this is called valve overlap.

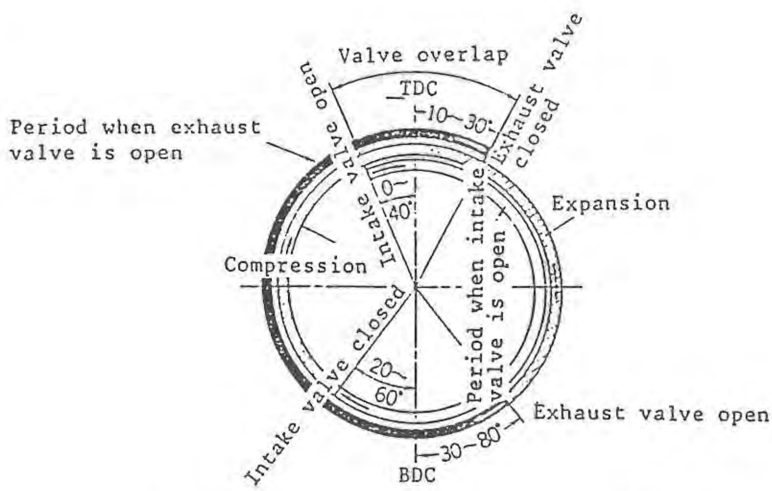


Fig. 4-21 Timing of Valve Opening/Closing

(5) Combustion chamber

The shape of the combustion chamber has a great influence on the combustible state of the fuel-air mixture, and in turn, the performance of the engine.

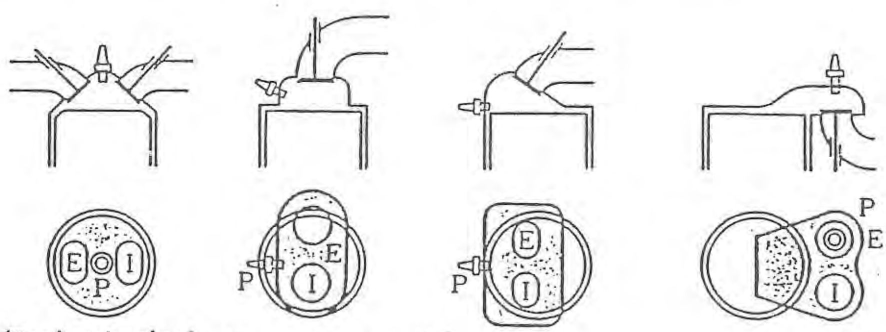
Depending on the arrangement of valves of the cylinder head, combustion chambers are available in the following shapes.

(a) Over-head valve type combustion chambers

This type of combustion chamber has a valve on the cylinder head, as shown in Fig. 4-22 (a).

In all of these types of combustion chambers, the valve area is large so that plenty of intake air can be inhaled and the surface area of the combustion chamber is small so that heat losses can be reduced.

Also, since a suitably strong turbulence is created for the flow of the fuel-air mixture, the flame propagation velocity1/ is increased and knocking2/ is prevented, thus leading to higher performance. That is why this type of combustion chamber is widely used in automobile engines.



(Semi-spherical shaped) (Bathtub shaped) (Wedge shaped)

(a) Over-Head Valve Type (b) Side Valve Type

P: Spark plug I: Intake valve E: Exhaust valve

Fig. 4-22 Combustion Chambers in Gasoline Engines

(b) Side valve type combustion chambers

This type of combustion chamber has the shape shown in Fig. 4-22(b). Since the heating surface area is large, the heat losses become large, and since for structural reasons it is impossible to raise the compression ratio, the combustion chambers of this type are used in relatively small engines.

3.3 Fuel System

A general outline of the flow of fuel from the fuel tank to the cylinders is shown in Fig. 4-23.

Notes: 1/ The velocity at which the flame surface moves in combustion. (See P. 32)

2/ See page 33.

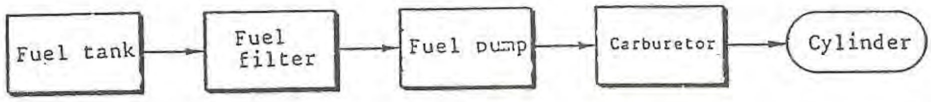


Fig. 4-23 Constituents of Fuel System

(1) Fuel pump

The fuel pump works to deliver fuel from the fuel tank to the carburetor, and diaphragm type pumps are most widely used. Fig. 4-24 illustrates a diaphragm type fuel pump and its mode of action.

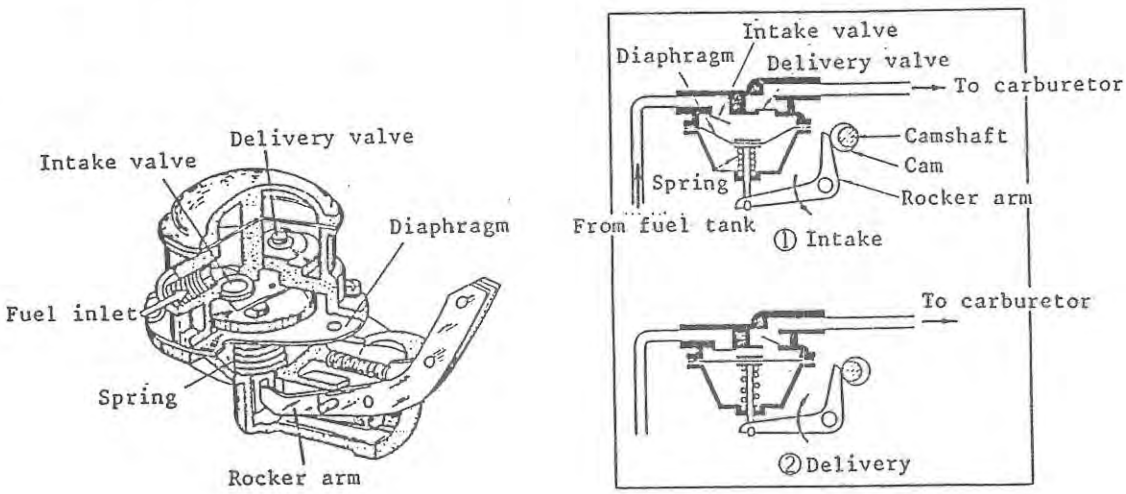


Fig. 4-24 Fuel Pump and Its Mode of Action

- This kind of fuel pump inhales and delivers fuel by transmitting the rotation of the crankshaft to the camshaft to vibrate the rocker arm, which in turn moves the diaphragm up and down. When the diaphragm shaft is pulled down by the rocker arm, the pressure in the pump chamber becomes lower, thereby opening the intake valve and allowing fuel to be drawn into the pump housing.

Next, when the diaphragm is pushed up, the pressure in the pump housing increases, so the intake valve closes, the delivery valve opens, and fuel is sent to the carburetor.

(2) Carburetor

The carburetor is a device for making the air-fuel mixture in the suitable mixture ratio[1] demanded by the engine and delivering it to the cylinders. The fundamental mechanism of a carburetor is shown in Fig. 4-25.

Depending on its degree of opening, the throttle valve adjusts the amount of intake of the fuel-air mixture and thereby regulates the output and rpm of the engine.

The air or choke valve, installed at the air inlet, functions to reduce the amount of air intake when starting the engine in cold weather, temporarily making a thick gas mixture. When the engine warms up to a certain extent after the engine has been started, this valve opens fully to provide a fuel mixture having the appropriate mixture ratio.

In actual practice, carburetors make use of various devices and machanisms to supply the suitable fuel mixture for a variety of operating conditions.

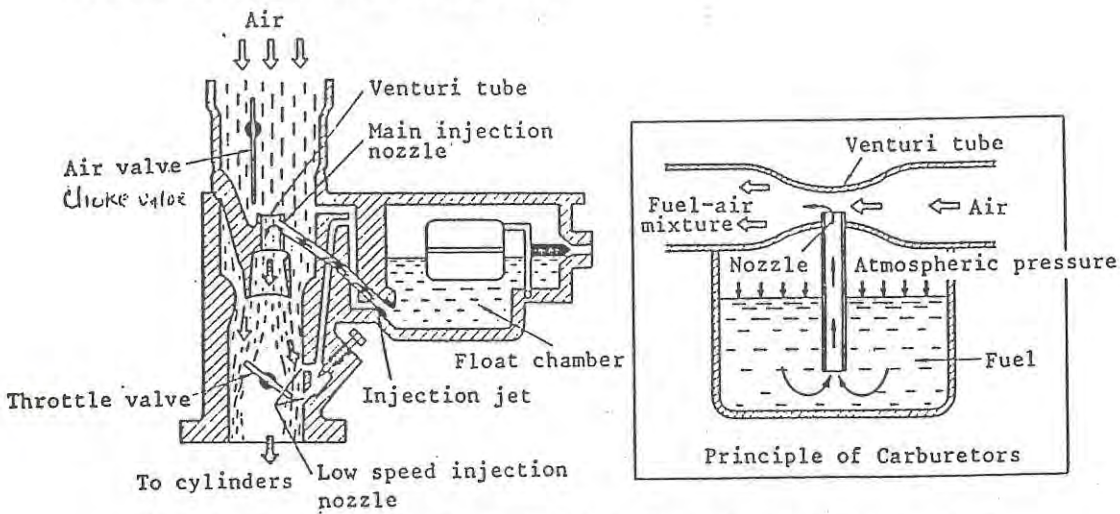


Fig. 4-25 Components and Mode of Action of Carburetors

1/ This is the temperature at which the fuel-air mixture can continue to burn self-sufficiently.

o In this Figure 4-25, when the air drawn into the cylinders during the intake stroke passes through the venturi tube, the narrowness of the passage causes the flow velocity to increase and the static pressure to decline. As a result, a differential pressure is created between the passage and the float chamber, which acts under atmospheric pressure. Consequently, the gasoline, whose flow rate is regulated by the injection jet, is sucked and sprayed through the nozzle, mixed with the air, and made into a mist.

Fig. 4-26 shows an example of a carburetor widely used in small engines, such as those of motorcycles.

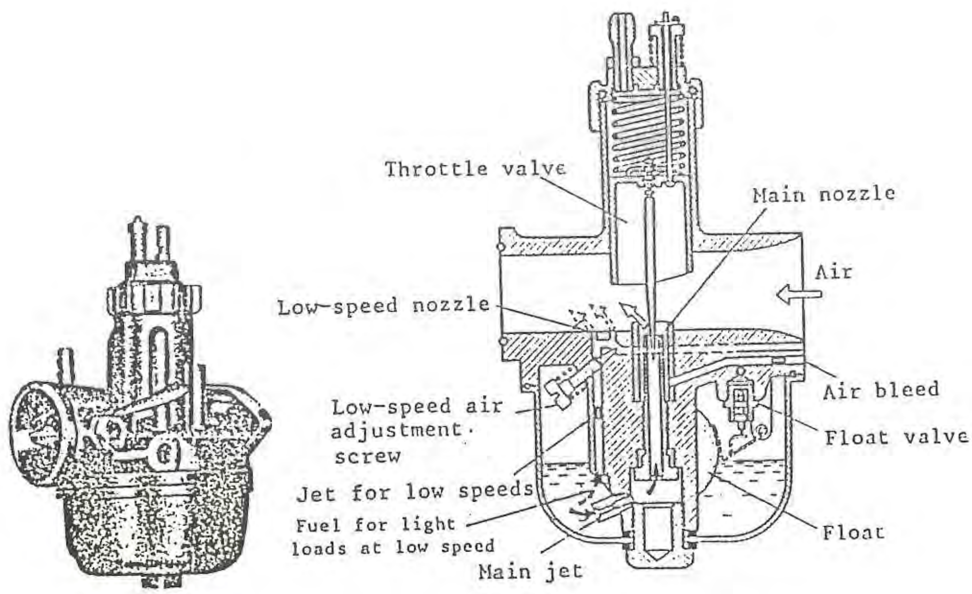


Fig. 4-26 AMARU Type Carburetor

o The low-speed nozzle shown in the drawing is used when the engine is operating at low speed or under light loads, at which times there is a greater proportion of residual gas. Since this gas dilutes the new fuel-air mixture, there is a need to supply a fuel-air mixture which is somewhat thicker. For that reason, a low speed nozzle is provided at the position shown in the drawing so that gasoline can be taken into the intake tube even if the throttle is only slightly open.

In the carburetor shown in Fig. 4-27, two venturi tubes are made into a single unit, and one or both of the venturi tubes is actuated in response to the rpm of the engine. Thus, this is an example of a twin carburetor which can provide the appropriate fuel-air mixture for every condition from low speed to high speed.

The air bleed shown in the figure functions to mix some air into the gasoline in the position infront of the main nozzle. This action causes air bubbles to form in the gasoline, thus encouraging vaporization or providing a somewhat thinner fuel-air mixture when the engine is operating under light loads.

To prevent the fuel-air mixture from temporarily becoming thin during acceleration, an acceleration pump is interlocked with the throttle valve and works to forcefully eject the suitable amount of gasoline from the acceleration nozzle.

o As shown in the Figure 4-27, at low speeds and light loads the primary passage actuates while at high speeds the negative pressure at the venturi tube actuates the diaphragm and causes the throttle valve for the secondary passage to open. As a result, both carburetor passages open at the same time.

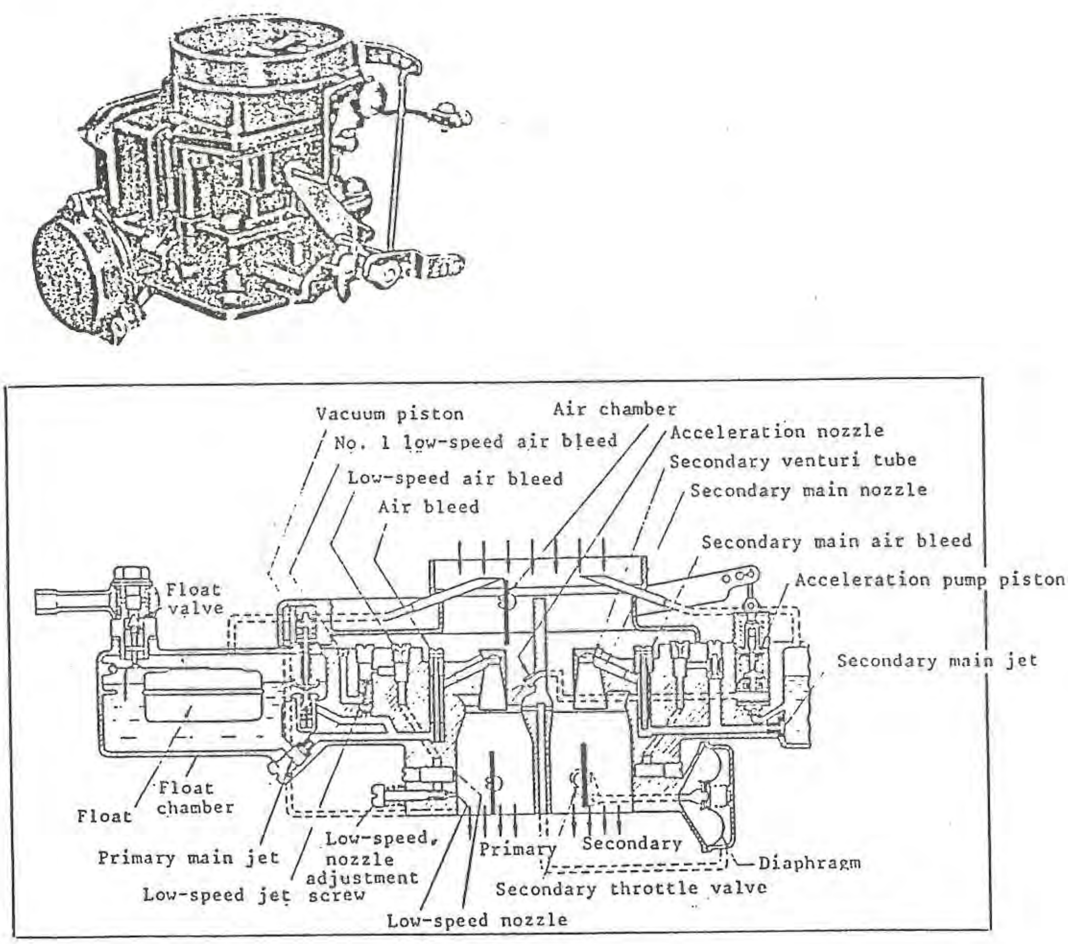


Fig. 4-27 Example of Twin Carburetor

Q. 1. Using Bernoulli's theorem, work out the equation for finding the decline in static pressure at venturi tubes in a carburetor.

3.4 Ignition Systems

The two basic kinds of ignition systems used in gasoline engines are the battery ignition system and the magneto ignition system. The battery ignition system makes it possible to obtain a steady high voltage even at low speeds, and since a storage battery is required to turn the starting motor, this system is widely used for automobile gasoline engines. On the other hand, the magneto ignition system is system whose power source is a small generator which uses a permanent magnet, and this system is used for small engines and engines for aircraft.

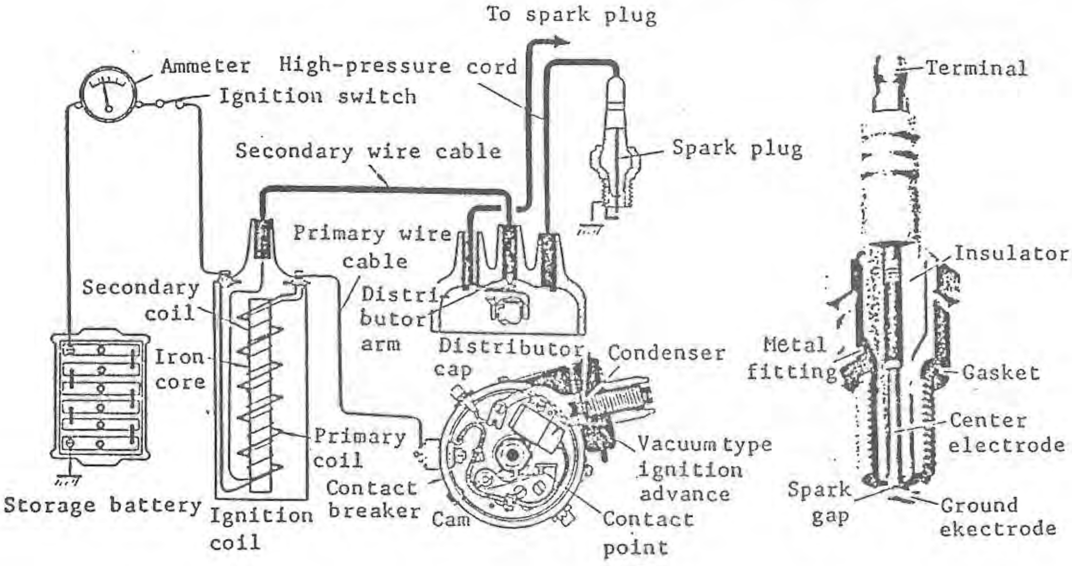


Fig. 4-28 Battery Ignition System and Spark Plug

- As shown in the figure, the storage battery serves as the power source and passes an electric current through the primary coil of the ingnition coil. This current is interrupted by the action of a cam which is driven by the rotation of the engine, and thereby generates a high voltage at the secondary coil. This high voltage is distributed to each cylinder's spark plug in accordance with the firing order and the resulting spark discharge ignites the fuel-air mixture. The spark gap of the spark plugs is about 0.7 to 1.0 mm, but to ensure that ignition occurs properly even when using a thin fuel-air mixture and for considerations of safety regarding the exhaust gas, measures have been considered to increase the spark energy and there is a tendency to make the spark gap relatively wider.

The device which distributes the high voltage generated by the ignition coil to the spark plugs in accordance with the firing order is called a distributor, and the distributor consists of a circuit breaker, ignition advance, and a distributor cap as shown in Fig. 4-29. However, the contact points of the contact breaker are a cause of breakdowns when they burn out. Therefore, to ensure positive ignition even when a thin fuel-air mixture is used, there is an increasing tendency to abandon contact points in favor of transistor spark circuits which have a magnetic pickup.

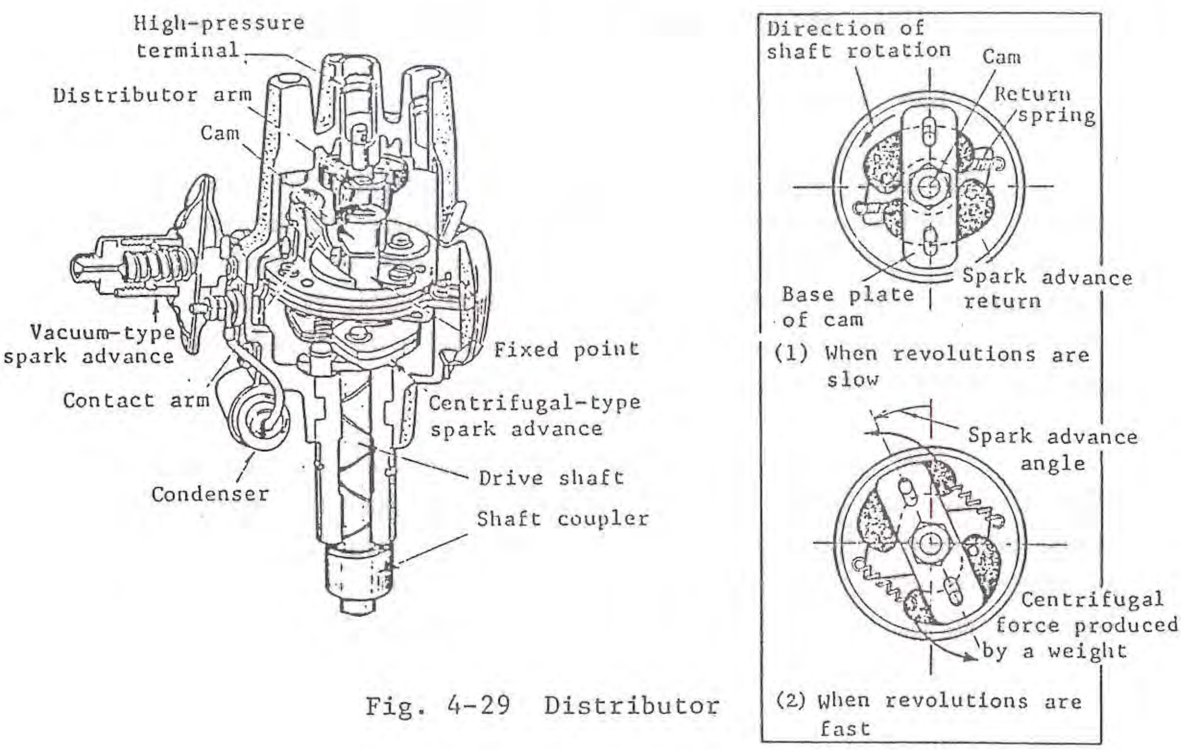


Fig. 4-29 Distributor

- The contact breaker opens and closes the points by the revolutions of a cam, thereby interrupting the primary current. The number of corners on the cam is equal to the number of cylinders, and the cam rotates at one-half the speed of the crankshaft, thereby opening and closing the pints.

- There are two basic types of spark advance systems: a centrifugal type spark advance system which automatically adjusts the spark advance angle when the engine speed changes, and a vaccum type which automatically adjusts the ignition timing in accordance with the load.

- The distributor cap is a single piece together with the contact breaker and is structured so that the distributer arm fitted to the top of the contact breaker cam rotates together with the cam. The high voltage induced by the ignition coil passes through the distributor arm and is applied to the peripheral terminals connected to each cylinder.

3.5 Lubrication System

Gasoline engines have some parts which are subject to friction, including parts which make reciprocating motion (such as pistons) and parts which make rotary motion (such as the crankshaft). When these parts are bathed with oil or covered with an oil film, solid friction is changed into fluid friction, and the overall friction is rapidly reduced.

A lubrication system is used to apply an appropriate oil film to the surfaces of parts which move against each other. There are many types of lubrication systems, and Fig. 4-30 shows an example of a pressurized lubrication system in which the lubrication oil is sent through the application of pressure.

o As shown in the figure, lubricating oil collects in the bottom of the oil pan, and the oil pump, equipped with a relief valve, sends oil to the main bearings, crank pins, camshaft, rocker arm shaft, and other parts, while the cylinder walls are lubricated by the oil leaking through the crank pins.

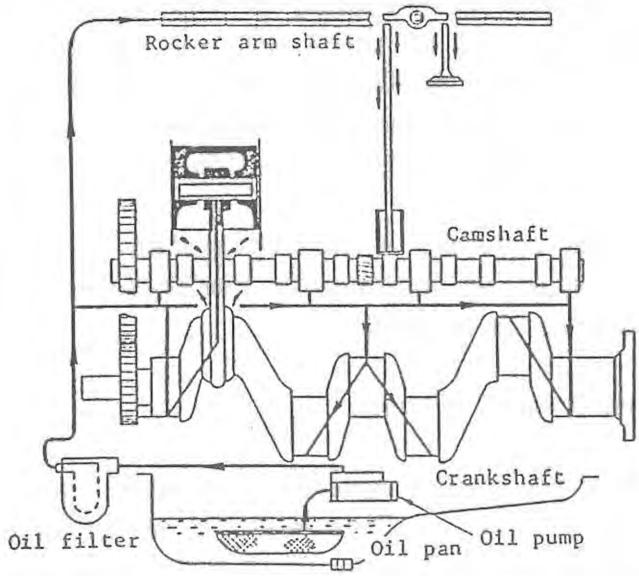


Fig. 4-30 Pressurized Lubrication System

The lubricating oil serves the following functions:

1) It reduces wear by reducing friction.

2) It has a cooling action by transferring the heat of friction to the outside.

3) It maintains the air-tightness between the cylinders and pistons.

4) It shuts off damp air to prevent corrosion and rust.

5) It provides an oil film which prevents noise and reduces shocks.

3.6 Cooling System

Since the temperature of the combustion gas in the cylinder rises as high as 1500 to 2000°C, overheating will occur unless appropriate cooling is carried out. Overheating is likely to cause seizing of the pistons and cylinders; vaporizing of some of the fuel in the fuel lines, which in turn leads to a shortage in fuel supply; a loss of viscosity of the oil; or a deterioration in lubricating. All of these problems can shorten the life of the engine. However, if the system is over-cooled, the combustion will become worse and the components of the fuel will stick to the spark plugs and to the inside of the fuel chamber.

For these reasons, a cooling system is needed to keep the engine running at an appropriate temperature. (The cooling water temperature is about 80°C).

(1) Water-cooled type

A water-cooled system uses water to cool down the system. The system shown in Fig. 4-31, in which water is forcefully circulated by a water pump, is in wide use.

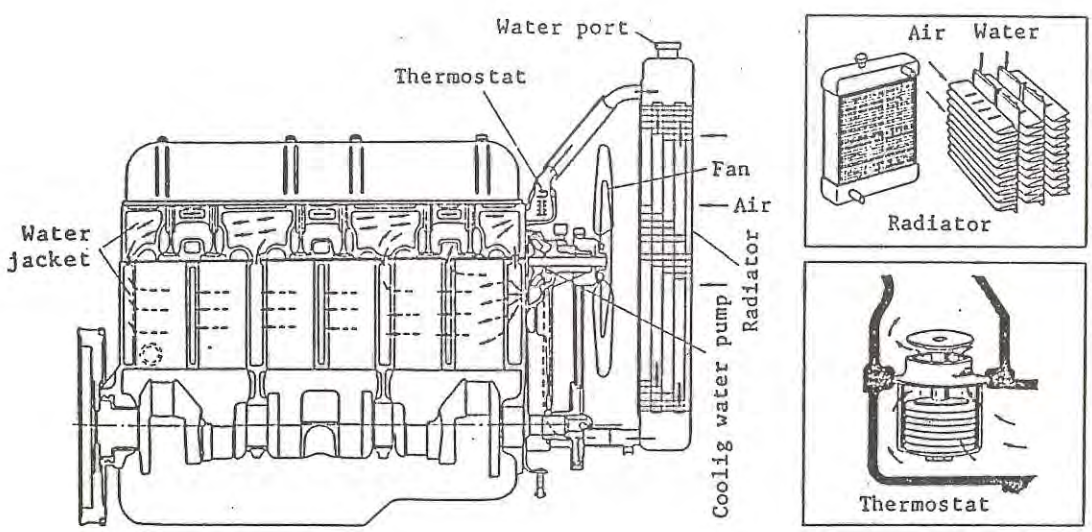


Fig. 4-31 Forced-Circulation Type Cooling System

- o As shown in the figure, cooling water is circulated by a pump through the water jacket attached to the cylinder block and cylinder head. Water which becomes hot enters the radiator, where it is cooled with a fan, and a thermostat is provided at the inlet of the radiator to control the flow of the hot water so that it does not get too cold.

(2) Air-cooled types

As shown in Fig. 4-32, an air-cooled system has several cooling fins along the outer circumference of the cylinders and cylinder head to provide a wide cooling area. The cooling system works using the air which hits the fins. The structure is simple and allows the engine to be made lighter, so air-cooled systems are often used on motorcycle engines.

With an air-cooled system, there is no worry about such problems as water leakage or freezing of the water in winter, and the engine warm-up time can be kept short. The major drawbacks are that these systems are rather noisy and it is difficult to obtain a high compression ratio.

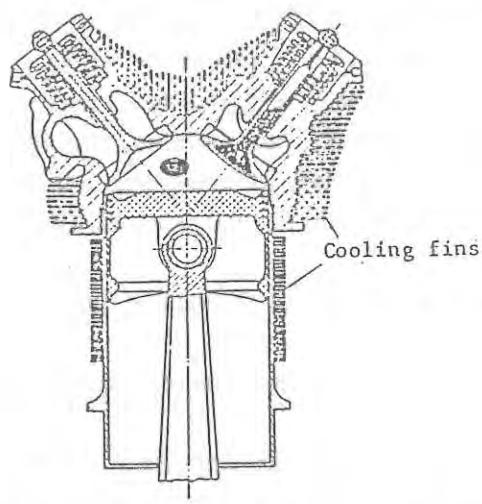


Fig. 4-32 Cooling Fins on an Air-Cooled System

3.7 Exhaust System

An exhaust system works to eject the gas burnt in the cylinders to the outside and, as shown in Fig. 4-33, consists of an exhaust manifold, exhaust pipe, and muffler.

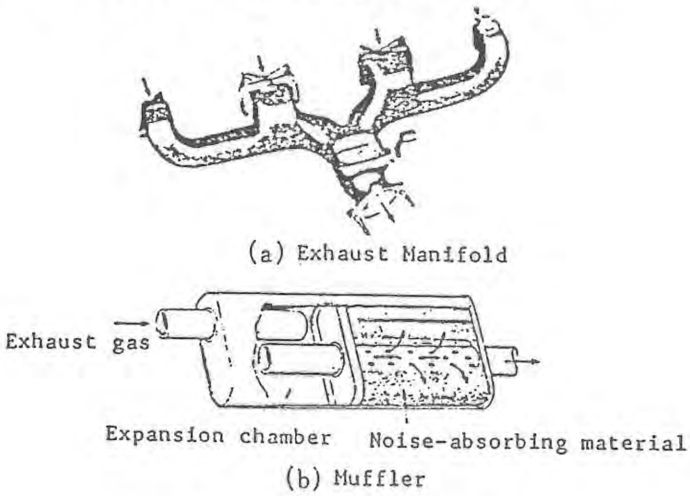


Fig. 4-33 Exhaust System

.A muffler is provided along the exhaust tube. The gas being emitted from the engin is at a pressure of about 3 - 5 kgf/ cm^2 and at a temperature of 600 - 800°C. If this high-temperature, high-pressure gas were released directly into he atmosphere, the gas would suddenly expand and cause a great explosion. For that reason, the exhaust gas passes through a muffler and is led on a winding passage, thus preventing sudden expansion of the gas and releasing it gradually into the atmosphere.

3.8 Fuel and Combustion in Gasoline Engines

(1) Kinds of fuels and their characteristics

The fuels used in internal combustion engines are ordinarily liquid fuels obtained by refining crude oil, and they are classified as gasoline, kerosene, light oil, and heavy oil. (See Table 4-3)

The gasoline used in gasoline engines must have suitable vaporization properties. Since the temperature in the cylinders is low when the engine is started, it is hard for gasoline to vaporize. Therefore, for starting the engine, it is desirable that many of the constituents of the gasoline have a low boiling point and good vaporization properties. If, however, the gasoline is too volatile, it will evaporate in the fuel line after the engine heats up or bubbles may form in the fuel line and make it impossible for the fuel to flow. This is called vapor lock.

On the other hand, if the gasoline contains many constituents whose boiling point is high, the fuel which could not vaporize in the cylinders may mix with the lubricating oil and deteriorate the lubrication performance of the engine. Accordingly, it is necessary to mix various ingredients having the appropriate boiling points.

Table 4-3 Characteristics of Liquid Fuels

Characteristics / Kind of fuel		Specific gravity	Distillation temp. (90% point °C1))	Amount of heat produced (kcal/kgf)	Theoretical mixing ratio (by weight)	Remarks	
Gasoline	For aircraft	0.69 - 0.72	190 or less	10400 or less	Approx. 14.8	Octane no. 80 min.	JIS K 2206
	For automobiles	0.72 - 0.75	200 or less			Octane no. 85 min.	JIS K 2202 (1-2)
Kerosene		0.78 - 0.85	320 or less	10300 or less	Approx. 14.7		JIS K 2203
Jet fuel		0.73 - 0.85	290 or less	10200 or less	Approx. 14.7		JP-4 2)
Light oil		0.84 - 0.89	350 or less	10200 or less	Approx. 14.2	Cetane no. 40 min.	JIS K 2204 (1-3)
Heavy oil		0.90 - 0.99		10000 or less	Approx. 13.9		JIS K 2205

Notes: 1/ 90% °C means the temperature, under certain conditions, at which 90% of the fuel will be distilled.

2/ Jet engine standards in the U.S.A.

(2) Combustion of fuel

To ensure that the fuel burns completely, it is important to mix the fuel with an appropriate amount of air and maintain a temperature above the ignition temperature.1/

Oxygen must be present for the fuel to burn, and since air contains about 23.2% oxygen by weight and 21% by volume, air is usually used as the source of oxygen. If the amount of combustible constituents2/ in the fuel is known, the theoretical amount of air needed for combustion can be found from the chemical reactions of those constituents. In gasoline, the theoretical ratio of air to fuel is about 14.8, and this is called the theoretical mixing ratio.

- o If the fuel-air mixture becomes too rich or too lean, ignition and combustion will not occur under electrical sparking. The range of mixing ratios which will ignite and burn under electrical sparking is 8 - 20, and these are called the flammability limits.

In a gasoline engine, air and fuel are mixed in a carburetor and the mixture is compressed in the cylinders. Therefore, the temperature and pressure of the mixture become high, and when ignition occurs under the electrical spark of the spark plugs, the fuel is suddenly burnt up.

The following points are important regarding the conditions of fuel combustion in the cylinders.

1/ This is the temperature at which the fuel-air mixture can continue to burn self-sufficiently.

2/ Usually carbon and hydrogen, but also includes sulfur. In gasoline, it includes various hydrocarbons (C_mH_n).

(a) Influence of ignition timing.

The fuel-air mixture in the cylinders receives heat from the cylinder walls and residual gas and its temperature increases further when it is compressed. When an electrical spark is introduced at that time, the fuel-air mixture suddenly burns and both the temperature and pressure rise further simultaneously. Fig. 4-34 is an indicator curve1/ showing experimental findings regarding the relationship between pressure and cylinder volume by changing the ignition timing.

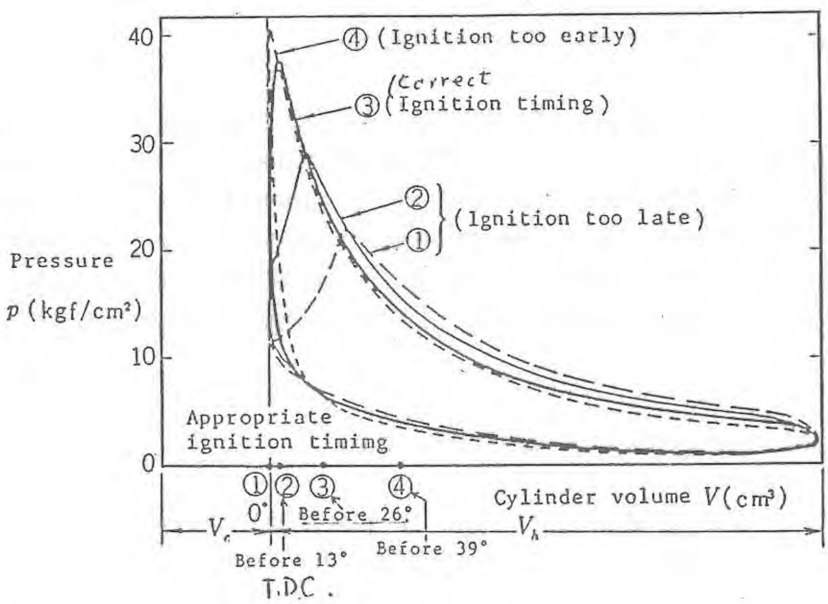


Fig. 4-34 Changes in Indicator curve According to Ignition Timing

---

1/ The device which records the relationship between the pressure inside the cylinders and piston displacement in an internal combustion engine is called an indicator, and the indicator curve is a graph of the recordings made by the indicator.

As can be understood from the figure, when the ignition is too early, the pressure and temperature become high just before TDC; when it is too late, the pressure does not rise very much and only the exhaust temperature increases. In either case, the engine output and thermal efficiency decline.

Thus, the ignition timing has an important influence on the way that the pressure in the cylinders rises and, in turn, is an important factor determining the performance of the engine.

(b) Flame propagation velocity

When a fuel-air mixture is ignited while it is within the flammability limits, the flame advances to the uncombusted portions of the fuel-air mixture at a virtually uniform speed. The speed is called the flame propagation velocity. Inside the cylinders, both the temperature and pressure become high and there are many disturbances, so the velocity is usually 20 - 30 m/s.

(c) Influence of mixture ratio

The combustion time of the fuel-air mixture varies according to the mixture ratio. If the mixture is a little thicker than the theoretical mixing ratio, in which the there is a slight of air, the maximum combustion speed can be obtained and the increased pressure makes it possible to obtain a higher output. However, the fuel is not consumed completely, and thus efficiency declines slightly.

(d) Preignition

When the cylinders are in an over-heated condition, the hot portions auch as the spark plugs and exhaust valves become sources of ignition, and thus the fuel-air mixture ignites and burns earlier than the specified ignition timing. This is called preignition, and as long as it is only on a small scale, the only problem will be that the engine will run a little roughly; when the preignition is excessive, however, the temperature of the cylinders will increase and the pistons may become burnt.

(e) Knocking and countermeasures

Knocking[1/] is a phenomenon which leads to a noise which sounds as if the cylinder walls were being hit with a hammer and causes the engine to run roughly. The output of the engine declines and the exhaust valves and pistons overheat until they sometimes burn up. As shown in portion AB in the indicator curve in Fig. 4-35, high frequency pressure vibrations are conspicuous in the final period of combustion.

1/ Knocking is the phenomenon in which unburnt gas bursts into spontaneous combustion. In knocking, as the combustion proceeds, the unburnt portion of the fuel-air mixture becomes because of the rising pressure of the gas, and as a result, its temperature rises. When this unburnt gas receives heat radiation from the flames, its temperature increases further. When the temperature of the unburnt gas exceeds the spontaneous combustion temperature, all of the remaining unburned gas is consumed at virtually the same time. The resulting shock waves cause the gas to vibrate violently, and the resonance with the cylinders causes a knocking sound.

Besides using anti-knock fuel, there are two main ways to prevent knocking:

1) Increase the flame propagation velocity so that all of the gas can be consumed normally before the unburned gas is subjected to spontaneous combustion.

2) Prevent spontaneous combustion of the unburned gas by lowering its temperature at the final period of combustion.

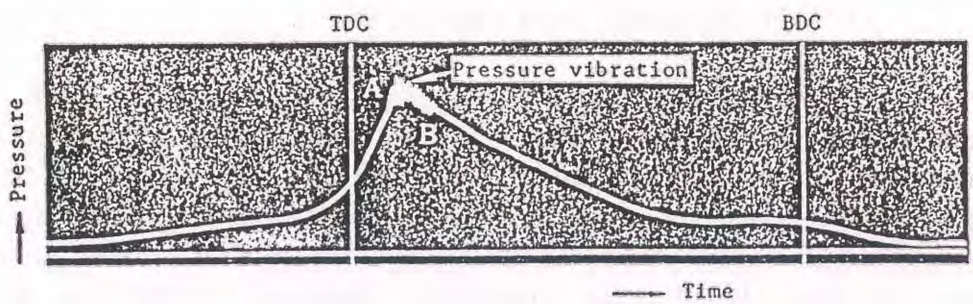


Fig. 4-35 Pressure Vibration of Knocking as Seen in an Indicator Curve

(f) Octane number

To increase the thermal efficiency and output performance of an engine, it is necessary to make the compression ratio as high as possible, but since a high compression ratio and the maximum output mixture ratio can lead to knocking, an anti-knock gasoline is used to prevent these problems.

The value used to express the anti-knock characteristics of a gasoline is called the octane number. The higher the octane number of a gasoline, the more difficult it is for knocking to occur.

- The octane number of iso-octane (C_8H_{18}), a fuel with high anti-knock properties, is set at 100 while that of normal heptane (C_7H_{16}), a fuel with low anti-knock properties, is set at 0. When these two fuels are mixed in a suitable proportion, the ratio by volume of iso-octane will represent the octane number of this fuel mixture. This is taken as the fuel, and a fuel whose anti-knock properties are to be measured is compared to this reference fuel. When the degree of knocking is the same, the octane number of the specimen fuel is determined to be the same as that of the standard fuel.

To improve the anti-knock properties of gasoline, small quantities of substances, called anti-knock additives, are sometimes added to the gasoline, and one of the most effective additives in wide use is lead alkyl. However, since lead alkyl is toxic, toxic substances also appear in the burnt gas of leaded gasoline containing this additive. For this reason, research is being carried out to improve unleaded gasolines. For safety purposes, a red colour solution is added to the leaded gasoline to indicate that they are toxic.

(3) Exhaust pollution

The exhaust gas which is emitted from the exhaust pipe contains such pollutants as carbon monoxide (CO), hydrocarbons (HC), nitrogen exides (NO_x), and lead compounds. Aside from the exhaust gas, there are also problems with emission of hydrocarbons from the fuel tank and vaporizer and with the leakage of combusted gas from the combustion chamber into the crank chamber. Therefore, one of the most important criteria is how to minimize the emission of harmful gases from engines by improving the combustion chamber, fuel supply system, and exhaust purification system.

- Carbon monoxide and hydrocarbons are produced by the incomplete combustion of the fuel; meanwhile, nitrogen oxides (mainly NO and NO_2) are produced when the combustion temperature is high at the time of explosion.

- The combusted gas which leaks from the combustion chamber through the clearances between the pistons and cylinders and into the crank chamber is called blow-by gas. An automobile engines, this gas is usually returned in the intake rather than being released into the atmosphere.

The main countermeasures for reducing and purifying the harmful substances in exhaust gas are described below, and when necessary two or more of these countermeasures may be used in combination.

(a) Recirculation of exhaust gas

In this method, part of the exhaust gas is returned in the intake pipe to soften the combustion in the combustion chamber and lower the combustion temperature, thereby minimizing the production of nitrogen oxides.

- When recirculation of the exhaust gas is carried out, ignition will become worse and combustion will become unstable, so combustion is stimulated and enhanced by increasing the fulidity of the gas in the cyliners of using two spark plugs.

(b) Use of catalytic converter

In this method, an oxidation catalytic converter (which reduces the carbon monoxide and hydrocarbons) or a three-way catalytic converter (which simultaneously reduces the carbon monoxide, hydrocarbons, and nitrogen oxides) is installed in the exhaust pipe.

(c) Compound swirl adjustment combustion

Based on the fact that the amount of carbon monoxide, hydrocarbons, and nitrogen oxides in the exhaust gas can be reduced if combustion is carried out with a thin fuel-air mixture, this method can be attained by the combustion of a lean fuel-air mixture which cosists of providing of a small amount of thick mixture and a larger amount of a lean mixture. That is the rich mixture is ignited in the auxilairy combustion chamber and the resulting flame ignites the lean mixture in the main combustion chamber.

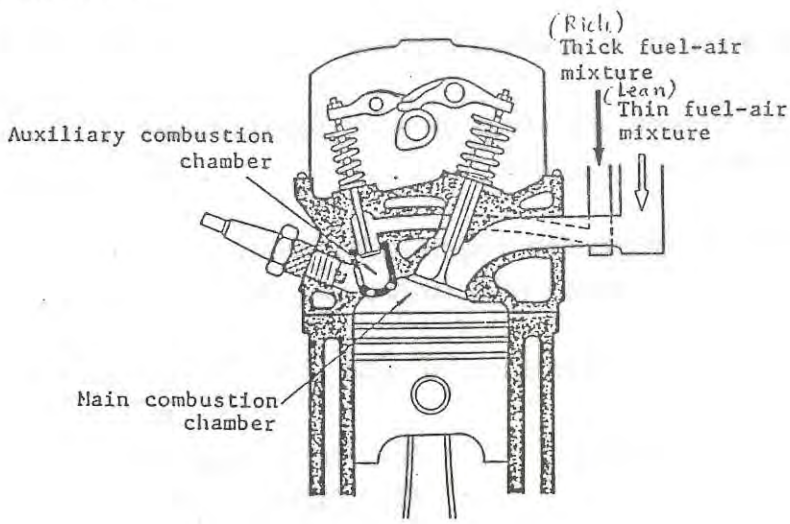


Fig. 4-36 Compound Swirl Adjustment Combustion

(d) Electronically controlled fuel injection

In this method, and electronic control system is used to inject a suitable amount of fuel into the intake pipe to match the amount of intake air, thus leading to combustion without waste and a reduction in carbon monoxide and hydrocarbons.

- An electronic control system is an automatic system which not only serves as a countermeasure for the exhaust gas but also regulates the ignition timing and knocking to create the optimum operating conditions of the engine from the viewpoints of fuel economy, operating performance, and engine output.

Questions ◎

1. In a gasoline engine, what components are needed between the point at which gasoline leaves the fuel tank and the point at which it enters the cylinders? Draw a sketch of the system.

2. Using Bernoulli's theorem, explain how a carburetor works.

3. What differences are there in structure between a 2-cycle and 4-cycle engine. Explain.

4. Describe the mechanism required to convert the reciprocating motion of the pistons into rotary motion of the output shaft.

5. Give a simple explanation of what the following are needed for.
   (a) Valve clearance (b) Valve overlap
   (c) Flywheel (d) Piston ring

6. In a gasoline engine, what kind of changes are required in the fuel-air mixture ratio with regard to changes in the engine speed (rpm) and load?

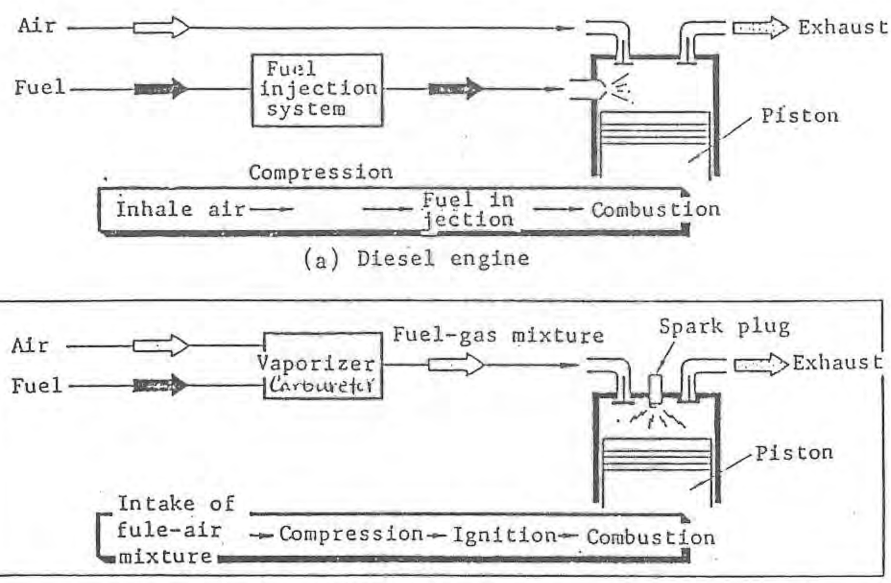
7. Explain what is meant by an octane number of 85.

4. Diesel Engines

Similarly to gasoline engines, diesel engines are engines in which fuel is burnt inside cylinders to move pistons and thereby obtain power. Therefore, the fundamental structure of the two types of engines are similar, though there are differences in the ignition system and fuel supply system.

4.1 Principle of Operation of Diesel Engines

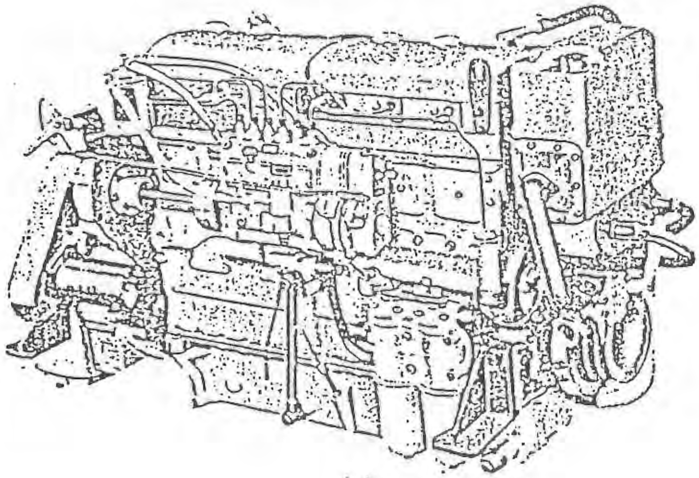
In contrast to gasoline engines which use an electrical ignition system, diesel engines make use of self or spontaneous ignition in which air is inhaled into the cylinders and subjected to high compression (compression ratios: 15 - 22), and then fuel is injected into the air which has reached a high temperature and high pressure resulting in combustion.



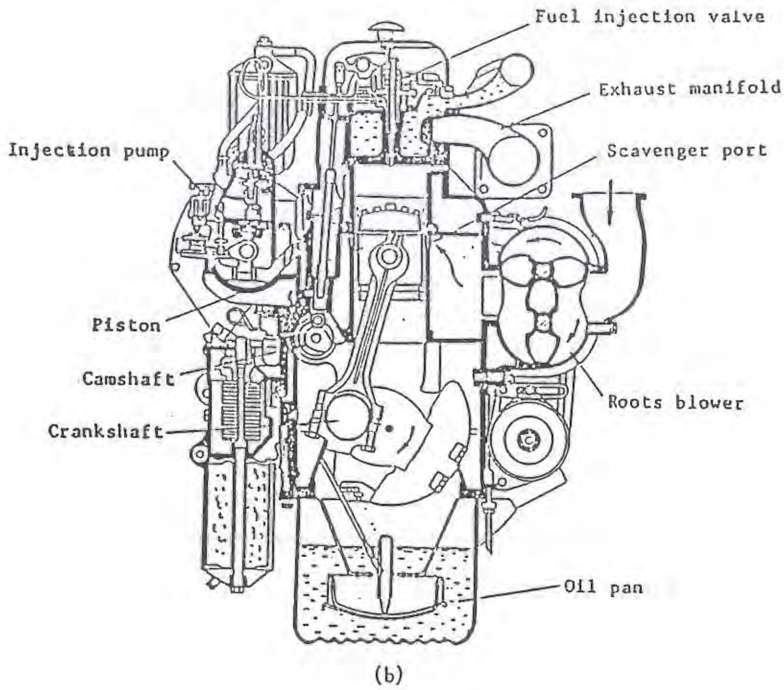
(b) Gasoline engine

Fig. 4-37 Diesel Engine and Gasoline Engine

Fig. 4-38 shows an example of the structure of a diesel engine.



(a)

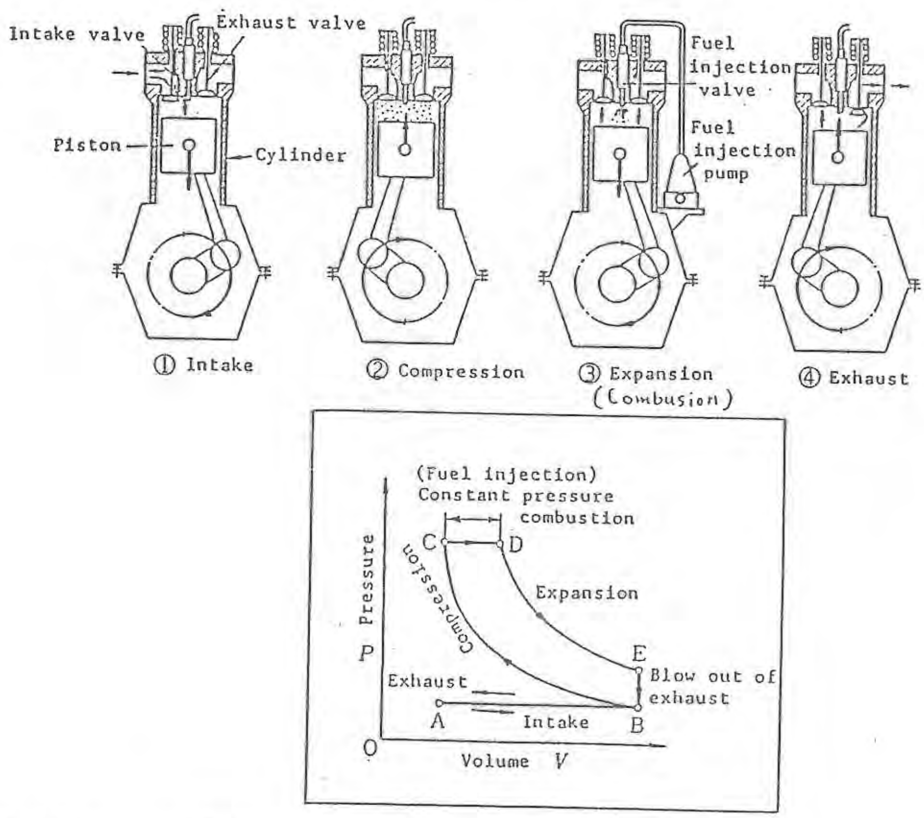


(b)

Fig. 4-38 Structure of Diesel Engine

(1) 4-cycle diesel engine

A 4-cycle diesel engine completes the four strokes of intake, compression, expansion (fuel consumption), and exhaust in two revolutions of the crankshaft. (See Fig. 4-39).



(1) Intake : Only clean air is inhaled by the intake valve.

(2) Compression : The inhaled air is compressed by the piston. The pressure of the air at this time is always extremely high and exceeds 20 kgf/cm^2 even at low speeds. For this reason, the temperature of the inhaled air reaches 500° to 700°C.

Near the end of the compression stroke, the fuel is injected from the injection valve at a high pressure, the fuel which has become a spray ignites spontaneously in the high temperature, high pressure air, and the temperature and pressure increase rapidly.

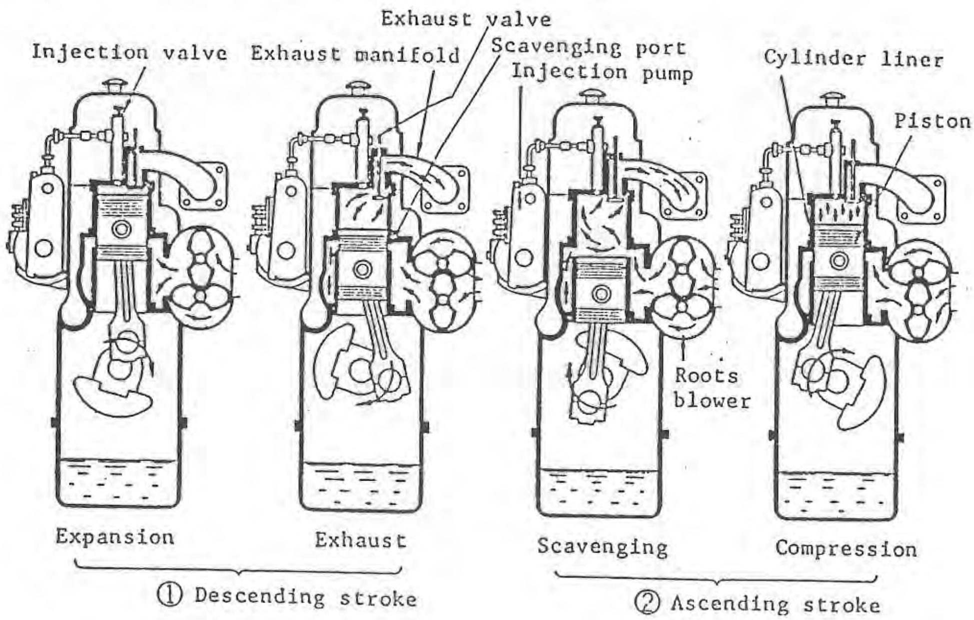
(3) Expansion : With the combustion of the fuel, the air in the cylinder expands and thereby pushes the piston down.

(4) Exhaust : The exhaust valve is opened, the piston moves up, and the exhaust gas is pushed out.

Fig. 4-39 Action of a 4-cycle Diesel Engine

(2) 2-cycle diesel engine

As shown in Fig. 4-40, cycles of two strokes of (1) expansion and exhaust and (2) scavenging and compression are completed in one revolution of the crankshaft.



(1) Descending stroke

Expansion : Slightly before the piston reaches top dead center, the fuel from the injection valve is injected into the high pressure, high temperature air and natural ignition occurs. Because of this combustion pressure, the piston is pushed down.

Exhaust : Near the end of the expansion stroke, the exhaust valve opens and the combusted gas escapes. Then the piston goes down and when almost all of the gas has been exhausted from the cylinder, a scavenging port installed in the cylinder wall opens.

(2) Ascending stroke

Scavenging : When the scavenging valve opens and the scavenging port opens, clean air is sent to cylinder by the scavenging pump and the remaining combusted gas is pushed out of the cylinder.

Compression : When the piston rises, the scavenging pump closes, the exhaust valve closes, the air is compressed and reaches a high temperature and pressure.

Fig. 4-40 Operation of a 2-cycle Diesel Engine

4.2 Combustion Chamber

Because diesel engines carry out combustion in a very short time by making the fuel into a spray and thoroughly mixing the fuel and air, various kinds of combustion chambers are available. (See Fig. 4-41).

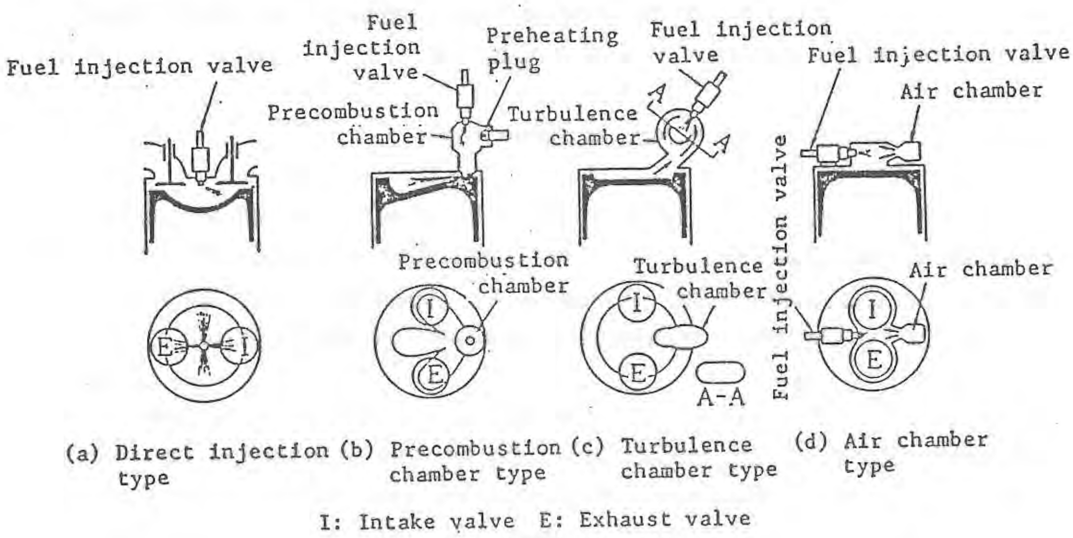


Fig. 4-41 Combustion Chambers of Diesel Engines

(a) Direct injection type

The direct injection type is made from a cylinder head and piston head and fuel is injected directly into a single combustion chamber (Fig. 4-41 a). Because the surface area of the combustion chamber is less than that of other chambers, and because there is no throttling part to provide resistance to the flow, the heat efficiency is high and startability is good.

However, this type of combustion chamber is very sensitive to the quality of fuel and injection. To obtain good injection, the injection pressure of the fuel must be high. Also, since knocking[1/] occurs easily, fuel with a high cetane number must be used and the maximum pressure of combustion becomes high[2/]

This type of combustion chamber is widely used on large and small 2-cycle diesel engines.

(b) Precombustion chamber type

As shown in Fig. 4-41 b, a small chamber called the precombustion chamber, which is approximately 30% of the total volume of the combustion chamber, is separately provided, and is connected to the main combustion chamber by small hole.

The fuel is injected into this small chamber and part of the fuel is consumed. Using the accompanying rise in temperature and pressure, the combusted gas and noncombusted fuel are injected into the main combustion chamber and, while being thoroughly mixed with air, the majority of the remaining fuel is burnt.

Even fuel with a low cetane number can be used and the injection pressure can be low.

The maximum pressure of combustion is low and operation is quiet, but the termal efficiency is not good.

1/ See page 52
2/ See page 53

In addition, the engine is sometimes hard to start and for that reason the precombustion chamber has a preheating plug or glow plug.

This type of chamber is widely used on small, high speed engines.

(c) Turbulence chamber (Swirl chamber)

As shown in Fig. 4-41 c, a spherical or flattened spherical turbulence chamber is provided. In the compression stroke the air which flows into here is made to flow in a swirl vortex pattern. When fuel is injected into this swirl flow, the air and fuel become thoroughly mixed and good combustion can be carried out.

This type of chamber is appropriate for high speed engines.

(d) Air cell chamber (Power cells or Energy cells)

As shown in Fig. 4-41 d, a small, separate chamber called an air chamber is provided, and some air is force into this chamber during the compression stroke. When fuel is injected towards the entrance of the air chamber, the piston goes down and air is injected from the air chamber, thoroughly mixing with the fuel and thus burning.

The maximum pressure of combustion is low and operation is quiet.

This type is not suitable for high speed engines.

4.3 Fuel injection system

The fuel injection system is composed of the fuel tank, fuel supply pump, fuel filter, fuel injection pump, and fuel injection valves. (See Fig. 4-42).

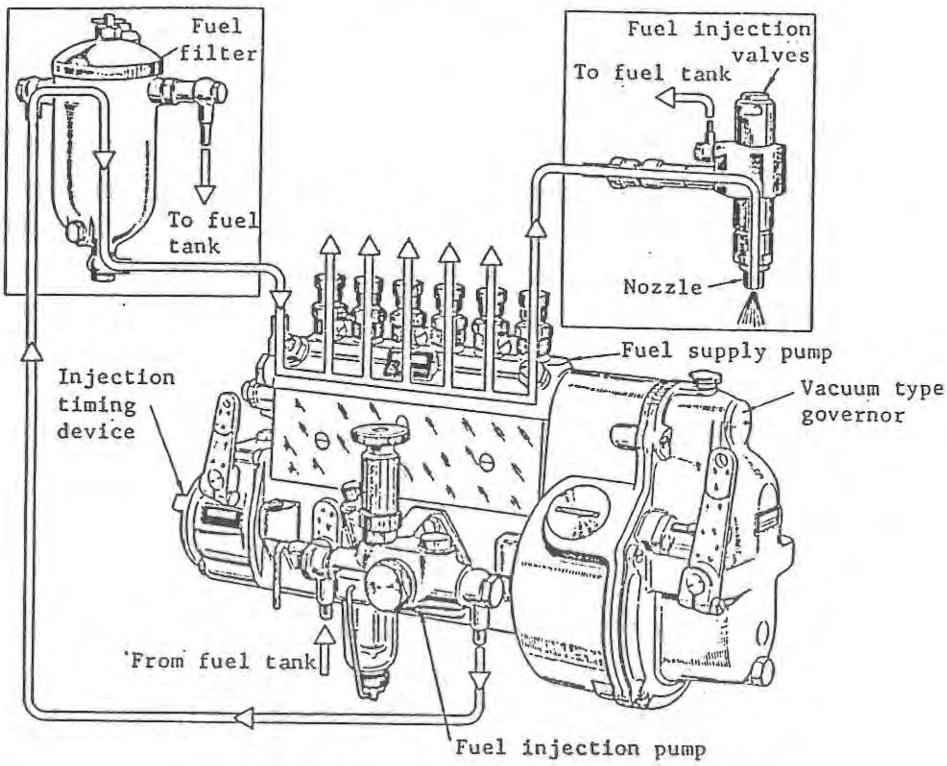


Fig. 4-42 Fuel system of diesel engines

The quality of fuel injection has a big influence on the performance of diesel engines, therefore, the following matters must be observed regarding the injection and atomization of the fuel.

1) The diameter of the spray particles must be small and uniform in size.

2) The dispersion of the spray should be uniform and have appropriate penetration, it should reach to in every corners of the combustion chamber, and should mix thoroughly with air.

3) Since the rotation speed and output change on a diesel engine, the amount of fuel injected changes. Therefore, the beginning and ending of injection should be clear and the injection timing and amount should be accurately and freely controlled.

(1) Fuel injection pump

The fuel injection pump shown in Fig. 4-43 is used to send the fuel which comes from the fuel filter to the injection valves of each cylinder in accordance with the injection order. The fuel injection pump is provided with a speed governor and an injection timing device so as to automatically control the amount and timing of injection depending on the size of the load and the speed.

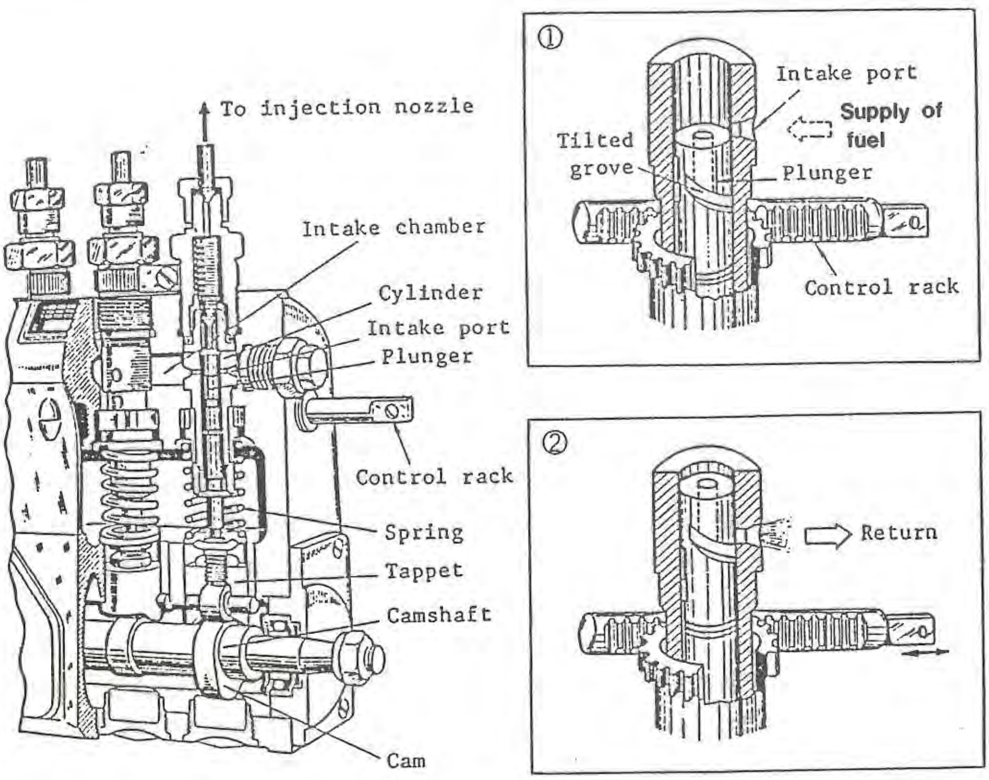


Fig. 4-43 Fuel Injection Pump (Bosch type) and Its Operation

- The injection pump is a plunger type which is driven by a cam and a spring. At the plunger head, there is a tilting groove and a central hole, and at the position shown in Fig. 4-43 (1), fuel is filled in the top of the barrel and forced to flow out by the raising of the plunger. When the plunger rises to the position shown in Fig. 4-43(2), the fuel returns to the intake port from the central hole and through the tilting groove, the pressure goes down, and injection ends.

- As shown in the figure, the amount of injection is controlled by moving the control rack to turn the plunger. This changes the position of the tilting groove, which in turn changes the return timing of the fuel, and as a result the amount of injection can be changed.

(2) Fuel injection valves

A fuel injection valve is used to inject the high pressure fuel sent from the injection pump into the combustion chamber.

Fuel injection valves are structured with automatic valve as shown in Fig. 4-44, and the pressure of the fuel acts on a needle valve. When that pressure exceeds a spring force, the valve opens and fuel is injected. When the pressure of the fuel goes down, the valve is closed by the force of the spring.

- The holes in the single-hole nozzle and multiple hole nozzle have an diameter of 0.2 - 0.5 mm. On the pintle nozzle and throttle nozzle, the tip of the needle pin sticks out from the nozzle and the spray spreads out conically into the air. Therefore, even if the injection pressure is low, the dispersion is good. Particularly with the throttle nozzle, the amount of initial injection is contracted, so the amount of injection in the firing lag period is small and diesel knock can be reduced.

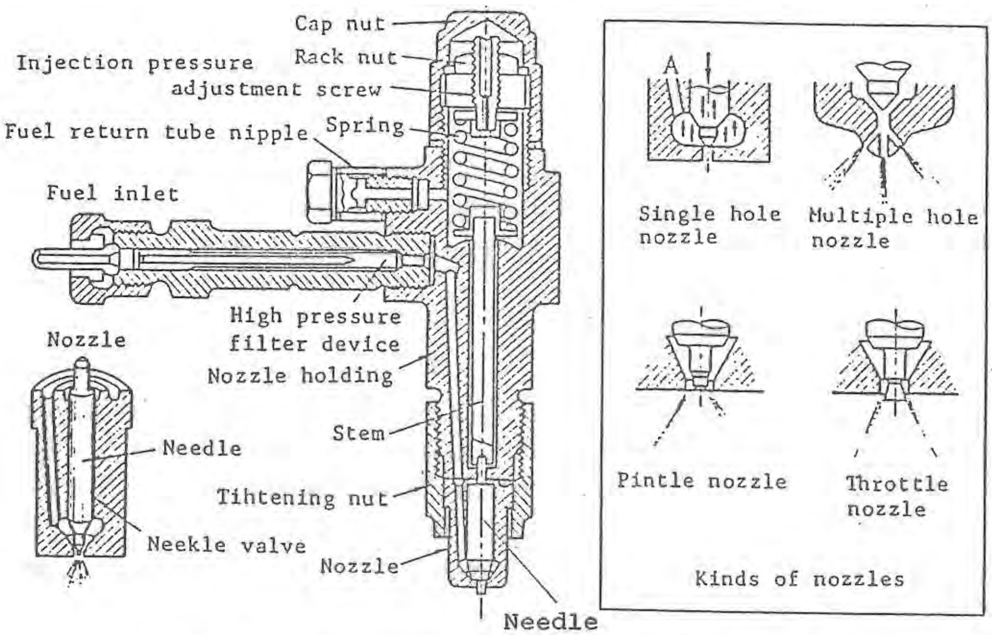


Fig. 4-44 Structure of Fuel Injection Valves

4.4 Fuels and Combustion in Diesel Engines

(1) Fuels for diesel engines

Generally, light oil is used for high speed diesel engines and heavy oil for medium and low speed engines. The fuel must have a good ignitability, a suitable viscosity, and few impurities which will cause corrosion.

(2) Combustion inside the cylinders

The air pressure at the end of the compression stroke in a diesel engine is 30-55 kgf/cm^2 and the temperature, which is increased by the heat from the walls of the combustion chamber and residual gas, is 500° - $700^{\circ}C$. The fuel injected into these cylinders is made into a fine spray and mixed with air. Ignition begins from that portion of the mixture which has reached the suitable level of fuel-air mixture and the pressure and temperature increase.

Looking at the combustion process of high speed diesel engines from the relationship between crank angle and pressure, as shown in Fig. 4-45, the following can be considered.

1) Ignition lag time

Fuel injection begins at point A and the fuel spray is heated by the compressed air inside the cylinder. The temperature of fuel approaches the ignition temperature, but combustion does not occur. In other words, up to point B the pressure curve is followed but only the pressure increases.

2) Explosive combustion timing

Ignition occurs at point B and most of the injected fuel burns at a constant volume, therefore between B and C the pressure inside the cylinders increases rapidly.

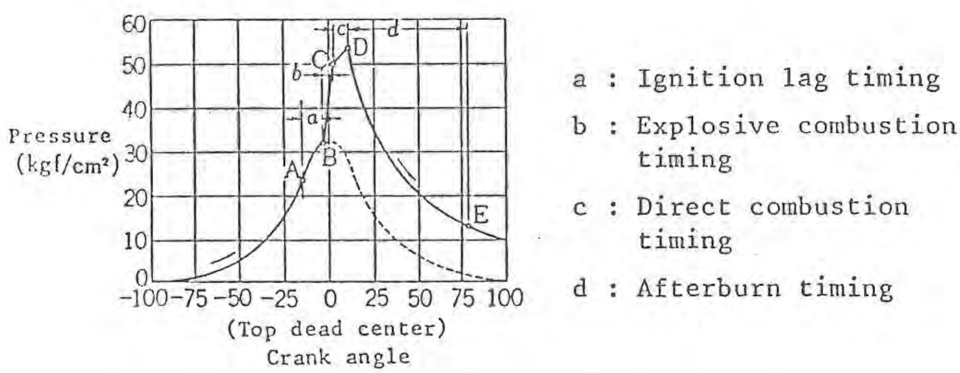


Fig. 4-45 Combustion Process in Diesel Engines

3) Direct combustion period

The injection of fuel continues even if point C is passed, and the injected fuel is consumed immediately.

The temperature in the cylinders is extremely high, virtually constant fuel consumption continues, and injection stops at point D.

4) After-burn period

The small amount of fuel which remains unburned when injection ends at point D continues to be consumed in the period up to point E. However, the combustion during this period only results in a higher exhaust temperature.

If the fuel-injection timing is too early, as shown by (1) in Fig. 4-46, the pressure will become too high but the output will not increase; if the timing is too late, as shown by (3) in the figure, there will be a slight increase in pressure, combustion will continue until near the end of the expansion stroke, and the output will decline.

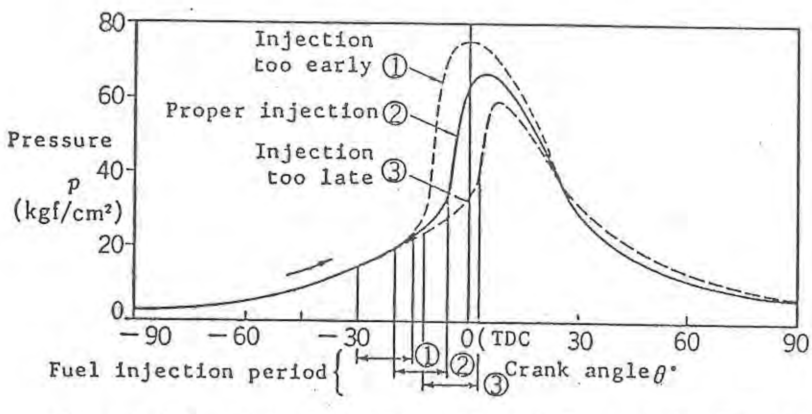


Fig. 4-46 Injection Period and Change in Pressure

(3) Diesel knocking

Knocking also occurs in diesel engines when the injected fuel accumulates during the ignition lag period and burns for a brief time. It occurs because the ignition lag period becomes longer and the pressure rise ratio increases extremely rapidly.

The effective ways to prevent diesel knocking are (1) to use a fuel which ignites easily, (2) to increase the compression pressure of the air and shorten the ignition lag to improve the injection timing and spray conditions, (3) to increase the temperature of the cooling water and the combustion chamber walls, and (4) to increase the disturbances in the flow of air in the combustion chamber.

(4) Cetane value

The cetane value is used to express in quantitative terms the ignitability of a diesel engine. The higher the cetane value of a fuel, the less likely it is to cause knocking.

- The cetane value for cetane ($C_{16}H_{34}$), whose ignitability is good, is set at 100 while the cetane value for alpha-methyl cetane ($C_{10}H_7$ (CH_3)), whose ignitability is poor, is set at zero. When these two fuels are mixed in a suitable proportion, the ratio by volume of cetane will represent the cetane value of this mixture. This is taken as the standard fuel, and a fuel whose ignitability is to be checked is compared to this standard fuel. When the ignitability of the two fuels is the same, the cetane number of the specimen fuel is determined to be the same as that of the standard fuel.

4.5 Increasing Engine Output through Supercharging

If an extra amount of air is sucked into the cylinders, it will be possible to ignite a correspondingly greater amount of fuel and thereby increase the engine output. The action of forcing additional air into the cylinders with a special compressor is called supercharging, and the compressor used is called a supercharger.

In gasoline engines, supercharging often causes knocking or pre-ignition, however, it becomes popular recently and for that reason is not used so widely. In diesel engines, however, an increase in the pressure of inhaled air is advantageous for combustion, so nowadays superchargers are used on most large and medium-sized high performance diesel engines. The use of a supercharger makes it possible to increase the output of an engine by 20-100%.

4.6 Comparison of Diesel Engines and Gasoline Engines

Diesel engines have the following major differences between the gasoline engines.

1) The fuel expenses can be kept lower because the thermal efficiency is better. Therefore, the fuel consumption ratio[1/] is low and operating expenses can be kept down.

2) The maximum speed of engine rotation is low, so the output per cylinder volume is low. However, the fluctuation in torque for the engine rpm is low, and relatively high torque can be obtained at low engine speeds.

1/ See pages 70-71

3) Structurally speaking, there is no need for a carburetor or ignition system in a diesel engine, so the frequency of breakdowns can be reduced. However, a fuel injection pump and injection valves are needed to inject the fuel at high pressure.

4) Because the explosion pressure is high, the structure of the engine must be sturdy. Thus, to make engines with the same output, a diesel engine will be heavier and more costly to produce than a gasoline engine.

5) A diesel engine generates slightly more noise and vibration when it is running.

Questions

1. For gasoline engines, the two-cycle system is used only in small engines whereas in diesel engines it is used widely on all sizes of engines. Why?

2. Describe the different causes for knocking in gasoline engines and diesel engines. How can knocking be prevented in each kind of engine?

3. Why is a supercharger often used on diesel engine?

4. Classify the different types of combustion chambers used in diesel engines and compare their advantages and disadvantages.

5. What is the difference between octane number and cetane value?

5. Rotary Piston Engines

A new kind of internal combustion engine for automobiles attracting attention is the rotary piston engine. This type of engine works on the same principle as that of a reciprocating piston engine, but has a completely different mechanism in which the main shaft obtains rotary motion from the rotary motion of rotors.

5.1 Principle of Operation of Rotary Piston Engines

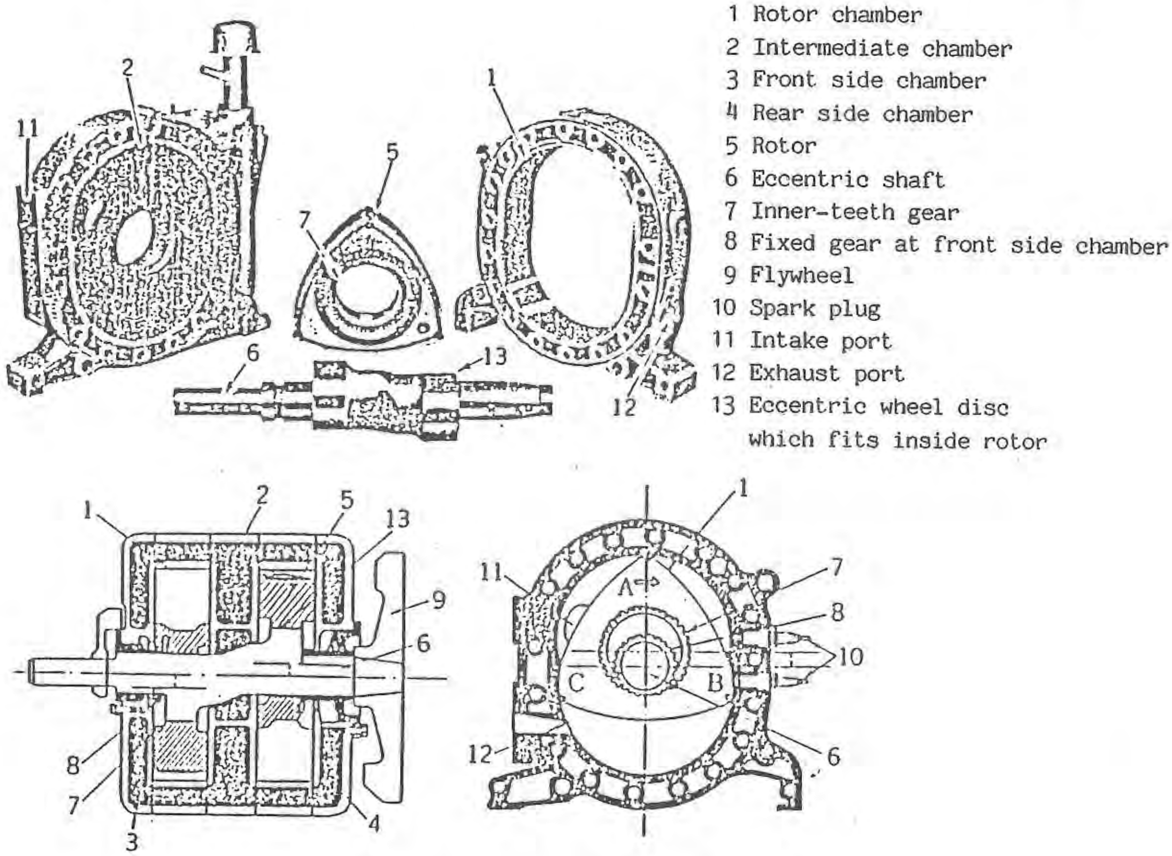
As shown in Fig. 4-47, a rotary piston engine[1/] is an engine in which all stages from air intake through exhaust are driven by the rotation of a central rotor. If compared to a reciprocating engine, the outer casing corresponds to the cylinders and the rotor responds to the pistons.

- The actuation chambers are formed between the rotor and inner wall of the rotor chamber and are sealed tight by the apex seals fitted to the three apexes (A, B, C) of the rotor, thereby creating three independent actuation chambers.

In part (a) of Fig. 4-47, the eccentric shaft serves as the output shaft and the eccentric wheel portion of the eccentric shaft supports the rotor. The external-teeth gear fixed to the side chamber meshes with the internal-teeth gear installed on the rotor, and they build or form a peritrochoid phase gear with a transmission ratio of i = 2:3. For this reason, while the rotor rotates on its own axis on the eccentric wheel along with

1/ The rotary engine was studied for a long time before it was made practical. The rotary engine now in use was developed in 1959 out of the successful experiments of Felix Wankel of West Germany, and thus it is also called a Wankel engine.

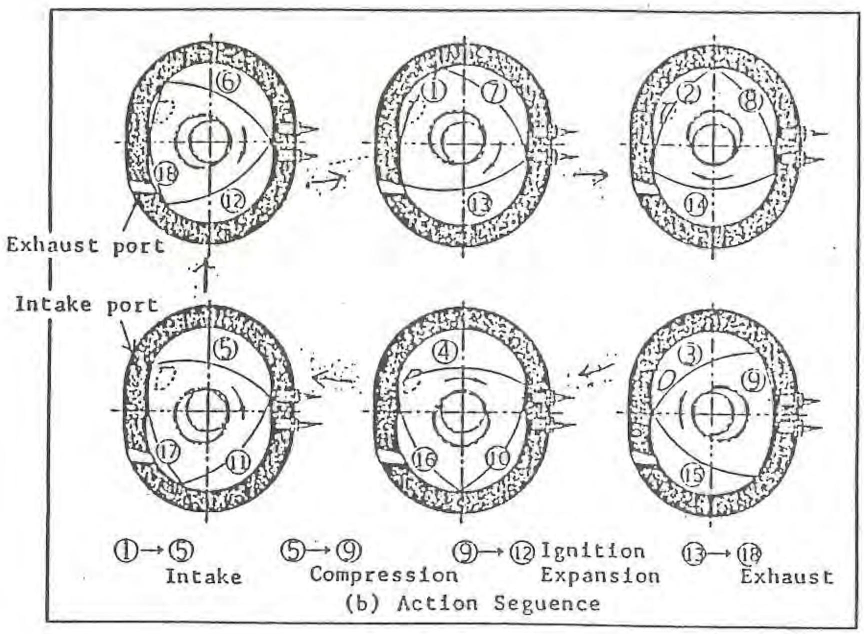
the rotation of the eccentric axis, it also revolves around the center of the eccentric axis. In the time that it takes for the rotor to make one revolution, the output shaft makes three* revolutions. In addition, the three peaks of the rotor slide while maintaining the air-tightness of the inner periphery of the rotor chamber, and during that time actuate the following strokes.

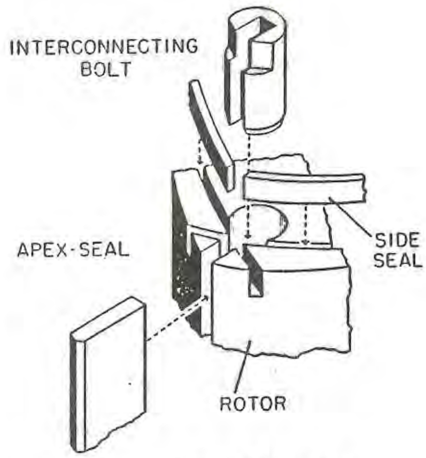


(a) Structure of Main Portion

---

* See page 60 or end of this chapter.





Seals for RC Engine

(b) Action Sequence

Fig. 4-47 Structure and Action of a Rotary Piston Engine

Intake stroke: In the upper left portion of Fig. 4-47(b), the rotor is a top dead center (TDC). When the rotor revolves clockwise, the actuation chamber inhales a fuel-air mixture as in the sequence of ① - ② - ③ - ④, and at position ⑤ reaches bottom dead center (BDC), where the intake stroke ends.

Compression stroke: At the end of the intake stroke, the intake port closes and the compression stroke continues through ⑤ - ⑥ - ⑦ - ⑧. When the rotor is at position ⑨ the fuel-air mixture is under maximum compression.

Expansion stroke: When the fuel-air mixture is ignited by the spark plug at (9), combustion and the expansion stroke continue through (9) - (10) - (11) - (12). In this stroke, the compression of the combustion gas works on the arrow-shaped surface of the rotor and imparts rotary force to the main shaft.

Exhaust stroke: At (13), the exhaust port opens and the exhaust gas is forced out during (13) - (14) - (15) - (16) - (17) - (18).

In a rotary piston engine, these four strokes repeat themselves and they are carried out at each of the three regions of the rotor. The rotor also serves the function of the intake valve and exhaust valve.

Fig. 4-48 shows the overall structure of a rotary piston engine.

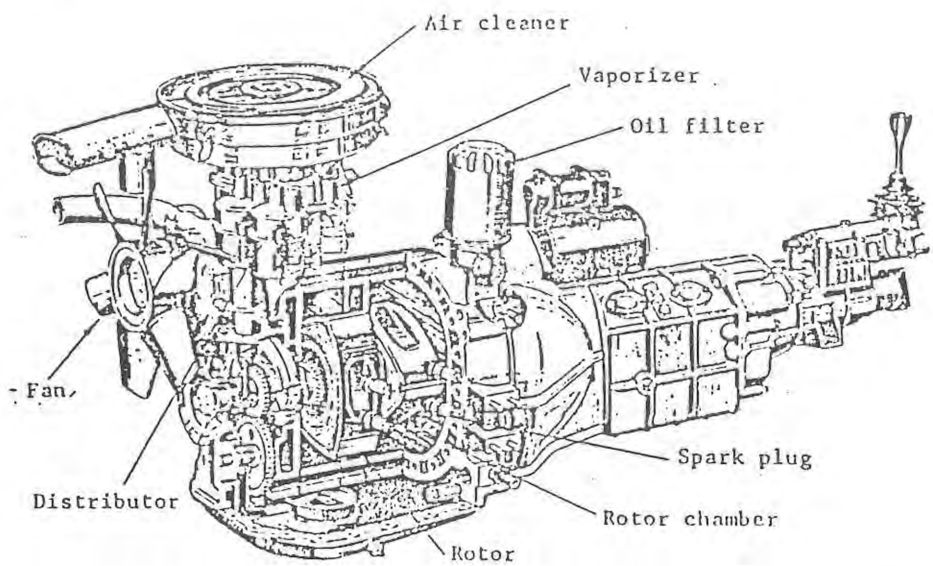


Fig. 4-48 Structure of Rotary Piston Engine

5.2 Features of a Rotary Piston Engine

Compared to a reciprocating piston engine, a rotary piston engine may be considered to have the following advantages.

1) Rotary engines are light-weight and have a simple structure, and because there are fewer moving parts, their durability can be improved. Fig. 4-49 shows a comparison of the weight per unit output of a gasoline rotary piston engine and gasoline reciprocating piston engine.

2) Because the engine is not influenced by a reciprocating inertial force, the allowable rotation speed can be increased.

3) There is little variation in torque.

4) There is little noise and vibration. (See Fig. 4-50)

One drawback, however, is that because the surface area of the combustion chamber is large, there is a lot of heat loss and increased fuel consumption.

Research and development efforts are still being directed at the mode of operation and structure of rotary engines, particularly in the areas of the fuel injection system, diesel system, and multi-stage expansion so that these engines can demonstrate their features even more effectively.

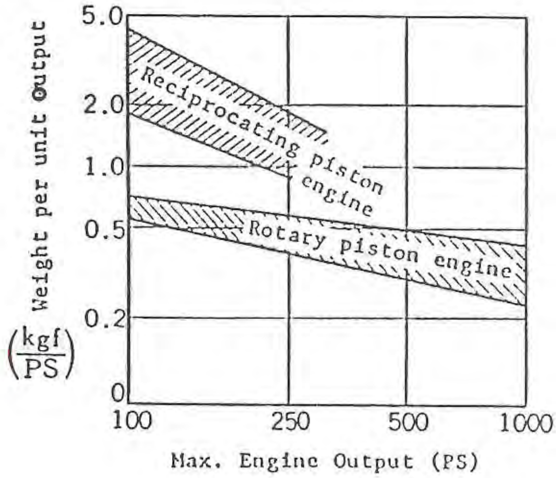


Fig. 4-49 Comparison of Weight per Unit Engine Output

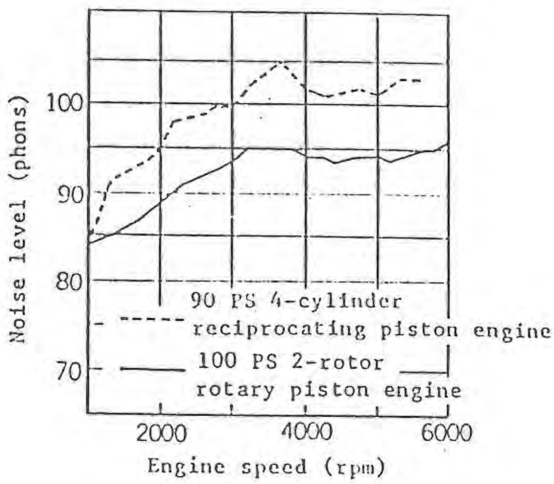


Fig. 4-50 Comparison of Engine Noise Levels (At Full Acceleration)

*In this gear arrangement, analysis of the gear train is made as follows:

Steps	Stationary Fixed Pinion (n)	Internal Rotor Gear (m)	Excentric Wheel (d) or Disc
Excentric wheel (d) locked	Turn pinion (n) one Rev. Anti-clockwise. (-1)	m turn 2/3 Rev. anti-clockwise. (-2/3)	No turn (d). (0)
Gears locked	Turn pinion (n) one Rev. clockwise. (+1)	(m) turns one Rev. clockwise (+1)	(d) turns one Rev. clockwise (+1)
Addition	-1 +1 = 0 Rev.	(-2/3+1)=+1/3 Rev.	0+1 = +1 Rev.

This means that the speed ratio of the Rotor gear to the excentric wheel (crankshaft) is 1 to 3.

6. Performance of Internal Combustion Engines

The performance of an internal combustion engine is expressed in terms of output, torque, fuel consumption ratio, and efficiency. Let us examine these fundamental factors.

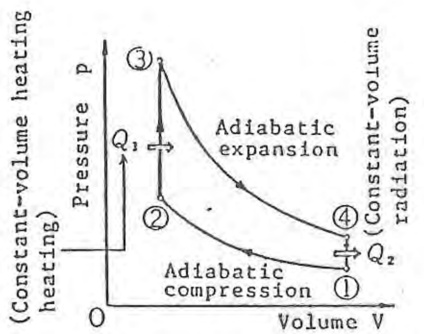
6.1 Basic Cycle and Theoretical Thermal Efficiency

The Carnot cycle, which is considered to be the ideal cycle of a heat engine, cannot be realized in actual engines, but a distinctive theoretical cycle can be considered for each type of heat engine.

Fig. 4-51 shows the theoretical basic cycle for each type of engine: the constant-volume cycle (also called Otto cycle) for gasoline engines, the constant-pressure cycle (Diesel cycle) for low-speed diesel engines, and the constant-volume constant-pressure cycle (Sabathe cycle) for high-speed diesel engines.

- o In the internal combustion engines which have been put into practical use, the working fluid changes its state from unburnt new gas to burnt gas during the cycle, so it makes theoretical considerations difficult. In the basic cycle, if we assume that (1) the working fluid is air, which is regarded as an ideal gas, (2) the combustion and emission of combustion gas are substituted with the heat supplied and with the heat radiated respectively (3) the expansion and compression are adiabatic changes, and (4) the specific heat of the gas is always constant, then the theoretical thermal efficiency can be expressed with the equations shown in the figure.

As shown in Fig. 4-51 (d), in any basic cycle the theoretical thermal efficiency increases as the compression ratio gets higher. Also, for a given compression ratio, the theoretical thermal efficiency is heighest for the constant-volume cycle, and decreases in the following order; the constant-volume, the constant-pressure cycle, and the constant-pressure cycle.



(a) Constant-Volume Cycle

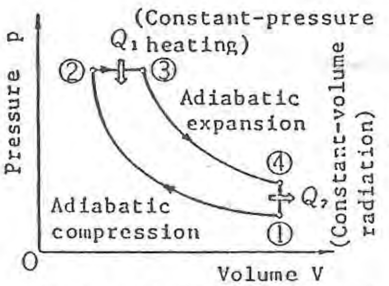
If the temperatures at points 1, 2, 3, and 4 are T_1, T_2, T_3, and T_4,

$$Q_1 = c_v G(T_3 - T_2)$$
$$Q_2 = c_v G(T_4 - T_1)$$
(c_v : Constant-volume specific heat)

Thermal efficiency $\eta_{thv} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{T_4 - T_1}{T_3 - T_2}$

$$= 1 - \frac{1}{\left(\frac{V_1}{V_2}\right)^{\kappa - 1}} \quad (\kappa : \text{Ratio of Specific heat})$$

$$= 1 - \frac{1}{\varepsilon^{\kappa - 1}} \quad \left(\varepsilon = \frac{V_1}{V_2} : \text{Compression ratio}\right)$$



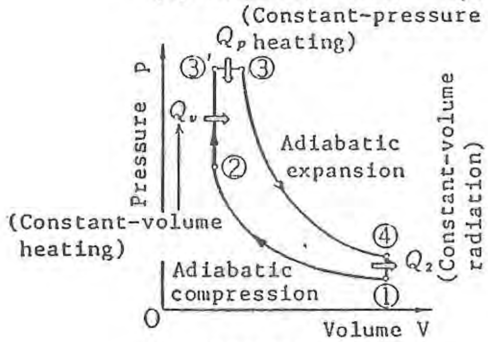
(b) Constant-Pressure Cycle

If the temperatures are determined the same way as in Fig. (a),

$$Q_1 = c_p G(T_3 - T_2)$$
$$Q_2 = c_v G(T_4 - T_1)$$
(c_p : Constant-pressure specific heat)

$$\therefore \eta_{thd} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{c_v}{c_p} \cdot \frac{T_4 - T_1}{T_3 - T_2}$$

$$= 1 - \frac{1}{\varepsilon^{\kappa - 1}} \cdot \frac{\sigma^{\kappa} - 1}{\kappa(\sigma - 1)} \quad \left(\sigma = \frac{V_3}{V_2} : \text{Cut-off ratio}\right)$$



(c) Constant-Volume, Constant-Pressure Cycle

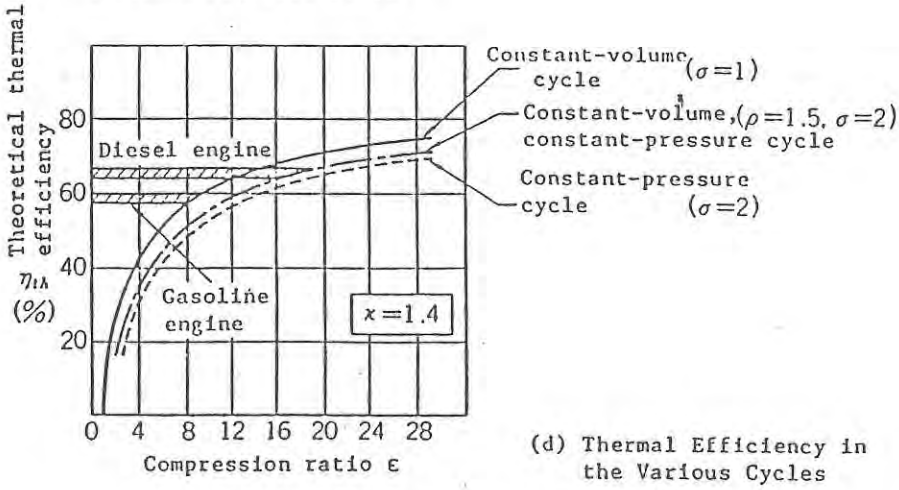
Similarly to Figs. (a) and (b),

$$Q_1 = Q_v + Q_p$$
$$= c_v G(T_3' - T_2) + c_p G(T_3 - T_3')$$
$$Q_2 = c_v G(T_4 - T_1)$$

$$\therefore \eta_{ths} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{c_v(T_4 - T_1)}{c_v(T_3' - T_2) + c_p(T_3 - T_3')}$$

$$= 1 - \frac{1}{\varepsilon^{\kappa - 1}} \cdot \frac{\rho\sigma^{\kappa} - 1}{(\rho - 1) + \kappa\rho(\sigma - 1)}$$

$$\left(\rho = \frac{P_3}{P_2} : \text{Explosion ratio}\right)$$



(d) Thermal Efficiency in the Various Cycles

Fig. 4-51 Basic Cycle and Their Thermal Efficiencies

6.2 Actual Cycles

As an example of a cycle in an actual internal combustion engine, Fig. 4-52 shows an indicator diagram for a four-cycle gasoline engine.

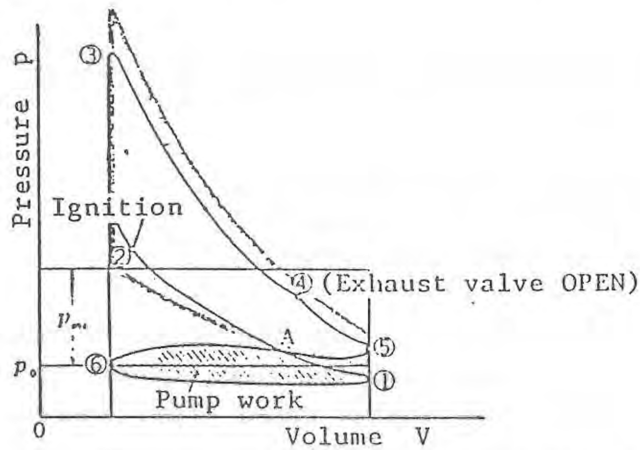


Fig. 4-52 Indicator diagram (Four-Cycle Engine)

In an actual engine, the characteristics of the working fluid change during the cycle and there are various kinds of losses, so consequently the engine's thermal efficiency is lower than the ideal thermal efficiency of the basic cycle.

(1) Kinds of losses

Let us consider the various kinds of losses which occur in an actual engine.

(a) Losses during intake

When an engine intakes a new air, the resistance in the intake pipes and valves causes the pressure of the inhauled air to drop below atmosperic pressure. This new air absorbs heat from the residual gas and cylinder walls, and as a result it rises in temperature and reduces in specific weight.

For this reason the amount of air inhaled into cylinders is less than the amount which is considered to have filled the cylinders under the original atmospheric conditions (absolute pressure p, absolute temperature T). The volumetric efficiency η_V in the following equation is used to express this percentage loss of the amount of intake.

$$\eta_V = \frac{\text{Volume of inhaled new air converted for conditions } (p, T)}{\text{Stroke volume } (V_h)}$$

$$= \frac{\text{Weight of inhaled new air}}{\text{Weight of new air which occupies the stroke volume under conditions } (p, T)}$$

- Generally, in the same kinds of engines whose cylinders have the same volume, the output at the same engine speed (rpm) increases as the volumetric efficiency becomes higher. To increase the output of an engine, it is necessary to increase the volumetric efficiency, but as the speed of a high-speed engine increases, the air-intake speed also increases causing the resistance of the new intake air to increase significantly and thus reducing the volumetric efficiency.

- Two possible ways to compensate for this are; (1) to increase the cross-sectional area of the intake pipe and manifold and the area of the valves in order to reduce the intake air speed (2) to shape each portion of the system so that the resistance to the flow of the new gas can be reduced.

(b) Loss caused by incomplete combustion

It is difficult to completely burn the fuel in the cylinders. The ratio of the thermal energy which is actually generated in the cylinders to the thermal energy that would be released from the supplied fuel if the combustion were perfect is called the combustion efficiency. Incomplete combustion occurs when there is too little air or when the combustion chamber is poorly shaped so that the air and fuel cannot nix thoroughly.

(c) After-burning

Theoretically, combustion is considered to be completed under constant pressure or constant volume, but this does not happen in actual combustion, in which a part of the combustion continues until near the end of the expansion stroke. The heat generated by the after-burn does not do any work, but merely increases the heat losses resulting in the exhaust temperature-rise.

(d) Heat loss from cylinder walls

The heat from the burning gas passes through the cylinder walls and is absorbed by the cooling water, cooling air, or lubricating oil. As a result, the temperature and pressure of the gas decline and the thermal efficiency drops.

(e) Exhaust loss

For structural reasons, piston engines cannot cause all of the gas in the cylinders to be expanded to the atmosphere. Moreover, in actual practice the exhaust valve opens at point (4) in Fig. 4-52, the pressure and temperature remain high, and the remaining combustion gas which has the ability to do work is released into the atmosphere. This is called exhaust loss.

(f) Pumping loss

In the exhaust stroke, because there is some resistance in the exhaust pipe and muffler, some work is must be done to push out the exhaust gas by using a pressure that is a little higher than the external pressure. When this work is added to the work of the suction stroke, this is called pump work, and the losses are called pumping losses.

(g) Mechanical loss

The loss which occurs due to the friction between shafts and bearings and between pistons and cylinders as well as the work done to drive the water pump, lubrication pump and other auxiliary devices needed to run the engine are called mechanical losses.

(2) Output and mean effective pressure

The output of piston engines is obtained from the pressure of the combustion gas acting on the pistons. The pressure acting on the pistons differs according to the position of the pistons, so if we consider the average value through all the expansion stroke, the portion of this value which does effective work is called the mean effective pressure.

The mean effective pressure found an indicator diagram is called the indicated mean effective pressure. In Fig. 4-52, the area left by subtracting area A 6 1 A representing the pump work from area A 2 3 4 5 A is converted into the area of the rectangle whose side corresponds to one stroke. Then the height of that rectangle indicates the mean effective pressure (Pi).

The output found from the indicated mean effective stroke is called the indicated output. If the indicated mean effective pressure is P_{mi} (kgf/cm^2) and the stroke volume is V_h (cm^3), indicated output N_i (kW) can be found from the following equation.

$$N_i = \frac{p_{mi} V_h z}{102 \times 100} \cdot \frac{na}{60} = \frac{p_{mi} \frac{\pi}{4} D^2 S z n a}{102 \times 60 \times 100} \qquad (4-29)^{1/}$$

D : Cylinder diameter

S : Stroke

z : No. of cylinders

n : Engine speed (rpm)

a : the inverse ratio of the rpm needed to complete one cycle (in a 4-cycle engine, a=1/2; in a 2-cycle engine, a=1)

The subtraction of the mechanical losses from the indicated output is the actual power available from the output shaft, and this is called the brake power. If the mechanical efficiency is η_m the brake horse power N_e is expressed by the following equation.

$$N_e = \eta_m N_i \qquad (4-30)$$

The mean effective pressure found from the brake power is called the brake mean effective pressure. When the brake mean effective pressure is P_{me}, its relationship with P_{mi} can be shown by the following equation.

$$p_{me} = \eta_m p_{mi}$$

The brake horse power can be measured with a dynamometer.

1/ To find N_i in terms of horsepower (PS), substitute 102 in the denominator with 75.

Ex. 1. What is the brake power (kW) of a 4-cycle gasoline engine with the following specifications?

Indicated mean effective pressure	: 12 kgf/cm^2
Cylinder (No. - Bore x Stroke)	: 4-75 mm x 80 mm
Engine speed	: 6,000 rpm
Mechanical efficiency	: 85%

(Solution)

If $\eta_m = 85$, $P_{mi} = 12$, $D = 7.5$, $S = 8$, $z = 4$, $n = 6{,}000$, and $a = 1/2$ in Equations 4-29 and 4-30,

$$N_e = \eta_m N_i$$

$$= 0.85 \times \frac{12 \times \frac{\pi}{4} \times 7.5^2 \times 8 \times 4 \times 6{,}000 \times \frac{1}{2}}{102 \times 60 \times 100} \fallingdotseq 71(kW)$$

(Answer: 71 kW)

$\because$ 1 kW = 102 kgf.m/s (PS) = 71 kW x $\frac{102}{75}$ = 71 kW
 1 PS = 75 kgf.m/s = 1.36 PS = 96.56 PS.

Q. 1. What is the brake power (kW) of a cargo-use 4-cycle diesel engine which has an indicated mean effective pressure of 10 kgf/cm^2, four cylinders (Bore 80 mm x stroke 96 mm), and an engine speed of 3,000 rpm? Assume that the mechanical efficiency is 82% (Ans, 38.8 kW).

(3) Engine torque

The pressure of the combustion gas acting on the pistons which exerts on the crankshaft produces a moment which tries to turn the crankshaft. This moment is called engine torque or output torque. If the engine torque is represented by T (kgf.m), the brake horse power can be found from the following equation.

$$N_e = \frac{2\pi n T}{60 \times 102} \text{(kW)} \quad (4-31)$$

n : Engine Speed (rpm)

As shown in Fig. 4-53, the torque produced by the pressure of the combustion gas fluctuates greatly according to the angle of rotation of the crank, so usually a flywheel with a large inertia force is installed. The flywheel acts to smooth the rotation by accelerating during the expansion stroke to absorb the turning force and decelerating during the other strokes to release the turning force.

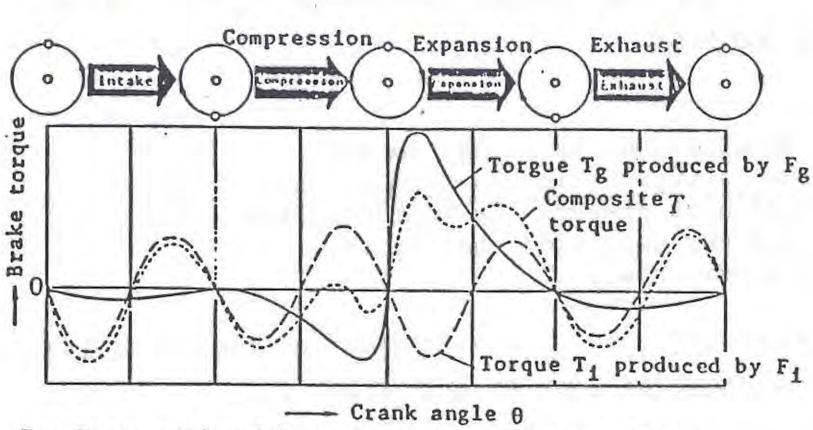


Fig. 4-53 Fluctuation in Engine Torque
(For 4-Cycle Single-Cylinder Engine)

Ext. 2. When Measured with a dynamometer, the brake power of a small gasoline engine for automobiles was shown to be 62 PS when the engine speed was 4,500 rpm. What is the brake torque (kgf.m) at this time?

(Solution) From Equation 4-31,

$$T = \frac{60 \times 75 \times N.}{2\pi n}$$

$$= \frac{60 \times 75 \times 62}{2\pi \times 4{,}500} \fallingdotseq 9.87 \text{ (kgf·m)}$$

(Answer: 9.87 kgf.m)

Q. 2. Find the brake power of an automobile engine when the maximum brake torque is 15.6 kgf.m and engine speed is 3,200 rpm.

(Answer: 69.7 PS)

(4) Net thermal efficiency

The net thermal efficiency η_e is expressed by the following equation.

$$\eta_e = \frac{\text{Value of work done by engine in unit time when expressed in the form of heat}}{\text{Amount of heat produced by fuel supplied to engine per unit time when it is consumed completely}} = \frac{102 N_e A}{B H_1} \quad (4\text{-}32)$$

Ne: Brake power (kW)   B : Amount of fuel consumed (kgf/s)

A : Equivalent heat of work (kcal/kgf.m)

H_1: Amount of heat generated by fuel (kcal/kgf)

Generally, the economy of an internal combustion engine is expressed by the amount of fuel consumed per hour for a brake power of 1 PS rather than by the thermal efficiency. This is called the fuel consumption ratio, and is expressed by the following equation.

$$f_e = \frac{B \times 10^3 \times 3\,600}{N_e} \ (\text{gf/PS} \cdot \text{h}) \qquad (4-33)$$

Ex. 3. Work out the relationship between η_e and f_e.

(Solution)

When (B/N_e) is canceled out from Equations 4-32 and 4-33,

$$\eta_e = \frac{10^3 \times 3\,600}{f_e} \times \frac{75 \times A}{H_l} = \frac{632.3 \times 10^3}{f_e H_l}$$

Q. 3. The fuel consumption rate of a certain internal combustion engine is 195 gf/PS.h. Find the net thermal efficiency. Assume that H_1 = 10,400 kcal/kgf.

(Answer: 31.1%)

(5) Heat balance

Of the heat produced when the fuel in an internal combustion engine is completely consumed, approximately 25-35% is converted into effective work while the remaining 65-75% goes into exhaust loss, cooling loss, and mechanical loss.

Fig. 4-54 gives an example of the heat balance in an automobile engine.

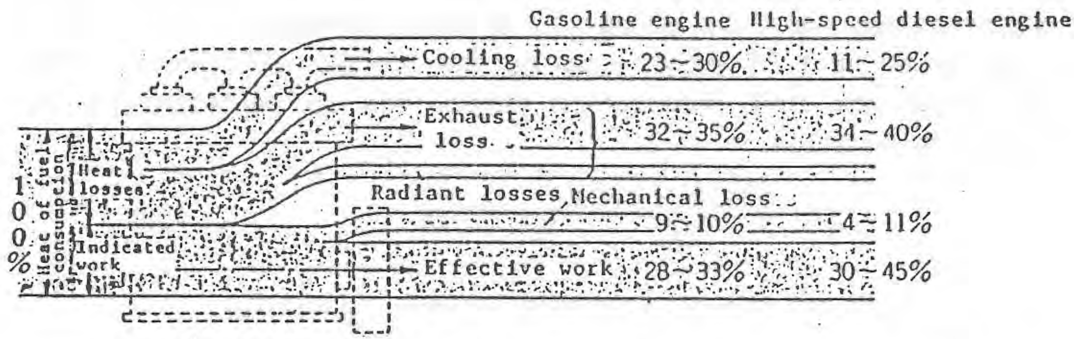


Fig. 4-54 Example of Heat Balance in Automobile Engines

6.3 Performance Tests for Internal Combustion Engines

There are various methods for conducting performance tests on internal combustion engines, depending on the kind of engine and the purpose of the test. The oridinary load test is specified by JIS.

A load test measures the output and fuel consumption rat under the various operating conditions in which the engine will be used.

Besides load tests, there are also endurance tests to test reliability and durability, high altitude tests for airplane engines, and various special tests for research purposes.

Fig. 4-55 gives an example of a performance curve which shows the results of a performance test on an engine which, unlike automobile engines, does not run at a constant speed.

The items which must usually be measured or checked in a performance test are shown in Table 4-4.

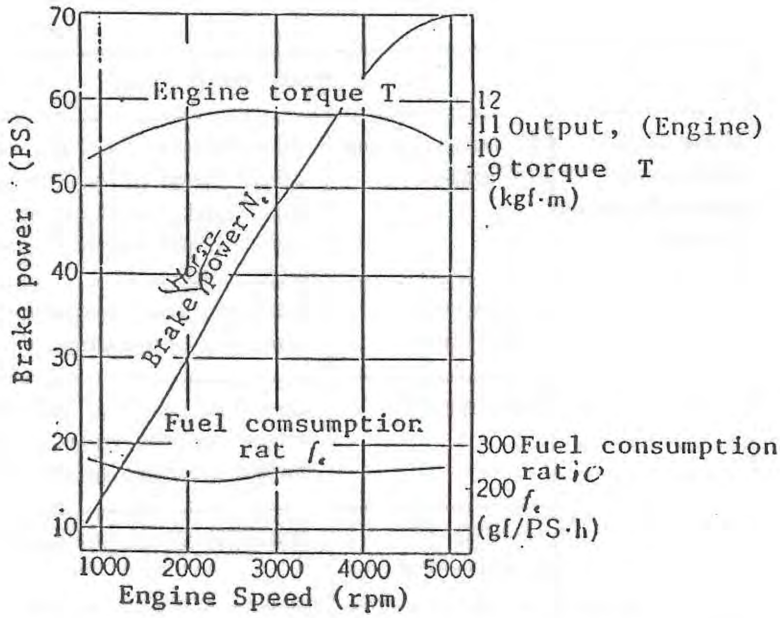


Fig. 4-55 Example of Performance Curve

Table 4-4 Items Measured in Performance Tests

	Measurement Items	
Items to be checked or measured before the test	Principal items in engine	Bore, stroke, and no. of cylinders; range of engine speeds; shape and structure of vaporizer or fuel injection system
	Atmospheric conditions	Weather, room temperature, humidity, atmospheric pressure
	Fuel quality	Specific gravity, calorific value, octane value, cetane number, distillation test
	Quality of lubricating oil	Specific gravity, viscosity
Items to be measured at specific points during the test	Items which must be measured	Dynamometer load, engine speed, amount of fuel consumption, temp. and pressure of lubricating oil, temp. at inlet and outlet for cooling water, degree of opening of throttle valve for vaporizer or injection pump
	Measurements taken for reference	Indicator curve, spark or injection timing, temp. and pressure of exhaust gas, constituents of exhaust gas (gas analysis and measurement of smoke density)
	Measurements taken for records	Knocking condition; vibration and noise; leakage of gas, oil, or water; battery charge
Measurements taken after operation		Amount of consumption of lubrication oil (for full running time), inspection of various points (loosen belts abnormalities, etc.)

Questions ———————————————— ◎

1. Give a brief description of the following terms and indicate the relationship between them: mechanical losses, mechanical efficiency, indicated power, brake power, net thermal efficiency, brake mean effective pressure, indicated mean effective pressure.

2. The net thermal efficiency of a diesel engine using a fuel which has a calorific value of 10,400 kcal/kgf is 34%. Find the fuel consumption rate.

(Answer: 179 gf/PS.H)

3. The fuel consumption of a 2-cycle diesel engine with a brake horse power of 10,000 PS, an engine speed of 120 rpm, and nine cylinders (cylinder bore; 750 mm, stroke: 1,500 mm) is 1,720 kgf per hour. The engine runs on heavy oil which has a calorific value of 10,200 kcal/kgf. Find the brake mean effective pressure, the fuel consumption ratio, and the net thermal efficiency. Also, when a supercharger is used to increase the brake horse power of this engine to 12,000 PS and the fuel consumption rate becomes 1,860 kgf per hour, how does its performance change?

(Answer: P_{me}: 6.3 kgf/cm^2, 172 gf/PS.H, 36%)

P_{me}: 1.2 kg.f/cm increased, 17 gf/PS.H reduced
3.2 to increased,

7. Gas turbine and Jet Propulsion Engines

In internal combustion engine, besides piston type engine like gasoline engine or diesel engine, there are other types of engines such as gas turbines in which the combustion gases generated by ignition of fuel drives the turbine blades, or jet or rocket engines that utilize the reaction force of the combustion gases's to propel the vehicles.

7.1 Working principles of gas turbine

Gas turbine is a prime mover that drives the turbine by using the high temperature high pressure combustion gases to obtain a turning force.

In piston engines, the strokes such as intake, compression, combustion or power, and exhaust are performed in the inside of the same cylinder, while, in gas turbine, as shown in a Fig 4-56. The combustion gases are produced through the equipment such as compressor, and combustor, and the gases enable the turbine to drive.

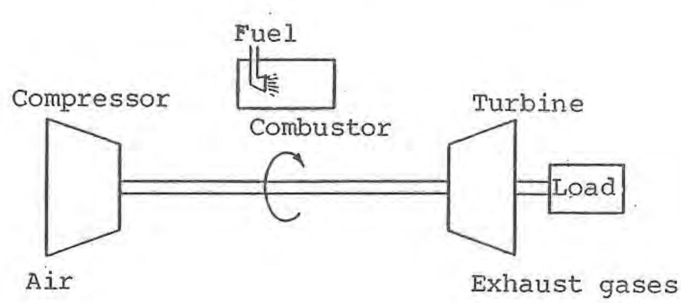


Fig. 4-56 Gas turbine cycle

Air enters the compressor through an inlet in which the pressure is raised, and from which it is delivered to the combustor. In the combustor, the fuel which is sprayed from the fuel injection nozzle is mixed with the compressed air and is ignited and thereby the constant-pressure combustion occurs. And this combustion gas expand and enable the turbine wheel to drive, resulting in the generation of power.

Fig 4-56 shows the cycle of the gas turbine. The gas turbines feature simpler construction with small number of the parts compared with the piston-type engine, absence of vibration, and speed fluctuation due to minimum torque changes.

And also the turbines have advantages in minimum consumption of lubricating-oil, in using low-quality liquid fuel or gas fuel in comparison with that of gasoline.

However, the gas turbines are required to use higher grade heat resistant steel and to equip with a large size of reduction gear equipment.

The thermal efficiency of the gas turbines can be attained about 30%, this value is not exceeding the efficiency of the high performances of steam prime movers and diesel engines. The output of the turbines ranges from several tens to (several) ten of thousands horsepower for generator drive, it has wide applications. There are two main cycles or types of air applications used in gas turbine engine. Fig 4-56 shows the open cycle type of the turbinein which the combustion gas whose the energy is converted into work is exhausted into atmosphere. On the contrary, the working fluids such as air, helium gas are expanded in a turbine and they are cooled and then fed into the compressor without exhausting the gas into open atmosphere, thus they are recircled repeatedly. Such a type is called closed cycle gas turbine.

Fig 4-57 shows the a closed cycle gas turbine type. This type is equipped with a heater in which the working fluid is preheated indirectly.

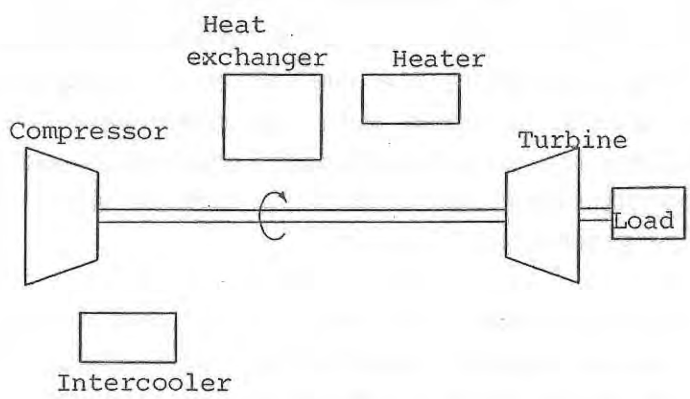


Fig 4-57 Closed cycle gas turbine

7.2 Main Construction of Gas turbine

(1) Compressor

Two basic types of compressors, are used in gas turbines; axial and centrifugal. The centrifugal type compressor is suitable for the relatively small type gas turbine because large pressure ratio can be easily obtained with one stage.

Axial flow compressor has complex construction and the pressure rise per stage is small, therefore, the usual axial-flow compressor is necessary to equip much stages in line to attain the same pressure level. Therefore, multistage axial compressor becomes relatively large in its size, however, its efficiency usually runs higher, as it is suitable for the large size turbine engines.

Fig 4-58 shows turbine wheels for axial-flow compressor, turbine and rotor for air compressor

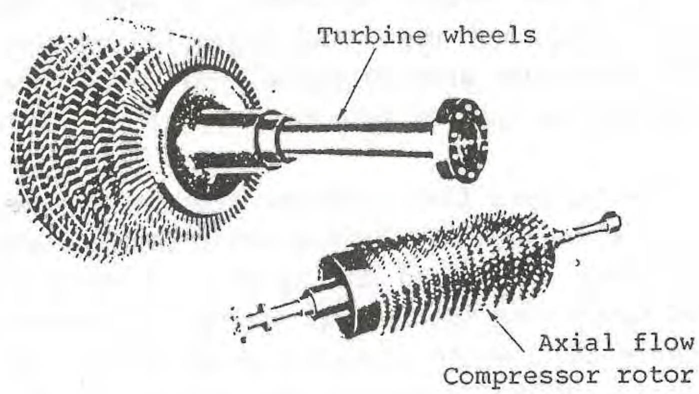


Fig. 4-58 Turbine wheel and compressor rotor

(2) Combustor

The combustor, as shown in Fig 4-59, contains a fuel injection nozzle to inject the fuel into compressed air flow and makes continuous combustion of fuel.

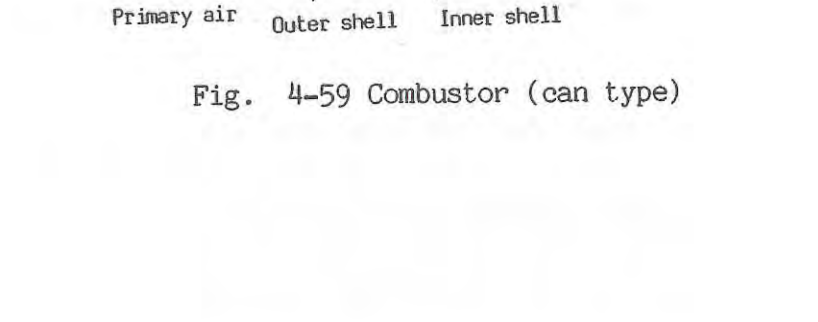


Fig. 4-59 Combustor (can type)

It forms double cylinder, a outer shell and a perforated inner shell and has a fuel injection nozzle. The fuel is delivered by the pump with 20 kg/cm^2- 50 kg/cm^2 pressure into the fuel nozzle and is sprayed into the inner shell to be ignited.

The sprayed fuel is mixed with the necessary amount of air for combustion which is introduced from the forward end of the inner shell and is ignited and burned. Another part of the air introduced flows into the annular passage and passes gradually through the inner shell while cooling the surface of the shell and then it is mixed with the combustion gas, thereby causing the combustion gas's temperature to decrease up to a specified level.

In the gas turbine engines which are used for the power station, they may have such large type combustors as many as 1-10.

In jet engine a small type combustor is used in plural forms, or an annular type combustor is used.

In general kerosene or light oil is used for gas turbines however sometimes natural gases, or refinery gases are used as well.

(3) Turbine

The turbine flades in a gas turbine encounter extremely high temperature combustion gases ranging 700 to 900^{o}c, the material used for the blades is required high-heat resistant property.

In a small gas turbines, the radial-inflow turbine (See Fig. 4-60) is commonly used. In this type, the combustion gas flows from the outer nozzle into the rotor blades in a radial, direction and the gas turns the direction of flow at 90^{o} (degree) angle and flows out in the direction of parallel to the rotor shaft.

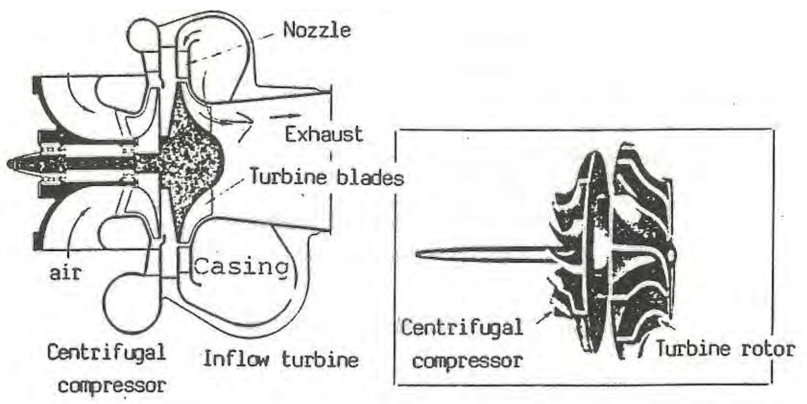


Fig. 4-60 Small radial inflow turbine

7.3 Cycles of gas turbine

(1) Theoretical cycle

It is common practice, to analyze the Brayton cycle as follows by assuming that;

(1) The working fluid is air and no losses occur anywhere.

(2) The compression and expansion processes should be performed adiabatically.

(3) The heat transfer occurs in the constant pressure processes.

This is basic cycle for gas turbine engines with constant combustion processes.

Fig 4-61 shows the Brayton cyle's P-V diagram.

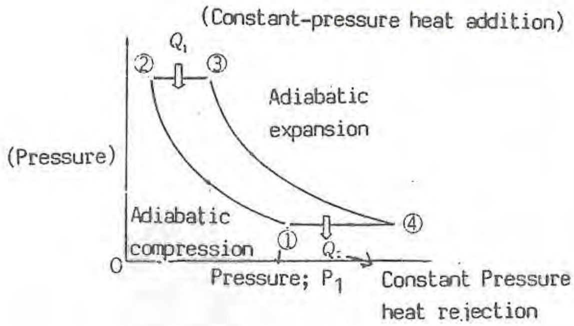


Fig 4-61 Brayton cycle

If the temperatures at points ①, ②, ③, and ④ are T1, T2, T3, and T4.

$$Q_1 = C_p \cdot G \ (T3 - T2)$$
$$Q_2 = C_p \ G \ (T4 - T1)$$

$$\therefore \eta \ th = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{T4-T1}{T3-T2} = 1 \frac{1}{\left(\frac{p2}{p1}\right)^{\frac{x-1}{x}}}$$

x = ratio of specific heat

(2) Actual cycle

In practical gas turbine, unlike the Brayton cycle, there are in a lot of losses such as compression loss, turbine loss, combustor loss due to incomplete combustion, combustion gas pressure loss in passages, and moreover there are gas leakage loss, external heat dissipation loss, power loss caused by drive of auxiliary machinery including fuel pump, etc.

As a result, the actual thermal efficiency is remarkably lowered. To increase the thermal efficiency, the intercooled reheat-regenerative cycle systems with a heatex-changer, a intercooler, and reheater have widely adopted.

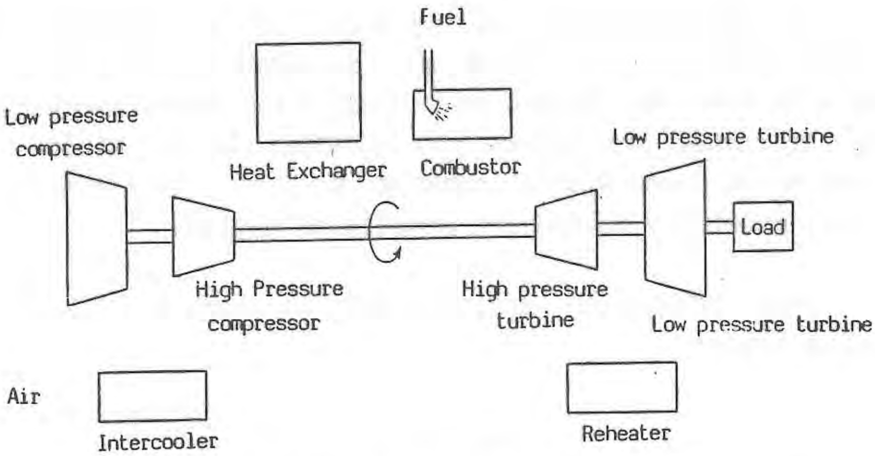


Fig. 4-62 Intercooled reheat-regenerative cycle

In actual gas turbines, it is common practice to arrange the compressors and turbines in many stages, as shown in Fig 4-62.

These arrangements are designed to combine the equipment according to the purpose and application of the turbines.

To improve efficiency of gas turbine it is necessary that, the combustion gas temperature at turbine inlet be maintained as possible as high in combination with the large pressure ratio. (In Fig 4-61 the pressure ratio is indicated pressure ratio by $p^2/p1$).

7.4 Jet propulsion engines

Jet propulsion is based on the principle creating an reaction force by exhusting gases ejected from the jet nozzle. The reaction force, is called thrust and is produced in a jet propulsion engine propelling the vehicles.

In general there are two types of jet engines, one is jet propulsion type whose the air is admitted from its front mixing with fuel and jetted their combustion gases rearward, the another is rocket propulsion type in which the propellant ejects the combustion gases without sucking the air. The former type of engine is generally called jet propulsion engine.

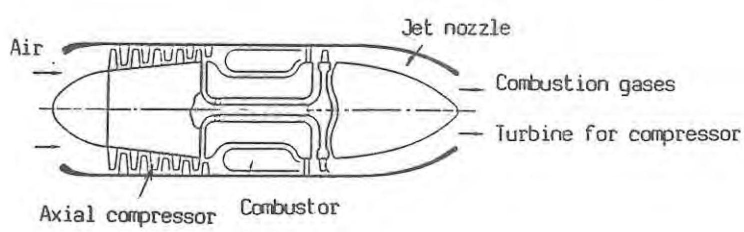
Jet propulsion engines can be classified into the following types:

- Jet propulsion engine
  - Jet propulsion
    - Turbojet engine
    - Turboprop engine
    - Ramjet engine
    - Pulsejet engine
  - Rocket propulsion - Rocket engine

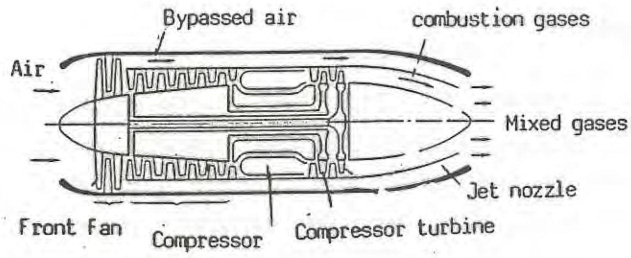
(1) Turbojet engines and Turbo-prop engine. (Fig 4-63)

As is shown in Fig 4-63(a) the engine that utilizes the gas turbine to make the ejection gases is called turbojet engine and used in high speed aircraft.

Fig 4-63(b) shows the engines that part of the air of the compressor is mixed with each other before passing the jet nozzle without guiding that air into combustor. This type of engine is called by-pass jet engine and is suitable for the operation relatively lower speed aircraft than that of turbojet engine.



(a) Turbojet engine



(b) By-pass jet engine

Fig. 4-63 Turbojet Section

At first, air enters from the front fan, and it is compressed by the compressor, the compressed air leaving compressor flows through the combustor where liquid fuel is ignited continuously making a high temperature combustion gasses. The combustion gases drives the compressor's turbine blades, and then the combustion gases and mixed air gases are ejected at high speed. The pressurized combustion gases cause the reaction force (thrust)to propel the engine forward.

Fig 4-64 shows a turbojet engine. The outer casing of the combustor forms annular shape. The fuel supply is designed to provide vapour by the evaporator pipe which is installed inside the combustor.

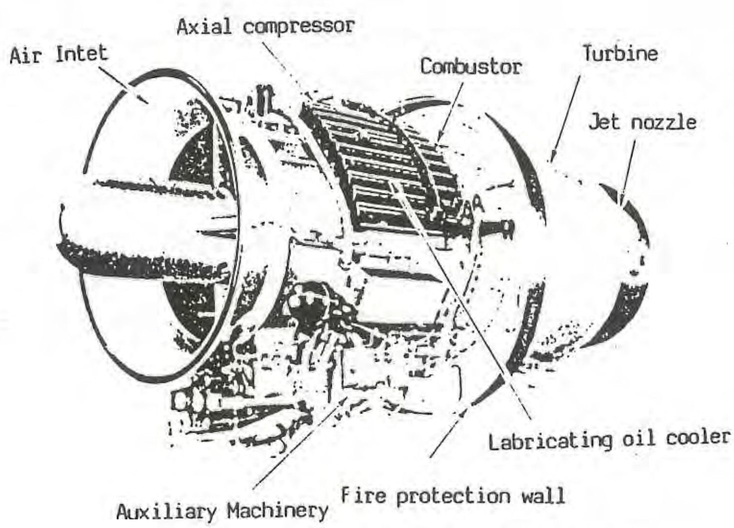


Fig. 4-64 Turbojet Engine

Turboprop engine

As is shown in Fig 4-65, the turboprop engine is equipped with multi-stepped turbine blades converting the combustion gas energy into both the turning forces of the propeller and the thrust produced by the exhaust gases as they escape through the rear of the engine. This engines are primarily being used in intermediate size aircraft, because they develop better efficiency (performance) at middle speed, and moderate altitudes.

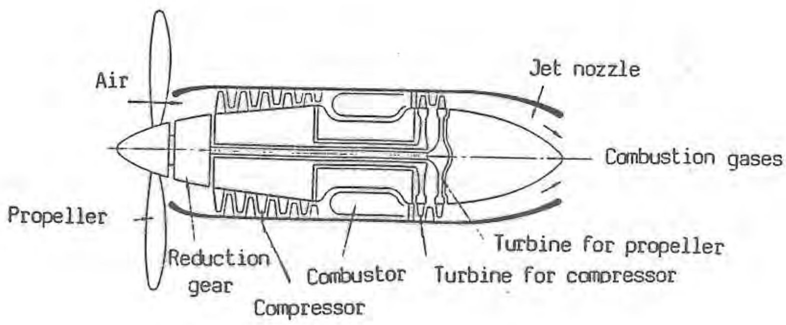


Fig. 4-65 Turboprop engine section.

(2) Ramjet and Pulsejet

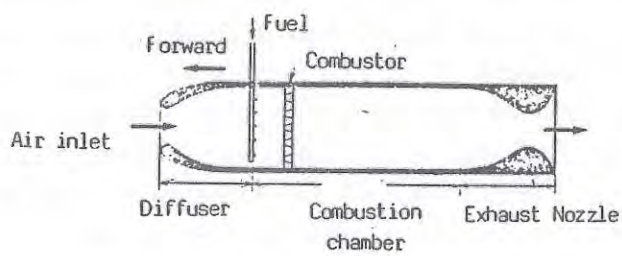
When the cruising speed of the engine becomes high such as supersonic level, the air entering into engine is compressed due to its dynamical pressure. This is called Ram effect and its pressure is called Ram-pressure.

The air flowing toward the engine with the super sonic speed, Mach number about 2, jet engines can function by ejecting the fuel into the air which is compressed by the Ram-pressure and by igniting the fuel allowing the engine to thrust due to the combustion gases's reaction force. The engine operating on this principle is called ramjet engine.

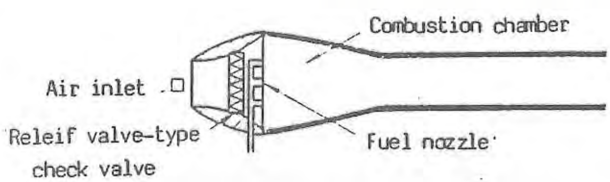
Fig 4-66(a) shows its working principle. It illustrates the essential features of the ramjet engine. It comprises three main components, a diffuser which is installed in the air entrance (followed by) a combustion chamber and an exhaust jet nozzle. In the diffuser, the air is further diffused so that its speed is reduced, as a result, the high pressure is obtained.

The ramjet is very simple structure without equipping the complex moving parts, and is suitable for the prime mover for the aircraft which cruises for long hours at supersonic speed.

However ramjet is not self-operating at zero flight speed because of absence of Ram pressure, therefore, it connot take-off by herself without another auxiliary prime-mover.



(a) Combustion chamber



(b) Pulse-Jet

Fig. 4-66 Operating Principles of Ramjet & Pulsejet

Fig 4-66(b) shows pulsejet engine section. The engine is equipped with minimum air-resistance check valve at the air-inlet section. The check valve is designed to be opened and closed intermittently according to the gas pressure. In this engine, when the fuel is ignited in the combustion chamber, the pressure rise due to the combustion causes the valve to close, and after the combustion gases are discharged to the atomospher, the check valve is opened to admit the air. Thus the combustion of the pulsejet is performed intermittently, and the escaping gasses push the engine forward fast enough to cause the air to enter under pressure, continuing the cycle. However, this action is not steady causing the vibration and large noise even though the efficiency at speed mach 1 or under is excellent.

(3) Rocket Engine

Like the jet engine, the rocket engine obtains thrust by the reaction force due to the discharging of the exhaust gases. The main difference is in the supply of oxygen to burn the fuel. Jet engines use oxygen from the air. Rocket engines not only carry their own fuel but also their own oxygen supply. This makes it possible for rocket engines to operate and develop thrust in high altitude or even in space, where there is small density of air or no oxygen no piston engine equipped aircraft or jet engine can cruise there. From the above reason, the rocket engines are mainly used in the fields of space craft.

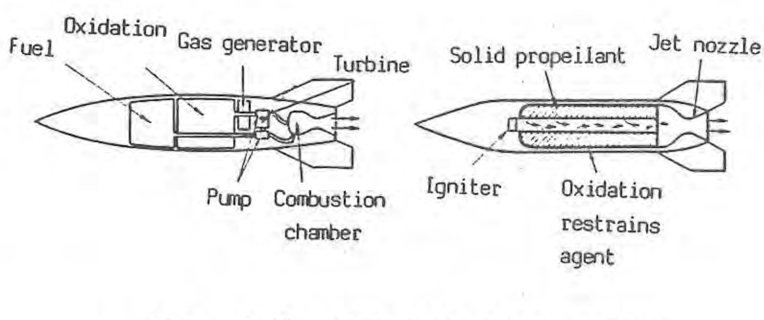


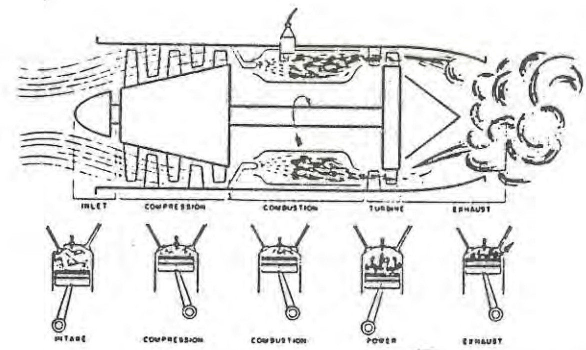
Fig. 4-67 Rocket Engine section

The propellant comprises fuel for engine and oxidizer for combustion and it is classified into a solid and a liquid types.

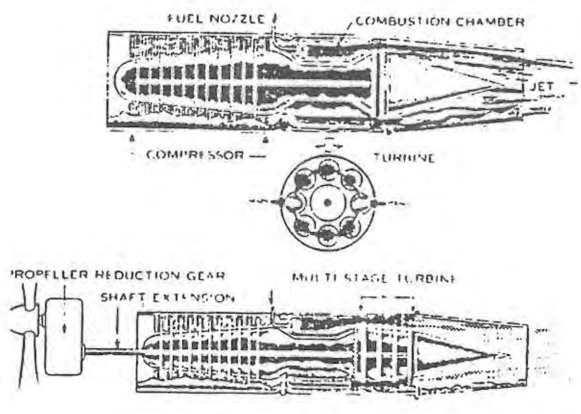
The solid propellants contain both fuel, an oxidizer, ammonium perchlorate CNH_4 CLO_4 and a catlyser, by means of mixing, polymerizing, and solidifing.

The liquit propellants is a mixture such as ethyle alcohol or kerosene, liquid oxygen, a combined material with aniline (C_6 H_5 NH_2) and nitric acid.

Appendix



Turbojet Continuous Cycle Compared with Four Stroke Cycle



Turboprop and Turbojet compared