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INTERNAL COMBUSTION ENGINE
FOR FISHING BOAT (I)

Basic principles of internal combustion engine

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CONTENTS

PREFACE

The present textbook is based on lectures given to the trainees of Marine Engineering Course at the Training Department, Southeast Asian Fisheries Development Center, during 1983-85. It is intended to provide an introduction to the principles of the internal combustion engine with special emphasis on the diesel engine and its marine applications.

This textbook deals with four main topics: heat engine and diesel engine; basic features of the diesel engine; horsepower and efficiency of the diesel engine; and the principles of combustion. It is intended for the trainees who have studied basic mathematics, physics and chemistry but have no prior knowledge of how an internal combustion engine works. The text is accompanied by numerous simple diagrams and occasionally a review lesson of basic science.

The scope of this introductory textbook is necessarily limited. We hope that the reader will be encouraged to continue his study of the subject in more detail. At any rate, the material contained in the present volume should be mastered by anyone who wishes to operate, service or sell diesel engines.

K Tobo

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LESSON 1. HEAT ENGINE AND DIESEL ENGINE

1.1. General

The principal sources of energy from which work may be obtained are the natural supplies of coal, oil, and gas, all of which will react with the oxygen in the earth's atomosphere and liberate energy. Many other substances in various states can be sources of energy. The splitting of the atom has progressed sufficiently so that such substances as uranium may also be regarded as sources of energy. Part of the chemical or atomic energy liberated by the various processes may be transformed into work by heat engine. Heat engines can be classified as below.

- Heat engine
  - External combustion engine
    - Piston engine - Steam reciprocating engine
    - Turbomachine - Steam turbine
  - Internal combustion engine
    - Piston engine - Diesel engine, Gasoline engine
    - Rotary engine
    - Turbomachine - Gasturbine jet engine

In both the external and internal combustion engine, the chemical energy liberated by the combustion process appears principally as internal energy in the products of combustion and is indicated by a high temperature of parts of the atomic pile. In the heat-engine process, heat is transferred from the products of chemical or atomic reaction to a thermodynamic medium such as H_2O which is permitted to exert a force on a moving piston or on moving turbine blades, thereby producing work.

The products of reaction are the thermodynamic medium for the internal combustion process, and these exert a force on the moving engine piston or moving turbine blades, thereby producing work; or, by expansion through a nozzle the products of reaction attain a high velocity and exert a jet or driving thrust on a reaction internal combustion engine and the transport apparatus to which it is attached, thereby doing work on the apparatus if it is in motion.

The external combustion process is used in engines ranging in size from toy steam engines to reciprocating engines developing several hundred horsepower and to steam turbines developing well over 100,000 ps. Reciprocating internal combustion engines range in size from the model aircraft engines of much less than 1 ps to large engines developing nearly 10,000 ps. Gas turbines range in size from about 100 ps in a small turbosupercharger to more than 12,000 ps in stationary power plants.

The internal combustion engine is inherently well adapted for transportation purposes, and it is in the automative and aviation fields that remarkable development has taken place. The Second World War resulted in a rapid development of the jet and turbine internal combustion engines. The recent application of the internal combustion engine to railroads has been brought about by the need for better performance and overall economy.

While the foregoing applications of the internal combustion engine have been most publicized, there are numerous other applications that are very important to various industries. Much of the power developed for the oil and gas industry is by means of liquid fuel or gas engines. Other important applications are found in the steel and marine industries, in numerous industrial plants, and in sewage-disposal plants.

1.2. External Combustion Engine

(1) In 1765 James Watt, an Englishman, invented a single-acting engine and in 1784 a reciprocating steam engine. Before this invention Chistian Huygens (Dutch), Papin (French), Sebaly and Newcomen (both British) had already invented the steam engines and had improved them, but they could not be put into actual use.

(2) The locomotive is a typical example of the external combustion engine which is now used much less than before due to recent fuel revolution. The explanation of Fig. 1-1 is as follows.

You put water into a boiler, heat it with fuel (coal, petroleum), lead generated steam into a cylinder through a pipe and a change valve. There is a movable component in the cylinder which moves from side to side and this is called a piston. This piston is pushed by the steam pressure in the cylinder. When the piston moves to the end, the change valve turns. This turning changes the way in which steam enters the cylinder as shown in Fig. 1-1 (b), and makes the piston move in the opposite direction by the steam pressure. Thus as shown in Fig. 1-1 (a) and (b), the piston repeats running from side to side and the device that transmits this motion into a rotary one by a crankshaft is a steam engine. In this case fuel is burned outside the cylinder, so this engine is called an external combustion engine.

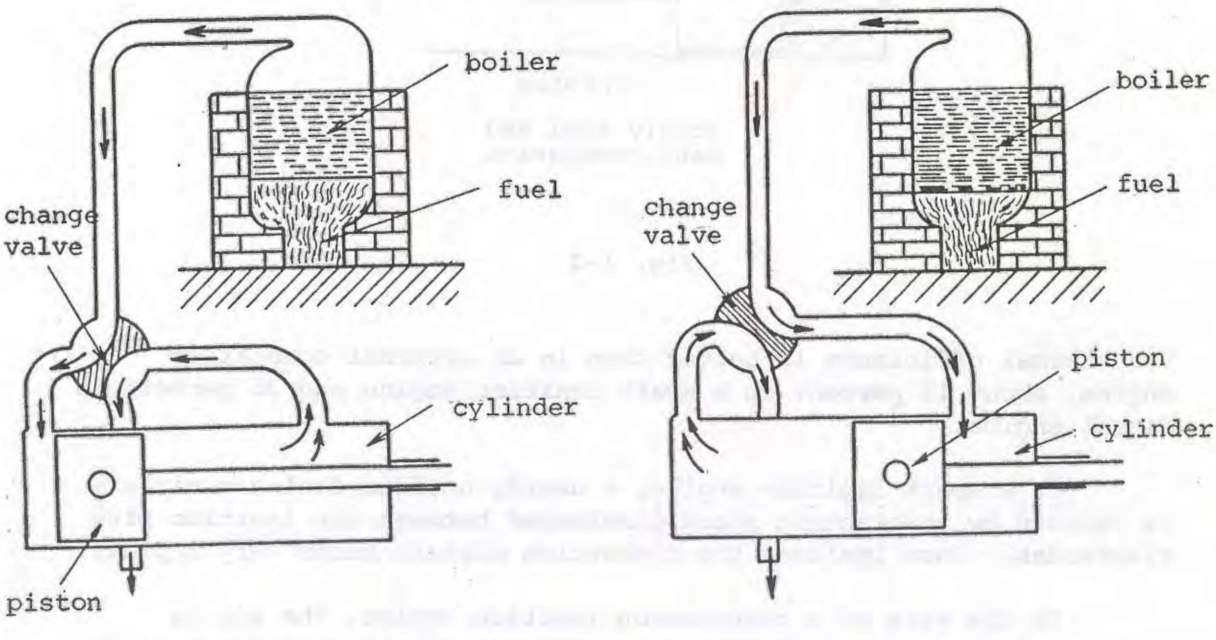


Fig. 1-1.

The heat energy which puts the wheels into motion is much less than expected because the heat is dissipated with smoke while fuel burns outside the cylinder and while steam is led into the cylinder through a pipe. The ratio of a given energy and the energy which actually does effective work is called thermal efficiency. The thermal efficiency of a steam engine is roughly 6 percent.

1.3. Internal Combustion Engine

There are various types of internal combustion engines such as the diesel engine, hot bulb engine, spark ignition engine and so on. In these engines, as shown in Fig. 1-2, fuel is put into a cylinder and then burned. Accordingly, in an internal combustion engine, heat is less dissipated than in an external combustion engine.

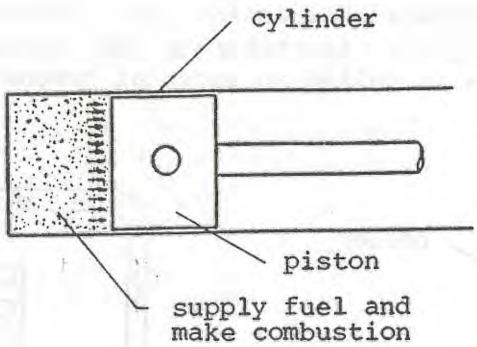


Fig. 1-2

The thermal efficiency is better than in an external combustion engine, about 15 percent in a spark ignition engine and 35 percent in diesel engine.

In a spark ignition engine, a nearly uniform fuel-air mixture is ignited by an electric spark discharged between the ignition plug electrodes. Once ignited, the combustion mixture burns very rapidly.

In the case of a compression ignition engine, the air is compressed to a very high pressure. Because of the high pressure the temperature of the air rises. A proper amount of fuel is injected into the compressed air and combustion takes place spontaneously.

1.4. Classification of Internal Combustion Engines

The internal combustion engines can be classified in terms of their specific characteristics, such as their ignition method, types of fuel, fuel supply, acting scheme, piston-crank connection, engine speed, arrangement of cylinders, cylinder cooling etc. These various methods of classification are explained in some detail below.

1.4.1 Ignition system

(a) Spark ignition engine (S.I. engine)

This is most commonly used in gas engines in which gasoline or kerosene, and recently propane gas, are used as fuel. After generating electricity by a magnet, a spark caused by a spark plug (which can be called a plug) ignites the fuel gas in the cylinder. Most cars use spark ignition engine.

(b) Hot-bulb engine (semi-diesel engine)

This engine has a hot bulb or a hot metal plate attached to the cylinder head. A burner heats up this hot bulb or hot metal plate and the fuel catches fire when it is blown against the hot bulb (hot metal plate).

As this engine can work with comparatively low compression, and it is not very complicated to operate, it has long been put to use as a boat engine.

(c) Compression-ignition engine (diesel engine, I.C. engine)

When you use an air pump for a bicycle, you may notice that the pump gets heated (see Fig. 1-3). The heat is generated by compressed air in the pump, not by friction of the pump parts. As the air is compressed, the pressure and temperature increase; conversely, as the air expands, the pressure and temperature decrease. Detailed information about this relation will be given later on.

You can easily imagine the fact that fuels catch fire if they are injected into highly heated air. In a diesel engine there is burning by heat of air compression, therefore, the question of compression becomes important.

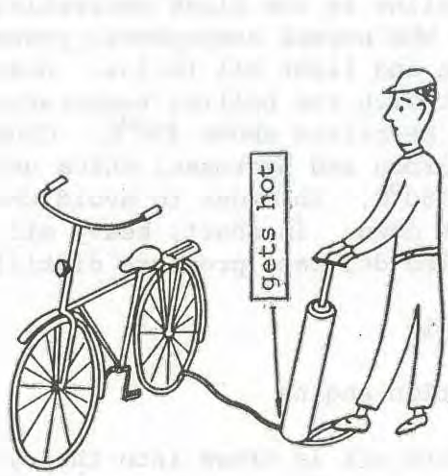


Fig. 1-3

1.4.2 Types of fuel

(a) Gas engine (spark-ignition engine). Propane gas is used as fuel;

(b) Gasoline engine (spark-ignition engine). In this engine gasoline vapor mixed in a fixed ratio with air by a carburettor is drawn into the cylinder;

(c) Light oil engine (spark-ignition engine, diesel engine);

(d) Heavy oil engine (hot bulb engine, diesel engine).

Petroleum is a complex mixture of organic compounds and its origin is not well known, but we can safely say that sea creatures were buried in the earth by natural disasters in the time immemorial and have changed into pertroleum over a long time. Petroleum is a combination of hydrogen and carbon, and we call it hydrocarbon. Gasoline, kerosene, light oil and heavy oil are produced by refining crude oil extracted from an oil field. Under normal atmospheric pressure water reaches its boiling point at 100°C whereas the boiling points of crude oil components vary from 30°C to roughly 355°C.

Gasoline is the first derivative produced by vaporizing crude oil in the normal atmospheric pressure and by distilling it. Kerosene and light oil follow. Heavy oil and asphalt consist of an ingredient with the boiling temperature of more than 350°C so the temperature must be raised above 350°C. Crude oil consists of chemical compounds of carbon and hydrogen, which undergo chemical reactions at more than 350°C. In order to avoid chemical changes, the pressure must be brought down. In short, heavy oil and asphalt are extracted by the so-called decrease pressure distillation.

1.4.3 Fuel supply

(a) Suction engine

Before air is drawn into the cylinder it has to pass through the carburettor. The fuel is turned into fog fuel, and both air and gas are absorbed into the cylinder. This is used in the spark ignition engine.

(b) Injection engine

Only air is absorbed into the cylinder and compressed. At a certain point, the atomized fuel is injected and ignited by the high temperature of the compressed air inside the cylinder. Examples of this type of engine are the hot bulb engine and diesel engine.

1.4.4 Operating cycle

(a) Four-stroke cycle engine

This type of engine is operated by repeating four strokes; suction-compression-explosion-exhaust. It is used most in spark-ignition engine and medium and small type of diesel engine.

(b) Two-stroke cycle engine

The engine runs by repeating two strokes, suction to exhaust and compression to explosion. This operative cycle is used most in spark-ignition engine and medium and large type of diesel engine.

Notes:

A full explanation of two-stroke and four-stroke cycles will be given in another lesson. We have used above the generally accepted terms: four-stroke cycle and two-stroke cycle. However, some reference books use the terms four-cycle or two-cycle engine, dropping the word "stroke". In any case, a cycle is completed by four or two strokes or cycle events.

1.4.5 Motion

(a) Single-acting engine

As shown in Fig. 1-4 (a), the pressure of burning gas makes the engine work only in one direction of the piston and this is widely used in the spark ignition engine, hot bulb engine and the large, medium and small type of diesel engine.

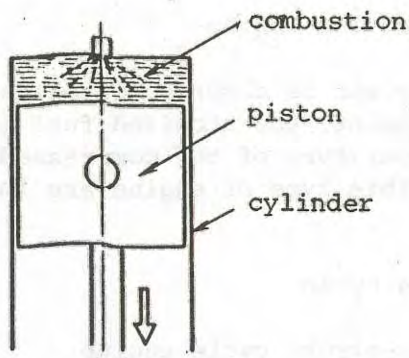


Fig. 1-4 (a)

(b) Double-acting engine

As shown in Fig. 1-4 (b), there are combustion chambers on both sides of the piston and this causes alternate combustion.

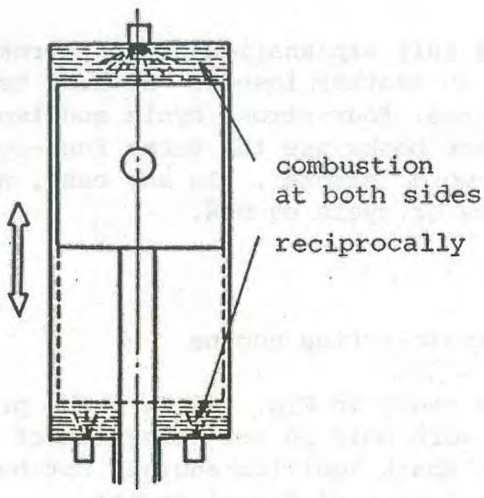


Fig. 1-4 (b)

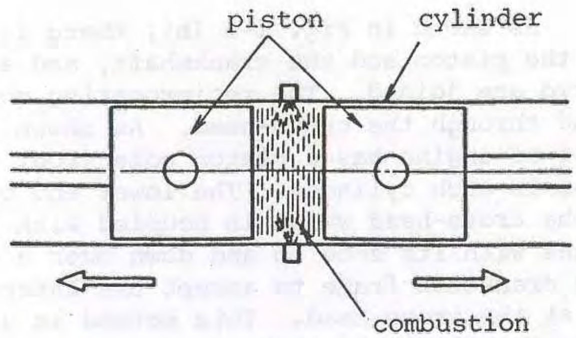


Fig. 1-4 (c)

(c) Opposite acting engine

As Fig. 1-4 (c) shows, the combustion chamber is set up between two pistons and causes them to move in opposite directions.

1.4.6 Piston connecting methods

(a) Trunk piston engine

In this type of engine, the piston and the crankshaft are joined directly with a rod (Fig. 1-5 (a)). This is mostly used in medium and small engines.

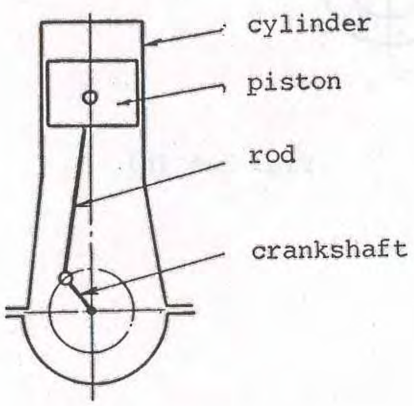


Fig. 1-5 (a)

(b) Cross-head engine

As shown in Fig. 1-5 (b), there is a piston pole and a rod between the piston and the crankshaft, and a cross-head is placed where the two are joined. The reciprocating motion of the piston runs the rod through the cross-head. As shown in Fig. 1-5 (b), the cross-head type of engine has a piston pole (rod) which is firmly fixed to the piston in each cylinder. The lower end of the piston pole is fixed at the cross-head which is coupled with the connecting rod and which slides with its shoe up and down over a guide, a flat piece fixed on the crankcase frame to accept the lateral force (side pressure) arising at the cross-head. This method is used mostly for large types of diesel engine. If there is no cross-head in a large engine and piston and crankshaft are connected directly, the piston will get a large side-pressure on its body and this pressure tends to cause scratches or sticking around the piston body.

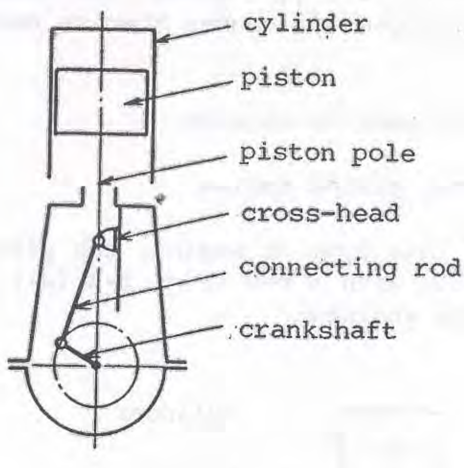


Fig. 1-5 (b)

1.4.7 Engine speed

Generally speaking, engine speed can be classified into high, medium and low speed, or merely high and low speed. There is no definite classification, but for your information there are also classifications by the number of engine revolutions and by the speed of piston.

(a) Classification by the number of revolutions/minute:

high speed	:	1500	rpm. and over
medium speed	:	700-1500	rpm.
low speed	:	700	rpm. and less

(b) Classification by piston speed:

		A	B
high speed	:	7-12 m/s	9-12 m/s
medium speed	:	6-8 "	6-9 "
low speed	:	5-6 "	4-6 "

Note: The reason why A is different from B is because various reference books show different numbers.

1.4.8 Arrangement of cylinders

Cylinders can be arranged in an engine in any one of the following ways:

(a) Horizontal engine.

The cylinders are in a horizontal position;

(b) Vertical engine.

The cylinders are positioned vertically;

(c) V-type engine.

The cylinders are arranged in two rows on a slant;

(d) W-type engine.

The cylinders are arranged in three rows;

(e) Star-type engine.

The cylinders are arranged radially into the shape of a star;

(f) Stand-on-end type engine.

The cylinders are put in an inverted position.

Vertical engine is chiefly used for the main boat engine, and V-type and horizontal type engine are also used there for special purposes.

1.4.9 Cylinder cooling method

(a) Water-cooled (liquid-cooled)

An engine using fresh water or sea water for cooling is called water-cooled engine. An engine which uses oil is called liquid-cooled engine. The water-cooled engine using sea water as a coolant is widely used for marine propulsion.

(b) Air-cooled engine

Air is circulated in the cylinder fins. This is applied widely in land-used engines.

1.4.10 Other classifications

Other classifications are possible, according to whether engines are used in agriculture, industry, for vehicles on land, or at sea. They can also be classified by the injection method into airless injection type and air injection type. These classifications, however, will not be discussed here.

1.5 Diesel Engine

1.5.1 Invention of Diesel

Diesel engine carries the name of its inventor, a German thermal engineer, Rudolf Diesel. He made his first model of internal combustion engine in 1893. It consisted of a single 3-meter iron cylinder in which the pressure during the trial run attained 80 atmospheres, at that time the highest mechanically created pressure. The engine exploded and Diesel went back to work on an improved version. A revised model appeared the following year and ran for a minute. Diesel spent two more years improving his engine and the commercial manufacture finally began in 1898.

Rudolf Diesel was born in Paris in 1858, son of German immigrants. The war between Germany and France drove them away from Paris, first to London, then to Germany. Young Redolf's extremely high scholastic attainment won him a scholarship to the prestigious Technical College in Munich when he was 18 years old. There he studied thermodynamics under professor Carl von Linde and graduated with the highest honors. After graduation he worked in Switzerland, Paris and Berlin. The engine which now bears his name is a result of 13 years of experiments, some of which nearly cost him his life. Rudolf Diesel's work as an engineer, inventor, internationalist and a pacifist made him famous early in his career. He was frequently invited to give lectures and attent symposia in different countries. In 1913, at the age of 52, he was invited to an engineers'convention in London. He disappeared at sea while crossing the English Channel in circumstances which have never been explained.

1.5.2 Characteristics of diesel engine

(a) The main characteristic of diesel engines which distinguishes them from other combustion engines is the method of igniting the fuel. In a diesel engine, the fuel is injected into the cylinder which contains highly compressed air. During compression of the air in the engine cylinder the temperature of the air goes up so that when the fuel, in the form of a fine spray, comes in contact with this hot air, it ignites, and no other external means of ignition is required. For this reason diesel engines are also called compression-ignition engines.

(b) Another important characteristic of the diesel engine is that the engine produces a torque which is more or less independent of the speed, as the amount of air taken into the cylinder during each suction stroke of the piston is little affected by the speed of the engine. The amount of fuel that can be burnt in the cylinder with each suction stroke and the useful effort developed by the action of the piston are, therefore, almost constant.

(c) Equally important is the fact that the diesel engine has a higher thermal efficiency than other heat engines, uses less fuel for the same power delivered, and in addition uses a fuel which is cheaper than gasoline.

(d) Naturally, there are also some disadvantages as compared with gasoline engines: (1) slightly greater weight for the same horsepower, (2) in high-speed engines, a certain roughness in operation, particularly at light loads, and (3) a considerably greater initial cost.

1.5.3 Standard structure of diesel engine

(1) The main part of the diesel engine is the cylinder. The cylinder consists of a cylinder block (case), cylinder liner, and cylinder head. Inside the cylinder liner, there is a cylindrical close plug called a piston, which can slide up and down along the cylinder liner wall. To seal the pressure inside the cylinder there are several piston rings between the piston and the liner. The piston rings are set in the grooves around the piston (see Fig. 1-6).

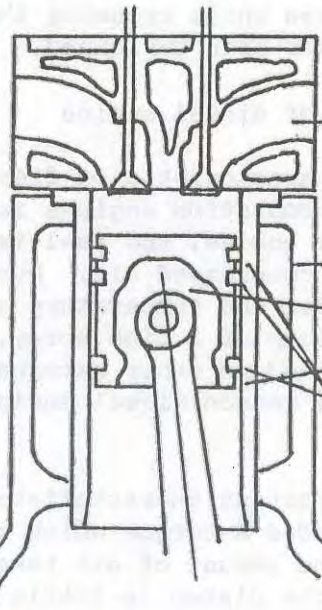


Fig. 1-6

(2) The piston is attached to the end of a piston connecting rod (or merely called a rod) by a piston pin and the other end is connected with a crankshaft.

(3) The crank changes a rectilineal motion into a rotary one, just like a treadle of a bicycle.

(4) The reciprocating motion of the piston is changed into a rotary motion by the rod and crank, and the power produced makes a propeller and dynamo rotate.

(5) A flywheel is attached to the end of the crank. It facilitates the rotary motion of the crank.

(6) The lower part of cylinder is attached to the crankcase which is a stable foundation. This crankcase holds the crank.

(7) The upper part of the cylinder is covered by a cylinder head. The part enclosed by the cylinder and the piston forms the combustion chamber. There is a pit to let the air in and on other one to let the exhaust gas out of the cylinder head. These pits are closed by an inlet valve and an exhaust valve respectively. The inlet valve and the exhaust valves open and close at fixed times according to the rotation of the crank. A nozzle is attached to the cylinder head in order to turn the fuel into fine spray before it enters into the combustion chamber. Full explanation about these will be given in another lesson.

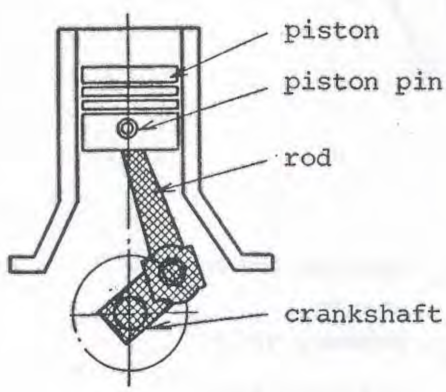


Fig. 1-7

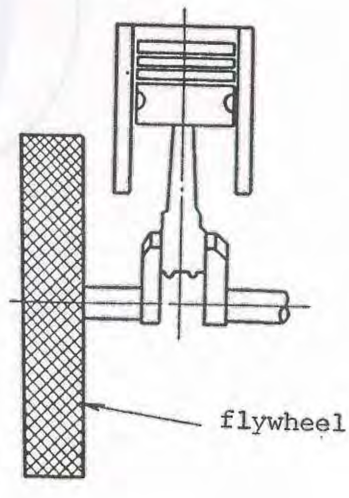


Fig. 1-8

(8) In addition to the standard structure of the diesel engine, other necessary equipment is listed below.

(a) Cam mechanism to open and close the inlet valve or the exhaust valve;

(b) Cooling equipment to take away generated heat;

(c) Lubricating equipment to supply oil into each part of the engine for smooth running;

(d) Fuel supplying equipment to give fuel a high pressure and to inject it;

(e) Clutch equipment to convey power and to reverse the rotary motion;

(f) Starting equipment to make the engine begin to work.

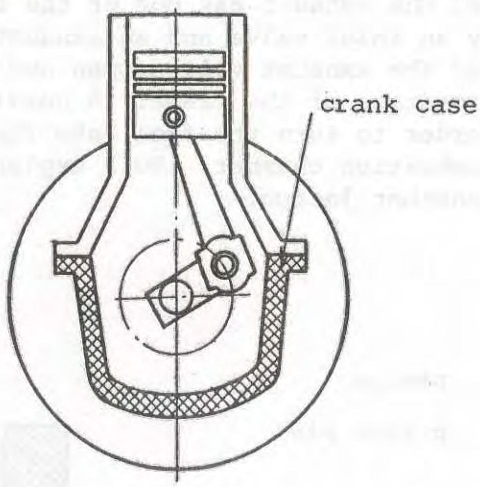


Fig. 1-9

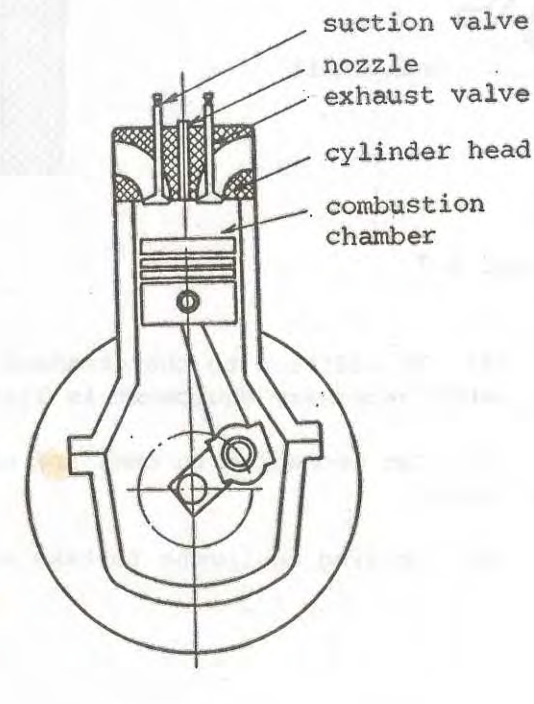


Fig. 1-10

LESSON 2. BASIC FEATURES OF DIESEL ENGINES

In Lesson 1, we learned the history of the diesel engine, the classification and the standard structure of engine. In this lesson you will learn the basic principles of how the diesel engine operates.

2.1 The Nature of Gases

(1) Boyle's law

In Fig. 2-1, a pressure gauge is attached to a cylinder. The smaller the cylinder volume, by raising a piston in the engine, the higher the indicator of the pressure gauge rises. This shows that the pressure in the cylinder is rising. Conversely, by lowering the piston and thus increasing the cylinder volume, the value shown by the indicator becomes lower.

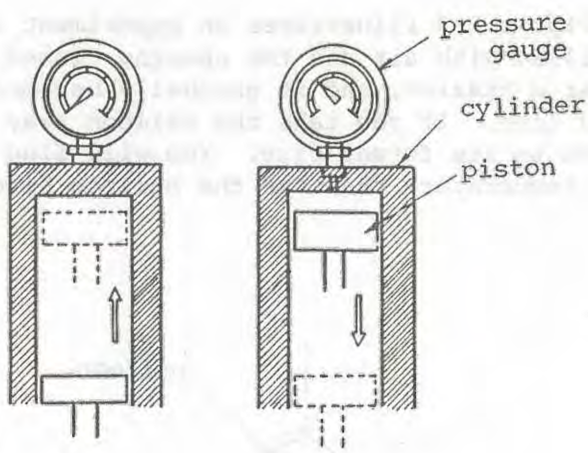


Fig. 2-1

This means that the pressure in the cylinder becomes low. If we examine the relationship between the increase and decrease of cylinder volume and the indicator of a pressure gauge, we find that the pressure roughly doubles if the air in the cylinder is compressed into half the volume and that the pressure increases roughly four times if the air is compressed into quarter of the original volume. This means that the volume of gas at constant temperature is inversely proportional to the pressure. This is called Boyle's law and is one of the important laws for studying diesel engine. Boyle's law can be expressed by the following formula:

$$\frac{P_2}{P_1} = \frac{V_1}{V_2} \text{ or } P_1 \times V_1 = P_2 \times V_2$$

$P \times V$ .... = constant

P .... = pressure

V .... = volume

P_1......... = pressure before compression

P_2......... = pressure after compression

V_1......... = volume before compression

V_2......... = volume after compression

and the temperature is constant.

(2) Charles's law

Figure 2-2 illustrates an experiment where a rubber balloon is filled with air and the opening closed tight. The balloon is warmed over a brazier, and it gradually becomes larger as shown by the dotted line. If you take the balloon away from the brazier, it is restored to its former size. You will find that the higher you make the temperature the more the balloon becomes inflated.

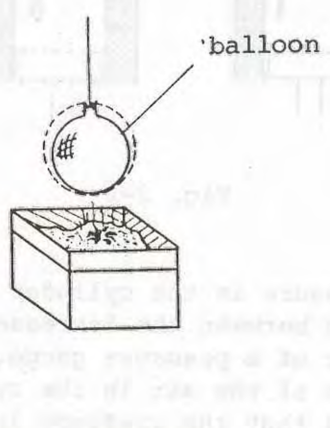


Fig. 2-2

If you increase the temperature by $1^{\circ}C$ with a fixed gas pressure, $\frac{1}{273}$ of the volume at $0^{\circ}C$ is added to the value. Actually, the case of a rubber balloon is slightly different because of its surface tension. At this point, the number 273 should be explained. Temperature constitutes a measure of how much we feel cold or hot. We set 0 degrees centigrade when water is changed into ice under normal atmospheric pressure, and 100 degrees centigrade when water is beginning to boil. We divide the difference between freezing and boiling point into 100 equal parts; one such part is called 1 degree centigrade. The calorific volume necessary to raise the temperature of one gram of water by 1 degree centigrade is called one caloric. We generally use the unit of centigrade to show temperature. In addition to the centigrade scale we sometimes use Fahrenheit (F) scale, and Kelvin (K) scale for absolute temperature. In the centigrade scale when heat is absorbed from $0^{\circ}C$, the temperature is lowered to $-1^{\circ}C.$, $-2^{\circ}C$. It is expressed with a minus quantity and the limit to which heat can be absorbed is shown as $0^{\circ}K$ of the absolute temperature, which is just the same as $-273^{\circ}C$. When you calculate the relationship between the volume and the temperature of a gas, you can use the following formula:

$$V = V_o (1 + \frac{1}{273} t) = V_o \frac{273 + t}{273}$$

If you change $t^{\circ}C$ to the absolute temperature, it becomes $T^{\circ}K$.

Accordingly $\frac{V}{T} = \frac{V_o}{273} = \text{constant}$

V .... volume of gas at $t^{\circ}C$

V_o .... volume of gas at $0^{\circ}C$

(3) Boyle's and Charles's laws

From Boyle's and Charles's laws we can construct the following formula:

$$\frac{P.V}{G.T} = \frac{P.r}{T} = \text{constant (R)} \quad \text{(r: specific volume)}$$

If we make R a fixed number, that is, a constant, it is

$$P.V = R.T.G \quad \text{or}$$

$$P.v = R.T$$

We call R a gas constant; it is always the same for the same kind of gas, but varies for different gases. Some values of R are given in the table below.

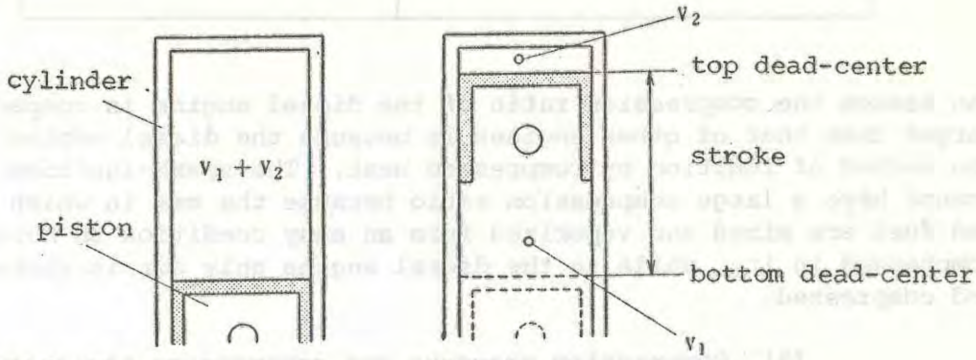
Table 2-1

Kind of gas	Gas constant	Specific heat		Specific heat ratio
	R	Cp	Cv	m = Cp/Cv
H_2	420.6	3.41	2.42	1.41
O_2	26.5	0.217	0.155	1.40
N_2	30.3	0.247	0.176	1.40
CO	30.3	0.242	0.172	1.40
Air	29.3	0.240	0.170	1.41
Steam	47.1	0.48	0.37	1.30
CO_2	19.2	0.21	0.16	1.30

Specific heat is the ratio of the amount of heat (calories) required to raise the temperature of a given mass of a substance 1°C, to the amount of heat required to raise the temperature of an equal mass of water 1°C. Since the calorific volume necessary to increase the temperature of 1g of water by 1°C is one calorie, we may say that the specific heat expressing the calorific volume necessary to raise the temperature of gas 1°C is measured with water as a standard. (If the specific heat value is measured while keeping the pressure fixed, it is different from the case of keeping the volume fixed. The specific heat value measured with fixed pressure is called specific heat at constant pressure, and it is shown with Cp. One measured with fixed volume is called specific heat at constant volume, and it is shown with Cv.) Generally speaking, specific heat at constant pressure Cp is larger than specific heat at constant volume Cv, because Cp includes not only energy to raise 1°C but also energy for thermal expansion. In the case of solids and liquids, this work-load is so small that it can be disregarded. The ratio of Cp and Cv is called specific heat ratio and it is 1.41 in the case of air.

(4) Compression ratio of internal combustion engine

The compression ratio indicates the value given by all of the compressed volumes divided by the remaining volume without being compressed. An explanation in a little more detail is as follows.



(a) before compression (b) after compression

Fig. 2-3

When a piston works from top to bottom in a cylinder, the lowest position of the piston is called the bottom dead center and the highest position of the piston is called the top dead center. The piston runs from the top dead center to the bottom dead center, and the distance is called a stroke. The ratio of the total volume of the cylinder shown in Fig. 2-3 (a) that is, with the piston at the bottom dead center and the volume shown in Fig. 2-3 (b) that is, with the top dead center, is called the compression ratio. It can be formulated as follows:

$$\text{Compression ratio } (\Sigma) \quad \frac{V_1 + V_2}{V_2} = \frac{V_1}{V_2} + 1$$

The compression ratio varies depending on whether it is spark-ignition, hot bulb engine, or diesel engine. The following table shows how the compression ratio generally goes.

Table 2-2

Type of engine	Compression ratio
Spark-ignition engine	05 - 12
Hot bulb engine	6 - 9
Diesel engine (14 cycle)	16 - 20

The reason the compression ratio of the diesel engine is comparatively larger than that of other engines is because the diesel engine employs the method of ignition by compressed heat. The spark-ignition engine cannot have a large compression ratio because the gas in which air and fuel are mixed and vaporized into an easy condition to burn is compressed in it, while in the diesel engine only air is sucked in and compressed.

(5) Compression pressure and compression temperature

We use the following formula to calculate the pressure and temperature after compression:

$$P_2 = P_1 \times \Sigma^m$$

$$T_2 = T_1 \times \Sigma^{m-1}$$

P_1 .... pressure before compression

P_2 .... pressure after compression

T_1 .... temperature at the beginning of compression

T_2 .... temperature after compression

Σ .... compression ratio

m .... specific heat ratio (compression index)

What we understand from these formulae is that the pressure and temperature change considerably according to the compression ratio and that the pressure and temperature after compression change greatly according to the stage of the air pressure P_1 and temperature T_1 before compression. Therefore, just when the engine begins to work, the pressure of inspiration and the temperature are low, but both rise considerably as the engine continues working.

The following is an example of how to calculate pressure and temperature after compression.

pressure before compression .... kg/cm^2
temperature before compression .... 60°C
compression ratio 18
specific heat ratio 1.3

In the above conditions, the pressure and temperature after compression are as follows.

(Pressure after compression):

$P_2 = P \times \Sigma^m$

$P_2 = 1 \times 18^{1.3}$ calculate with this numerical value

$18^{1.3}$ here is the same as $18^{\frac{13}{10}}$ Looking up log in a logarithmic table, you will find that it is 1.2553.

Then, $1.2553 \times \frac{13}{10} = 1.63189$

In a table of logarithms 63189 comes into 428.
So, $\underline{1}$.63189 becomes "2" in the number of a unit.
Thus the numercial value becomes 42.8
$1 \times 42.8 = 42.8$ (kg/cm^2)

(Temperature after compression):

$T_2 = T_1 \times {}^{m-1}$

$T_2 = (273 + 60) \times 18^{1.3-1}$

Calculate with this numercial value
$18^{1.3-1}$ here is $18^{\frac{3}{10}}$

Looking up log 18 in a logarithmic table, you will find that it is 1.2553

So, $1.2553 \times \frac{3}{10} = 0.37659$

In a table of logarithms 37659 comes into 238.
Thus, $\underline{0}$.37659 becomes "1" in the number of unit
Therefore, the numerical value is 2.38

$2.38 \times 333 = 792.54$ ($^{\circ}$K)

$792.54 - 273 = 519$ ($^{\circ}$C)

These calculations are so difficult to make that you are only required to know the general principle.

2.2 Four-Stroke Cycle

Figure 2-4 shows operation of a four-stroke cycle diesel engine in the order of suction-compression-explosion-exhaust. The motion of the engine is always repeated in the same order.

(1) Suction stroke

As shown in Fig. 2-4 (a), the piston moves from the top dead center to the bottom dead center by the rotary motion of the crank to which the piston is connected by a rod. At this time the inlet valve is opened by cam equipment. The piston's movement makes the pressure in the cylinder lower than that in the open air and opening of the inlet valve allows the air to enter into the cylinder. The difference between the diesel engine and spark-ignition engine is that the former sucks in an inflammable gas, and the latter only air.

(2) Compression stroke

When the crank revolves and the piston goes over the bottom dead center, the inlet valve closed as shown in Fig. 2-4 (b) As the piston goes to the top dead center, the air in the cylinder is beginning to be compressed. The compression ratio, as explaned before, is higher in diesel engine than in other internal combustion engines and the pressure after compression becomes high. If the temperature of compressed air is high, even a poorly combustible heavy oil, if introduced in the form of a fine spray will ignite and combust easily.

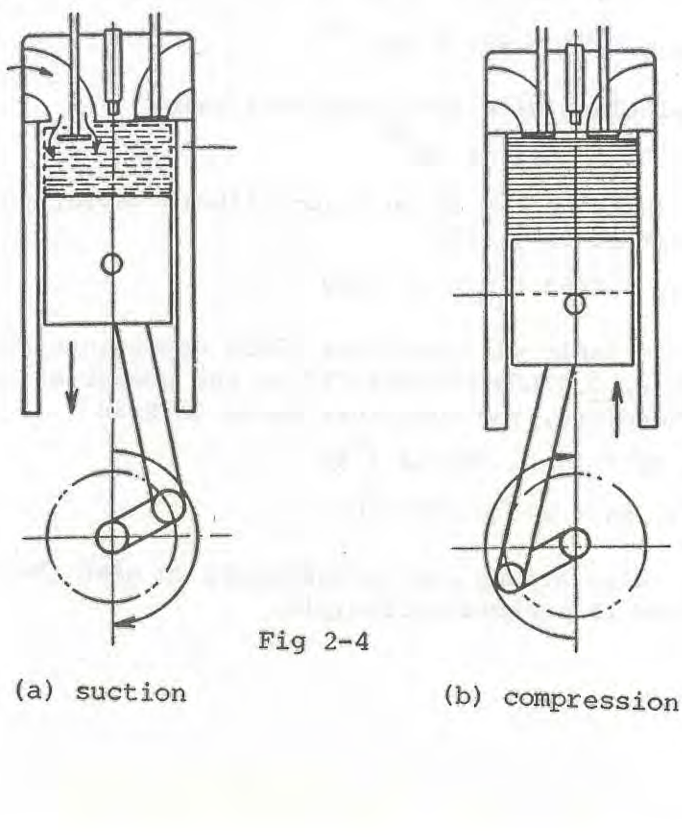


Fig 2-4

(a) suction (b) compression

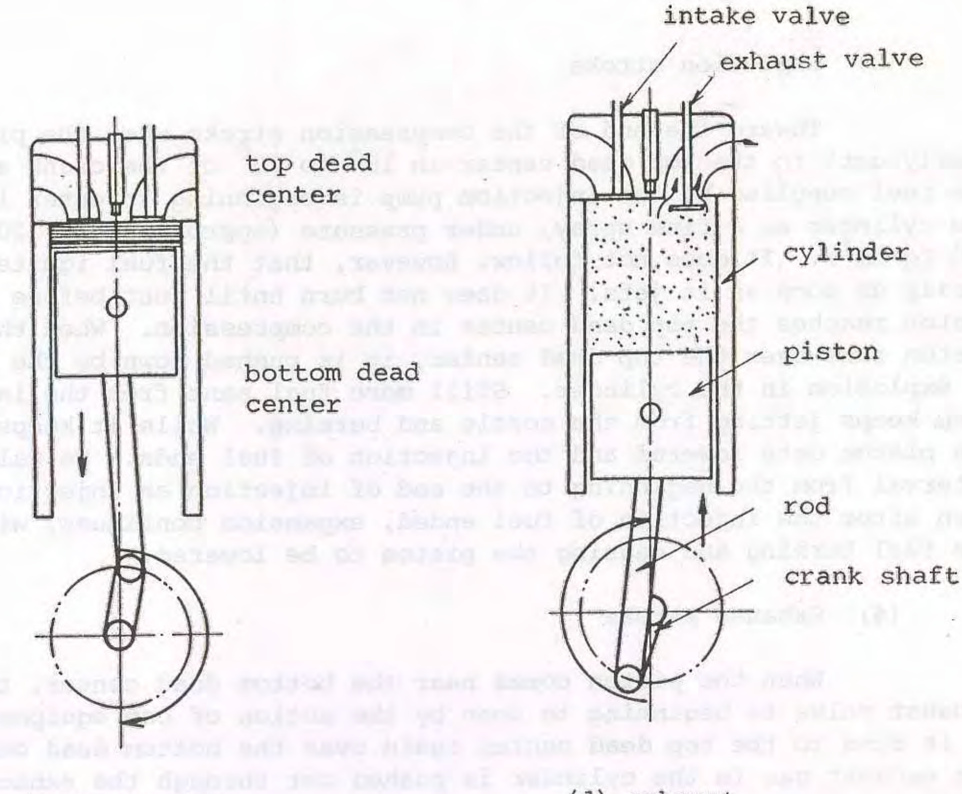


Fig. 2-4

The compression pressure of different internal combustion engines is shown in the following table.

Table 2-3

Kind of engine	Compression pressure kg/cm^2
Small gasoline engine	6.5 - 8
Light-oil engine	6.5 - 6
Hot-bulb engine	8 - 14
4-cycle diesel engine	36 - 42

(3) Explosion stroke

Toward the end of the compression stroke when the piston nearly gets to the top dead center in 10^{o} to 20^{o} of the crank angle, the fuel supplied by the injection pump is beginning to enter into the cylinder as a fine spray, under pressure (approximately 120 - 250 kg/cm^2). It does not follow, however, that the fuel ignites easily as soon as it jets. It does not burn until just before the piston reaches the top dead center in the compression. When the piston runs over the top dead center, it is pushed down by the pressure of explosion in the cylinder. Still more fuel sent from the injection pump keeps jetting from the nozzle and burning. While it keeps jetting, the piston gets lowered and the injection of fuel ends. We call the interval from the beginning to the end of injection an injection term. Even after the injection of fuel ended, expansion continues, with the fuel burning and causing the piston to be lowered.

(4) Exhaust stroke

When the piston comes near the bottom dead center, the exhaust valve is beginning to open by the action of cam equipment. As it runs to the top dead center again over the bottom dead center, the exhaust gas in the cylinder is pushed out through the exhaust hole. When the piston comes a little before the top dead center, the inlet valve is opened to let fresh air into the cylinder from the outside.

In this way the repeating motion of suction-compression-explosion-exhaust-suction-compression-explosion-exhaust continues.

2.3 Two-Stroke Cycle

As described in the previous chapter, the four-stroke cycle engine works only one stroke for every two revolutions of engine crankshaft in each cylinder, i.e. every fourth stroke is a firing stroke.

In the two-stroke cycle engine, one working stroke occurs for every revolution of the engine crankshaft, i.e. every alternate stroke is a firing stroke.

(1) When the piston is at the bottom of its stroke (as shown in Fig. 2-5 (a)), it fully uncovers the air inlet (scavenge) ports arranged circumferentially round the cylinder wall just above the top of the piston. Air from a blower enters the cylinder through these ports and scavenges the exhaust gases out through the open exhaust valve in the cylinder head.

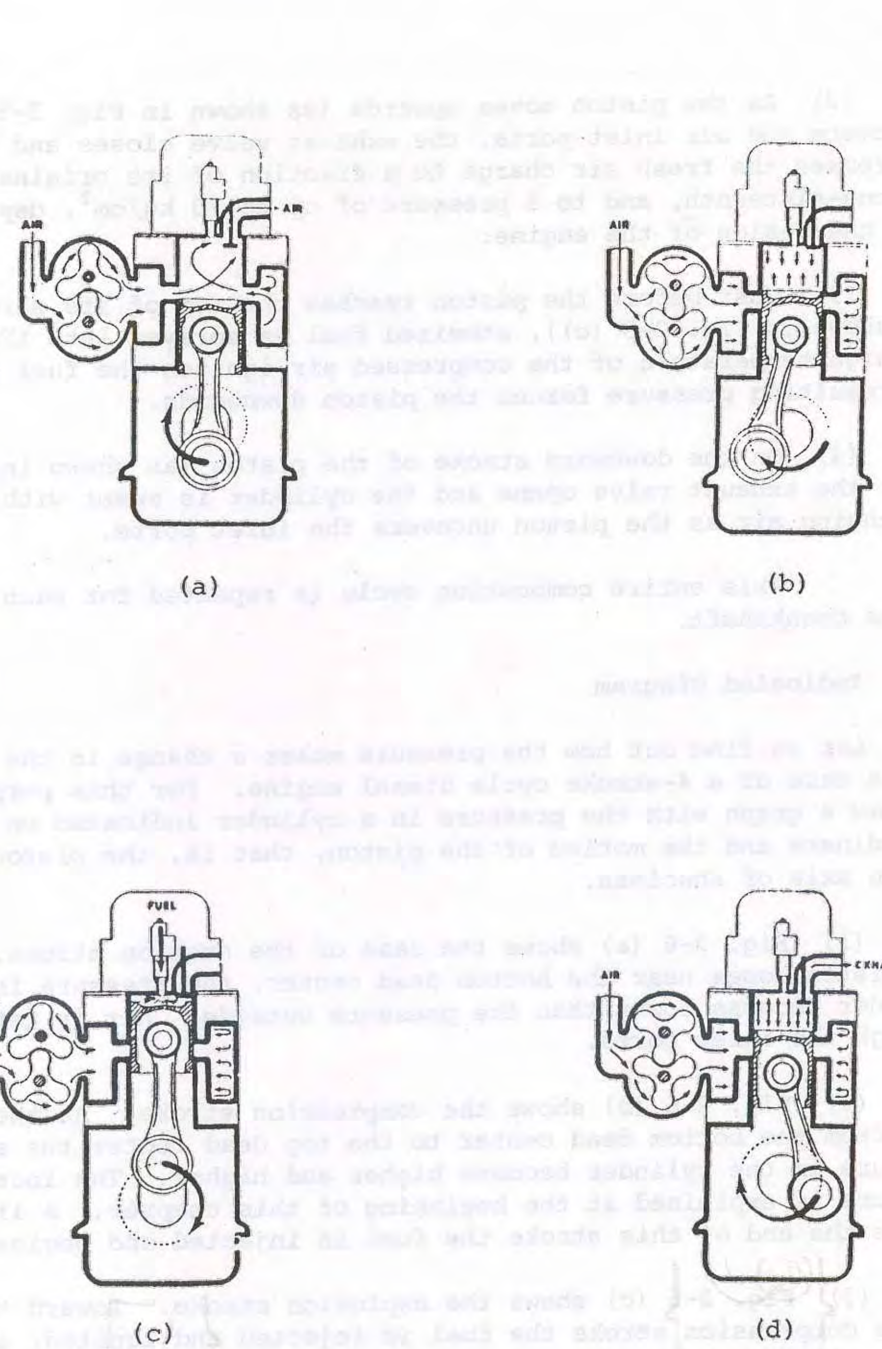


Fig. 2-5

(2) As the piston moves upwards (as shown in Fig. 2-5 (b)), it covers the air inlet ports, the exhaust valve closes and the piston compresses the fresh air charge to a fraction of its original volume, say one-sixteenth, and to a pressure of up to 70 kg/cm^2, depending upon the design of the engine.

(3) Just before the piston reaches the top of its stroke (as shown in Fig. 2-5 (c)), atomized fuel is sprayed into the cylinder. The high temperature of the compressed air ignites the fuel spray and the resulting pressure forces the piston downwards.

(4) On the downward stroke of the piston (as shown in Fig. 2-5 (d)), the exhaust valve opens and the cylinder is swept with clean scavenging air as the piston uncovers the inlet ports.

This entire combustion cycle is repeated for each revolution of the crankshaft.

2.4 Indicated Diagram

Let us find out how the pressure makes a change in the cylinder in the case of a 4-stroke cycle diesel engine. For this purpose let us draw a graph with the pressure in a cylinder indicated on the axis of ordinate and the motion of the piston, that is, the piston stroke on the axis of abscissa.

(1) Fig. 2-6 (a) shows the case of the suction stroke. As the piston comes near the bottom dead center, the pressure in the cylinder becomes lower than the pressure outside. Air is let in through the inlet ports.

(2) Fig. 2-6 (b) shows the compression stroke. As the piston runs from the bottom dead center to the top dead center the air pressure in the cylinder becomes higher and higher. The increase in pressure is explained at the beginning of this chapter. A little before the end of this stroke the fuel is injected and begins burning.

(3) Fig. 2-6 (c) shows the explosion stroke. Toward the end of the compression stroke the fuel is injected and ignited, and this burning lowers the piston. Even after the fuel injection ends, the fuel which has not burned by this time continues burning. Thus the combustion gas keeps the pressure high till it pushes the piston, and this power is sent to the crankshaft through the rod.

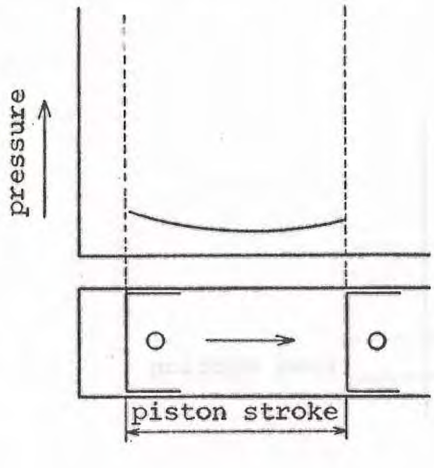


Fig. 2-6 (a)

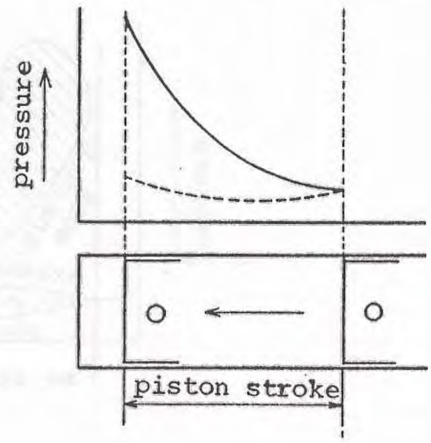


Fig. 2-6 (b)

(4) Fig. 2-6 (d) shows the exhaust stroke. When the piston comes near the bottom dead center, the exhaust valve is opened to let the burning gas out. As the piston rises, it expels the burning gas. The pressure in the cylinder becomes a little higher than that in the open air because the gas is pushed out through the exhaust hole.

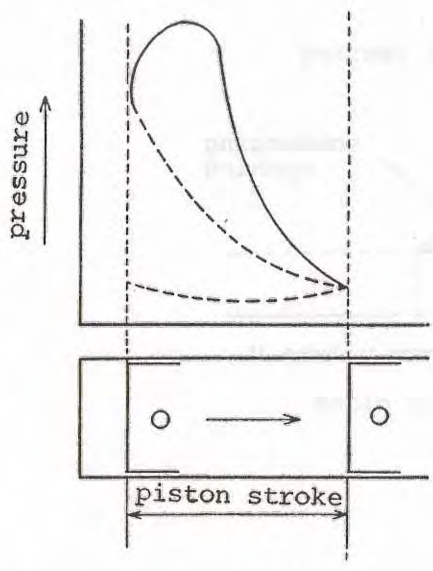


Fig. 2-6 (c)

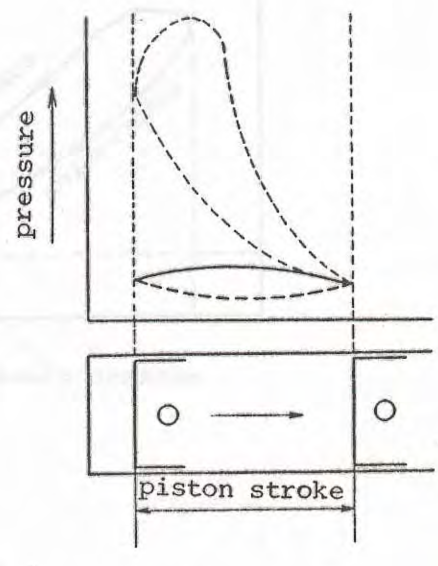


Fig. 2-6 (d)

(5) Fig. 2-7 is a graph in which Fig. 2-6 (a) to (d) are arranged into one. Such a graph is called an indicated diagram. The power calculated by this indicated diagram is called the indicated horsepower.

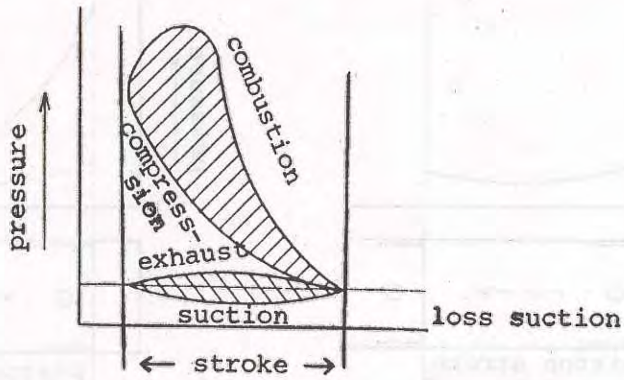


Fig. 2-7

(6) Fig. 2-8 shows the indicated diagram of the two-stroke cycle diesel engine. The work "scavenging" in the two-stroke cycle engine has nearly the same meaning as in the four-stroke cycle engine. The main purpose of scavenging is not only intake of fresh air but also driving out the residual exhaust gases.

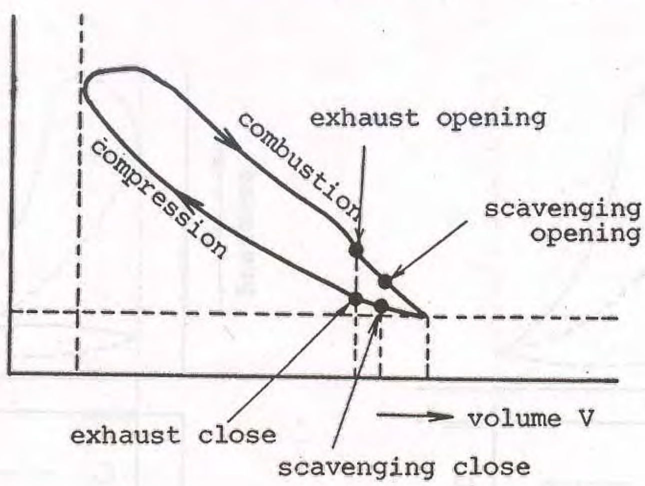


Fig. 2-8

LESSON 3. HORSEPOWER AND EFFICIENCY OF DIESEL ENGINES

Lesson 2 dealt with the basic general principle of the diesel engine. In this lesson, we shall study about the horsepower and efficiency of the diesel engine.

3.1 Horsepower

(1) H.P. (horsepower) or P.S. (Pferdestärke, German for horsepower)

1 horsepower in the metric system = 76 kg-m/sec
= 735.5 w = 736 w
= 0.9864 × 1 horsepower in the British system

1 horsepower in the British system = 33,000 ft-lbs/min
= 550 ft-lbs/sec
= 76.042 kg-m/sec
= 745.8 = 746 w

(2) The metric system is now used in many countries so that horsepower will be explained in this system. If you lift the weight of 75 kg 1 meter, we call the work-load that we've done the work of 75 kg-m. But the problem is how long it takes to complete the work. There is a difference between the power necessary for the work of 75 kg-m per second and the power necessary to do the same work in 2 seconds. Everyone thinks that the work per 2 seconds is easier than that per second. So what is expressed with a set time is a horsepower. One horsepower is decided to be the power to lift the weight of 75 kg-m per second.

(3) In Britain, length is usually expressed in feet and weight in pounds. So 1 horsepower is 550 ft-lbs/sec in the British system, which is slightly different from that in the metric system.

3.2 Indicated Horsepower (I.P.S. or I.H.P.)

This shows the work done in a cylinder with a unit of horsepower.

The formula for horsepower (4-cycles) is as follows:

$$I.P.S. = \frac{Pmi \times A \times L \times N}{75 \times 60 \times 2} \times Z$$

Pmi .... indicated mean effective pressure (kg/cm^2)
A .... section area of cylinder (cm^2)
L .... piston stroke (m)
N .... number of revolutions per minute (r.p.m)
Z .... number of cylinders

In the case of a 2-cycle engine, the formula is as follows:

$$I.P.S. = \frac{Pmi \times A \times L \times N}{75 \times 60} \times Z$$

(1) Indicated mean effective pressure

In Lesson 2 it was explained how the pressure in a cylinder changes according to each stroke, suction-compression-explosion-exhaust. The pressure is measured by an indicator and we can see the work done in the cylinder with this measurement. Fig. 3.1 is an indicated diagram in which the compression and explosion strokes are shown. The graphs shows distance on the axis of abscissa and pressure on the axis of ordinate.

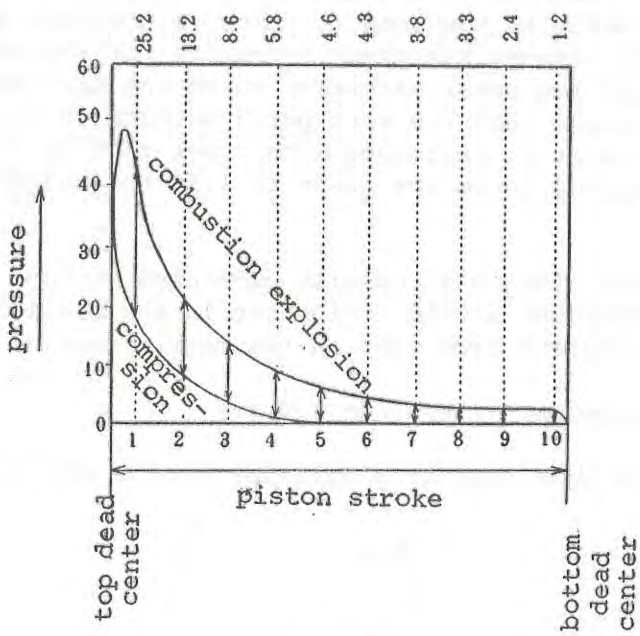


Fig. 3-1

The area inside the two curves shows the work-load, and the size of the area corresponds to the size of the work-load. As the piston comes near the top dead center from the bottom dead center, the air in the cylinder gets compressed and the pressure becomes high. Toward the end of the compression stroke fuel is injected, and when it ignites the explosion pushes the piston down. When the piston is at the top dead center there is a very high pressure, and the pressure in the cylinder becomes lower and lower as the piston descends. The pressure of the explosion curve differs from that of compression curve on the same position of two strokes. We call this difference the effective pressure. The effective pressure changes when the piston changes position. The effective pressure works to rotate the crankshaft, and works to the next compression stroke or another work-load. It is very difficult to describe the amount of effective pressure, therefore we usually use the term "mean effective pressure".

The method of calculating the mean effective pressure is as follows. If the indicated diagram is drawn accurately with an indicator as in Fig. 3-1, you divide piston strokes into 10 equal parts and measure the pressure with a rule attached to an indicator.

In the case of Fig. 3-1, if part 1 is 25.2, part two 13.2, part three 8.6, part four 5.8, part five 4.6, part six 4.3, part seven 3.8, part eight 3.3, part nine 2.4, and part ten 1.2, then the mean effective pressure is,

$$Pmi = \frac{25.2 + 13.2 + 8.6 + 5.8 + 4.6 + 5.4 + 3.8 + 3.3 + 2.4 + 1.2}{10}$$

$$= 7.24 \ (kg/cm^2)$$

This 7.24 kg/cm^2 is the calculated mean value of the pressure which pushes the piston from top dead center to bottom dead center; in reality, the pressure varies from 25.2 kg/cm^2 in part 1 to 1.2 kg/cm^2 in part 10.

(2) The sectional area of the cylinder and the piston stroke.

The volume from the bottom dead center to the top dead center is called the cylinder volume (see Fig. 3-2).

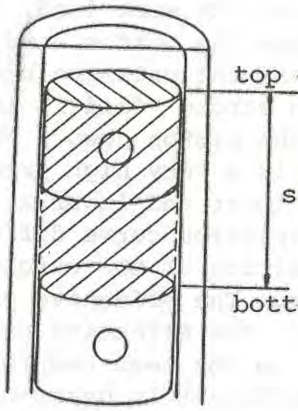


Fig. 3-2

In order to measure this volume we use the following formula:

$$V = \frac{\pi}{4} D^2 . L$$

V .... cylinder volume
D .... diameter of cylinder
L .... piston stroke
π .... ratio of circumference of a circle to its diameter (3.14)

(3) Revolution per minute

The revolving number of the engine shows the number of times the piston is pushed down by combustion. The higher the number of revolutions, the higher the work-load to push the piston down by combustion. Therefore in the case of a 4-cycle engine there is one combustion per 2 rotations of engine, so the numerical value 2 is placed in the denominator of the formula for calculating the horsepower.

(4) 75 × 60

The reason why the numerical value "75" is placed in the denominator is because the work-load is changed into the horsepower, and a horsepower is 75 kg m/sec. Number "60" is placed in the denominator because the number of revolutions per minute is converted into the number of revolutions per second.

(5) If you increase the mean effective pressure, the cylinder volume and the number of revolutions per minute, you can make the horsepower larger too, as this formula shows. But you can not make the cylinder volume (the diameter of piston and the stroke) larger after an engine has been completed. Because the cylinder volume is fixed, you have to adopt the method of raising the mean effective pressure or increasing the number of revolutions per minute, that is, the number of combustions per minute. For this, you should design the combustion chamber so as to get effective combustion and to let air fully into the cylinder. The amount of air in the cylinder can also be increased by attaching a super-charge.

3.3 Brake Horsepower (B.P.S. or B.H.P.)

Brake horsepower is also called net horsepower. This is the power obtained from the crankshaft as the actual power which can operate various kinds of machines.

To measure brake horsepower we use a dynamometor. There are various types of dynamometers:

(a) Friction dynamometer (Prony brake, Rope brake)
(b) Water dynamometer (Froude type, Junkers type)
(c) Electric dynamometer
(d) Fan dynamometer (Fan brake)

3.4 Mechanical Efficiency

The heat (calories) generated by combustion of fuel in the cylinder can not wholly be used effectively. It was explained in the previous chapter that the power turned out to do effective work is known as indicated horsepower. The power which can actually run a working machine and is obtained from the crankshaft is called the brake horsepower. There is a power consumed by a machine's motion between the indicated horsepower and the brake horsepower. We call it the mechanical loss. So the brake horsepower is when the mechanical loss is deducted from the indicated horsepower: Brake horsepower = (indicated horsepower)-(mechanical loss)

The mechanical losses are usually divided into three groups:

(a) Friction loss

There is the friction by the run of the piston ring and the liner, the friction by the crankshaft and the bearing metal.

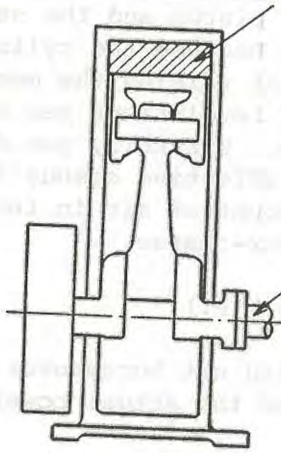


Fig. 3-3

(b) Loss by equipment operation

Some auxiliary equipment uses energy for its operation, for example water pump, oil pump, fuel pump and so on.

(c) Pump loss

This is the power used to let fresh air in or to push exhaust gas out as the piston runs up and down in the cylinder.

The smaller this mechanical loss is, the better. When you assemble an engine, you will find it necessary to assemble it so accurately as to put a right clearance in every part and put each part in a right place after the overhaul of engine for fear this mechanical loss may increase. It is the mechanical efficiency that shows to what extent the indicated horsepower is the effective horsepower, that is, the brake horsepower.

$$\text{Mechanical efficiency} = \frac{\text{brake horsepower}}{\text{indicated horsepower}} \times 100\ (\%)$$

The mechanical efficiency of an internal combustion engine is generally as follows:

Table 3-1

Type of engine	Mechanical efficiency (%)
Small gasoline engine	76 - 81
Light oil engine	76 - 80
Hot-bulb engine	65 - 82
Four-cycle diesel	75 - 84
Two-cycle diesel	82 - 85

3.5 Thermal Efficiency

Energy generated by the combustion of fuel in the cylinder cannot all be turned into effective work. Some of it is taken away by cooling water and escapes with the exhaust gas as heat energy. How much energy is lost in this way is expressed by the so-called "heat balance". Some examples are given in the following table.

Table 3-2

Type of engine	Cooling loss (%)	Exhaust gas and radiation loss (%)	Friction loss (%)
Small gasoline engine	31 - 37	31 - 35	7 - 12
Light oil engine	39 - 41	30 - 33	7 - 13
Hot-bulb engine	18 - 23	40 - 56	8 - 10
Four-cycle diesel	21 - 25	33 - 39	6 - 9
Two-cycle diesel	24 - 28	33 - 38	6 - 8

The ratio of the energy changed into effective work and the energy given to the engine is called the thermal efficiency:

$$\text{Thermal efficiency} = \frac{\text{energy changed into work}}{\text{energy given to engine}} \times 100\ (\%)$$

The thermal efficiency is devided into the indicated thermal efficiency and the brake thermal efficiency.

The indicated thermal efficiency is the rate of the energy from which the work-load is actually generated in a cylinder, that is, the rate of the energy which is calculated from the indicated horsepower and all the energy given to the engine.

The brake thermal efficiency is the rate of the energy into which the work-load gets from the crankshaft as power, that is the brake horsepower:

Brake thermal efficiency = (indicated thermal efficiency) × (mechanical efficiency)

3.6 Rate of Fuel Consumption

(1) If the consumed fuel is Qkg when the engine is put to operation with a fixed load per hour, the amount of fuel per one horsepower per hour is as follows, if we put Bps brake horsepower there as the load:

$$\frac{Q\ (kg)}{B\ (ps)} \times 1{,}000 = b\ (g/ps.h)$$

This b (g/ps.h) is called the rate of fuel consumption. This rate of fuel consumption is used for easy comparison because it is inconvenient for us to be unable to compare different volumes of engine fuel consumption only with the use of fuel consumption Qkg.

In order to know the fuel consumption, we measure the weight of the fuel consumed at fixed intervals directly with a platform balance, or we can measure the volume with a bottle.

(2) To calculate how much fuel is needed for the engine having a definite rate of fuel consumption b (g/ps.h) with B.P.S. per H hours, the following formula is used:

$$Q = \frac{b \times B.P.S. \times H}{\delta \times 10^3}$$

Q .... fuel consumption (kg)
b .... rate of fuel consumption (g/ps.h)
B.P.S. ..... brake horsepower (ps)
H .... operating hours (h)
δ .... specific gravity of fuel

Heavy oil 0.88 - 0.90
Light oil 0.82 - 0.86 } approximately

(3) The rate of minimum fuel consumption of internal combustion engines is generally as shown in the table below.

Table 3-3

Type of engine	Rate of fuel comsumption (g/ps.h)
Small gasoline engine	250 - 300
Light oil engine	300 - 390
Hot-bulb engine	230 - 350
Four-cycle diesel engine	165 - 215
Two-cycle diesel engine	165 - 180

(4) An example

Let us calculate the amount of fuel needed in order to operate an engine having the rate of minimum fuel consumption 210 g/ps.h for 3 hours in succession with 25 horsepowers of brake horsepower.

(Use 0.88 as the specific gravity of fuel)

$$Q = \frac{210 \times 25 \times 3}{0.88 \times 10} = 17.9 \ (\ell)$$

When you design the fuel tank of a vessel, you need to increase the volume of the fuel tank by 1.2 to 1.5 times, or else you may find it difficult for the engine to run with the shortage of fuel.

3.7 Torque

The power obtained from the crankshaft of the engine makes the propeller and/or generator revolve and the magnitude of the revolving power (torque) with which you can operate becomes an important consideration.

The torque can be calculated with the following formula:

$$T = \frac{60 \times 75 \times B.P.S.}{2\pi N} = \frac{716.2 \times B.P.S.}{N}$$

T .... torque (m.kg)
B.P.S .... brake horsepower
π .... ratio of circumference of a circle to its diameter (3.14)
N .... revolution (r.p.m.)

LESSON 4. THE PRINCIPLES OF COMBUSTION

In this lesson we shall study the general principles of combustion.

4.1 The Minimum Amount of Air Necessary for Combustion

The fuel used in the engine is a chemical compound of mainly carbon (symbol C) and hydrogen (symbol H) in which small quantities of sulfur (symbol S), oxygen (O) and so on are contained as impurities. If we know how much air is necessary to burn each component we can calculate the total amount of air needed for fuel combustion.

(Carbon)

$C + O_2 = CO_2$ .... carbon dioxide : complete combustion

(12kg) + (32kg) = (44kg)

$2C + O_2 = 2CO$ .... carbon monoxide : incomplete combustion

(24kg) + (32kg) = (56kg)

(Hydrogen)

$2H_2 + O_2 = 2H_2O$ .... steam : complete combustion

(4kg) + (32kg) = (36kg)

(Sulfur)

$S + O_2 = SO_2$ .... sulfur dioxide : complete combustion

(32kg) + (32kg) = (64kg)

That is, $\frac{32}{12} = \frac{8}{3}$ kg of oxygen is needed to burn 1 kg of carbon completely, $\frac{32}{4} = 8$ kg of oxygen to burn 1 kg of hydrogen completely, and $\frac{32}{32} = 1$ kg of oxygen to burn 1 kg of sulfur completely.

So, if we add up the weight of carbon, hydrogen, sulfur and oxygen contained in 1 kg of fuel, the weight (G) of oxygen necessary for burning these completely is as follows:

$$G = \frac{8}{3}C + 8H + S - O \text{ .... (kg)}$$

Air consists of 23% of oxygen (O_2) and 77% of nitrogen (N_2) in weight, and of 21% of oxygen and 79% of nitrogen in volume. Therefore, $\frac{100}{23}$ kg of air is needed to get 1 kg of oxygen. The weight of air (A) needed to burn 1 kg of fuel is,

$$A = \left(\frac{8}{3}C + 8H + S - O\right) \times \frac{100}{23} \text{ .... (kg)}$$
$$= 4.35 \left(\frac{8}{3}C + 8H + S - O\right)$$

If there is 87% of carbon, 9% of hydrogen, 0.6% of sulfur and 3.4% of oxygen contained in the fuel, the minimum weight of air needed to burn these completely is:

$$A = \left(\frac{8}{3} \times 0.87 + 8 \times 0.09 + 0.006 - 0.034\right) \times \frac{100}{23}$$
$$= 13.09 \text{ .... (kg)}$$

It is shown as weight. If we put the specific gravity in the standard condition of air into 1.293 kg/m^3, in order to change it into volume, we get

$$A = 3.36 \left(\frac{8}{3}C + 8H + S - O\right) \text{ .... } (m^3)$$

Note: In the standard conditions of 760 mm-Hg and $0^{\circ}C$, the theoretical air volume for different types of fuel is shown below.

Table 4-1

Type of fuel	theoretical air volume	
	kg/kg	m^3/kg
Paraffin series (light)	Ca. 15.0	Ca. 12.2
Paraffin series (heavy)	" 14.7	" 12.0
Naphthene & olefin series	" 14.6	" 11.9
Aromatic series (light)	" 13.1	" 10.7
Aromatic series (heavy)	" 14.1	" 11.4

4.2 Excess Air Ratio

The air volume given in the above table is the minimum necessary for combustion. In reality we can not expect complete combustion only with these volumes. For complete combustion, more air should be given. The ratio of actual volume of air supplied and the minimum volume of air necessary for burning is called the excess air ratio.

$$\text{Excess air ratio} = \frac{\text{volume of actually supplied air}}{\text{minimum volume necessary for burning}}$$

The larger this ratio and the excess air volume, the higher the loss of heat by exhaust. So far as fuels are burned completely, the smaller this volume is, the better. The rate of diesel engine is 1.5 to 2.0 in full load. The excess air ratio increases and the injection volume decreases as the engine load becomes low.

4.3 Types of Combustion Chamber

Various kinds of combustion chamber are so devised that air and fuel in a cylinder are fully mixed for good combustion. Combustion chambers can be classified roughly as follows:

single chamber engine .... direct injection type

double chamber engine — pre-combustion chamber type / swirl chamber type / air cell type

4.3.1 Direct injection

This type, as Fig. 4-1 shows, has one combustion chamber into which fuel is directly injected and it is used much in a comparatively large type of engine (the diameter of cylinder is more than 180 mm). Of course, some small engines also have this type of combustion chamber.

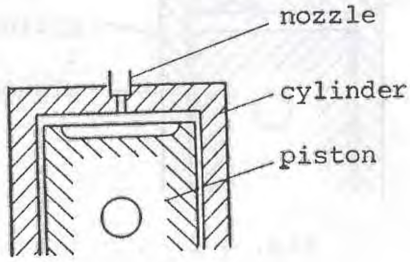


Fig. 4-1

A single chamber engine has the following advantages:

A) The shape of the combustion chamber is simpler than that of a double chamber engine and the production is easy;

B) It has a good starting;

C) The rate of fuel consumption is smaller than for a double chamber engine and it is approximately 160 - 200 g/ps.h.

On the other hand it has the following disadvantages:

D) A comparatively good quality of fuel is needed because it is sensitive to the quality of fuel;

E) The nozzle is often clogged up because the injection pressure of fuel is high (more than 200 kg/cm^2) and the bore of the nozzle is small;

F) It tends to cause knocking because the maximum pressure in the cylinder is high;

G) It is unfit for high-speed revolution.

4.3.2 Pre-combustion chamber

There is a pre-combustion chamber with about 35% of the whole volume of combustion chamber in a cylinder and a principal combustion chamber. The fuel is injected into the pre-combustion chamber from a nozzle. In this type of engine a part of fuel is burned in the pre-combustion chamber and the remaining fuel is injected into the main combustion chamber by the high pressured generated, and there it is burned completely.

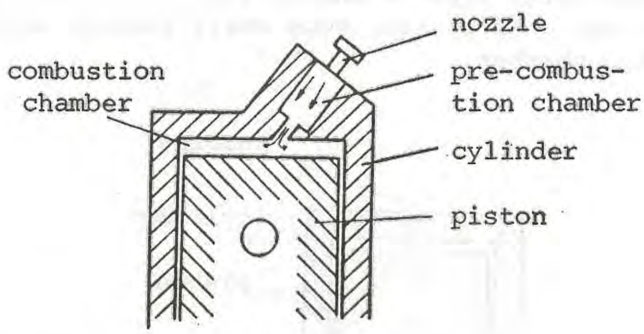


Fig. 4-2

The pre-combustion chamber type is used much when there is a comparatively small diameter of cylinder and for high-speed engines. It has advantages as follows:

A) Poorer quality fuel can be used, compared with that used in the direct injection type;

B) The injection pressure of fuel is comparatively small (approximately 120 kg/cm^2) and a large bore or nozzle will do. You can avoid clogging the nozzle by using pintle-type nozzle;

C) The maximum pressure in the cylinder is low;

D) It is not sensitive to the change of time of fuel injection;

E) It can make an engine revolve with a high speed.

The disadvantages of this type of engine are as follows:

F) The structure of the cylinder head is so complicated that it is difficult for us to make it;

G) Because it has bad starting, compared with a direct injection type, a step auxiliary for combustion is needed;

H) The fuel consumption ratio becomes large (200 - 250 g/ps.h) because a part of the fuel is burned in the pre-combustion chamber.

These advantages and disadvantage can be found also in the double-chamber engine (swirl chamber type, air cell type). The advantages of the direct injection type become the disadvantages of the double-chamber engine.

4.3.3 Swirl chamber

The structure of this type looks like that of a pre-combustion chamber type. The volume of swirl chamber type occupies roughly 70% of the whole volume of the combustion chamber.

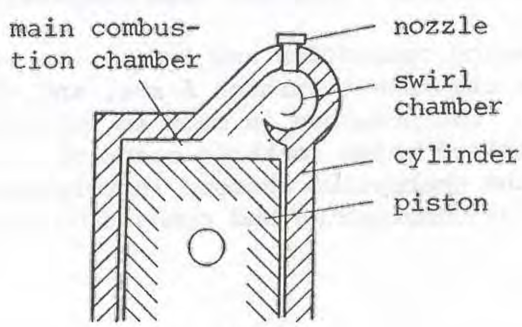


Fig. 4-3

The air compressed by the piston is let in the swirl chamber in which the air is swirled. Fuel is injected into this swirled air and burned. This type is suitable specially for high-speed revolution and is used in the engines for vehicles.

4.3.4 Air cell

This type resembles that of the swirl chamber engine, and the fuel injection is done in the main combustion chamber. An air chamber cell corresponding to 60-70% of the whole combustion chamber is attached to the cylinder or the piston. The air compressed by the piston is saved and as the piston runs down, combustion is kept going with the supply of fresh air from the air cell. Compared to other double chamber engines, this type has advantages of good starting, gentle combustion and quiet motion.

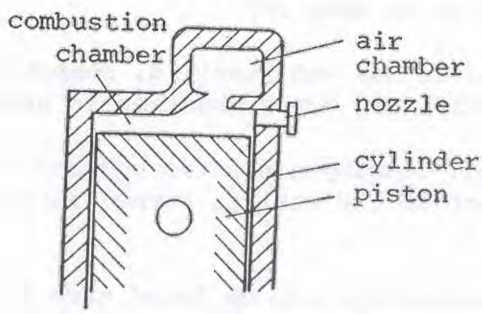


Fig. 4-4

4.4 Process of Combustion

Combustion in a diesel engine proceeds as follows: the air is sucked in and compressed (compression ratio 16-20) under high pressure (36-42 kg/cm^2). Fuel is atomized and injected into the combustion chamber where it becomes mixed with the high-temperature air, catches fire and burns.
The pressure increases by combustion and lowers the piston which supplies power to the crankshaft through a rod, and the combustion ends at a fixed time. The progress is made in succession of four stages which are explained below in their order of occurrence.
How the pressure in the combustion chamber is relative to the crank angle in the process of compression and combustion is as shown in Fig. 4-5.

The area from the middle of the graph to the left shows compression stroke before the top dead center, and the area to the right shows the explosion stroke after the top dead center.

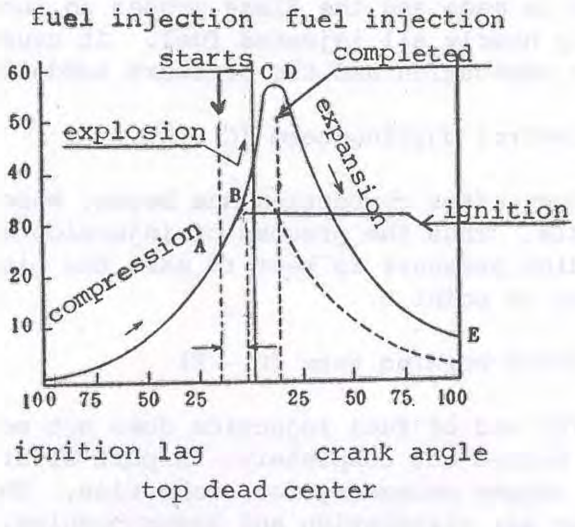


Fig. 4-5

As the piston rises, air is compressed and the pressure becomes higher. If the combustion is not completed the pressure becomes lower and lower, as shown by the dotted line, as the piston gets lowered after it runs over the top dead center. Theoretically speaking, a rising curve of the compressed pressure resembles a falling curve of the piston. As soon as the fuel is injected,the pressure suddenly becomes higher with the combustion of this fuel. Even after the fuel injection, expansion continues with combustion. The pressure becomes low with the expansion curve in the right of Fig. 4-5 as the piston descends.
The work is done corresponding to the area enclosed by the falling curve in non-combustion and the falling curve in combustion. If we classify the state after an injection into four terms, it is as follows:

(1) Ignition lag term (A → B)

Because fuel is injected through the nozzle, it doesn't follow that it begins to burn immediately. A drop of injected fuel is first vaporized with the high temperature in the cylinder and soon gets to the ignition point and burns. The period between the fuel injection and self-ignition of fuel is called the ignition lag.

(2) Explosive combustion term ($B \rightarrow C$)

During the ignition lag term the preparation for combustion is made. After the preparation a part of fuel catches fire by which a flame is made and the flame proves an incentive to burning simultaneously nearly all injected fuel. It causes an abrupt, that is, explosive combustion and the pressure suddenly becomes high.

(3) Control burning term ($C \rightarrow D$)

Even after combustion has begun, more fuel is injected from the nozzle. Thus the process of injection and combustion continues. High pressure is kept to make the piston push and the injection ends in point D.

(4) After-burning term ($D \rightarrow E$)

The end of fuel injection does not mean that fuel already injected has burned out completely. A part of it remains out of contact with oxygen necessary for combustion. This comes into touch with oxygen by air circulation and keeps burning. After these steps combustion ends.

If the ignition lag is too long, the fuel volume from injection increases before firing. When the fuel ignites, explosive combustion causes a sudden rise in pressure. This causes knocking.

If the succeeding combustion is too long, the thermal efficiency of diesel engine is decreased, because the combustion energy should be taken to the exhaust manifold without working. To get good thermal efficiency, it may be necessary to shorten the term of injection or to advance the injection timing. But this may bring a sudden increase of pressure in the cylinder, so you cannot shorten or advance too much. The timing should be set to get rather a low maximum pressure and short after-burning.

4.5 Diesel Knocking

While the diesel engine is in operation, especially slow, we can hear a knocking sound. There is a mechanical knocking sound made by the wear of the piston pin pushing, and a sound made by combustion. You may find them difficult to distinguish, but if a knock is heard from around the combustion chamber when we turn the crank speedily in the state of decompression without supplying fuel to the engine, you may safely regard it as a mechanical knocking sound made by the piston pin or cause by the lack of top clearance. You should inspect the engine because it may be damaged if operation is continued in this condition. Further details of the knocking sound by combustion are given below (in the case of a diesel engine it is called a diesel knock and it is different from the knock of a gasoline engine).

(1) Knocking of gasoline engine

Figure 4-6 shows the cylinder section of the gasoline engine. In the case of a gasoline engine, gas mixed with air enters into the cylinder in the suction stroke.

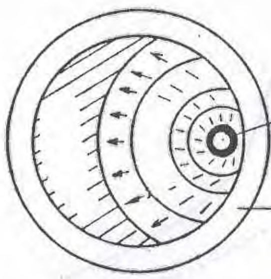


Fig. 4-6

This mixed gas is compressed (it cannot be compressed too much and the compression ratio is approximately 4.5, the pressure after compression is about 7 kg/cm^2) and toward the end of the compression stroke an electric spark is given off from a spark plug and with it the mixed gas in the cylinder burns in an explosive combustion by which the piston gets lowered. If you inspect a very short interval of combustion in a little more detail, you will find the course as follows.

(A) The mixed gas around the spark plug is ignited.

(B) The flames spread out radially from the spark plug to the outside by degrees and are propagated (Fig. 4-6).

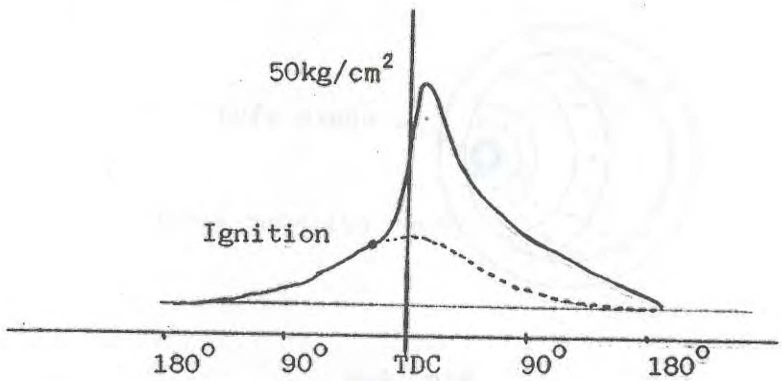
(C) Mixed gas which is not burned yet is pushed to the front of flame by the pressure of burned fuel into compression.

(D) The pressure and temperature of compressed and mixed gas which is not yet burned become higher and higher and the gas ignites by its own temperature (Fig. 4-7).

(E) A knocking sound is made by the cylinder wall vibrating with the pressure wave caused as the mixed has not yet burned comes to spontaneous ignition at a stretch.

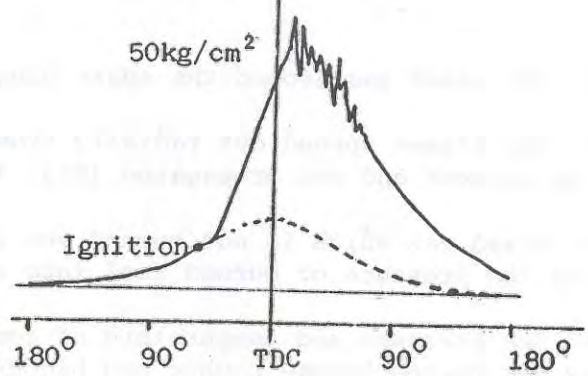
Furthermore, the following trouble may be caused by knocking:

(a) overheating of cylinder;
(b) lack of power and bad working condition;
(c) increase of stress in all parts.



(a)

Fig. 4-7



(b) knocking

Fig. 4-7

(2) Knocking of diesel engine

Fig. 4-8 shows cross section of a diesel engine cylinder. A diesel engine does not have a spark plug which a gasoline engine has. Unless there is an ignition lag, each drop of atomized fuel injected from the nozzle catches fire soon.

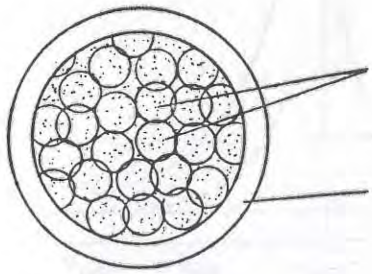


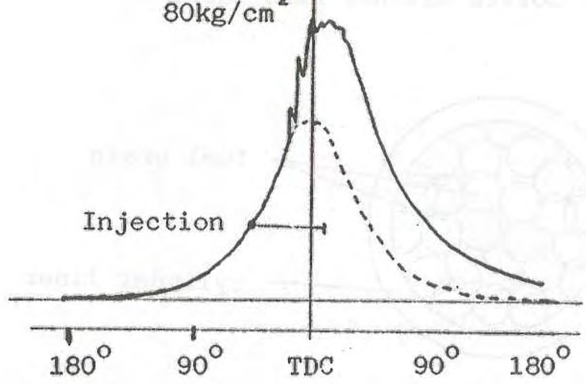
Fig. 4-8

If the fuel burns at once as soon as it is injected knocking doesn't occur.

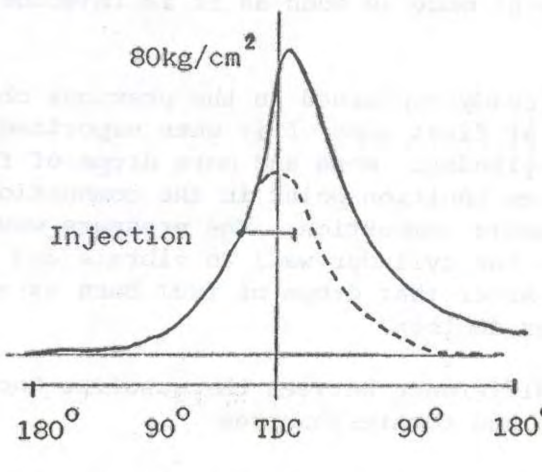
As already explained in the previous chapter, when the fuel is injected at first some of it gets vaporized by the high pressure in the cylinder. More and more drops of fuel are injected and when it reaches ignition point in the combustion chamber there is a sudden explosive combustion. The pressure wave made by this combustion forces the cylinder wall to vibrate and this makes a knocking sound. After that drops of fuel burn as soon as they are injected one after another.

(3) The difference between the gasoline knock and the diesel knock and countermeasures

Both gasoline and diesel knock are caused by vibration of the cylinder wall through sudden combustion, but the difference is that the diesel knock occurs with the first combustion and the gasoline knock at the end of combustion. In comparison with the change of both pressures by a knocking combustion, there is difference as shown in Fig. 4-7 and Fig. 4-9. The reasons for knocking are contrary to each other. Therefore the ways to avoid knocking are contrary too.


80kg/cm²
Injection
180°
90°
TDC
90°
180°

(a)


80kg/cm²
Injection
180°
90°
TDC
90°
180°

(b)

Fig. 4-9

Table 4-2

Description	Gasoline engine	Diesel engine
Compression ratio	Lower the ratio, as a high compression ratio promotes natural ignition	A higher compression ratio causes less late ignition thus preventing knocking
Suction pressure and suction temperature	A higher suction pressure and suction temperature promote self-ignition at un-combustion part. Suction pressure and temperature should be lowered	A higher suction pressure and suction temperature in the initial stage of injection cause less late ignition
Fuel ignition point	Use a fuel that is hard to cause self-ignition	Select a fuel with good ignition point as well as high catane number content
Temperature of cylinder	Make the cooling water temperature low so as to cool the cylinder wall, in order to prevent self-ignition which would result in knocking	Low coolant water temperature and the temperature of cylinder wall make the ignition late. Try to raise this, as well as suction temperature
Cylinder volume	The larger the volume of cylinder, the longer propagation of fire resulting in knocking. Therefore install two spark plugs	The larger the cylinder volume, less escane of gas temperature due to compression, resulting in earlier ignition
Swivelling speed	Decreased swivelling speed causes knocking	A drop in revolution or injection ratio (decrease the quantity of fuel needed for sudden combustion)

4.6 Terms Relating to Combustion

4.6.1 Flash point and ignition point

(A) Flash point

Heat is added to the fuel by degrees and when you allow vaporized fuel to come near flame, it catches fire. We call this minimum temperature the flash point. Even after the combustion has started around the flash point, only vaporized fuel burns and the combustion ends soon. If the temperature gets higher than the flash point by 20-30^{o}C., the generating speed of vapor increases and combustion continues as more vapour is generated. We call this minimum temperature the fire point. The flash point is not so important for combustion in the cylinder, but it is important for storage of fuel conveyance and handling.

(B) Ignition point

As we heat fuel in the air, it self-ignites at a certain temperature. We call this minimum temperature the ignition point, which has an important relation with combustion in the cylinder. That is, if we heat a mixture of air and fuel, the molecular movement becomes more active, the collision frequency of fuel molecules and oxygen molecules increases, the reaction of oxidation begins, and heat is generated. During a low temperature this reaction of oxidation is slow and the generated heat volume is less than the thermal capacity absorbed around by the conduction of heat, but as the temperature rises the reaction speed increases. When the generating heat capacity becomes more than radiant heat capacity in the end, the temperature rises. Oxidation becomes more active with this heat and increases suddenly above a certain temperature. Finally flame appears and there is combustion. We call this spontaneous ignition or self-ignition.

4.6.2 Octane number and cetane number

(A) Octane number

The cause of knocking in operation of gasoline engine has a close relation with the quality of fuel. The quality which prevents knocking is called anti-knock property and it is the octane number that is a measure of this anti-knock property. The large the octane number the higher the anti-knock property of fuel. Iso-octane fuel has the greatest anti-knock property and its octane number is also the highest. Normal heptane has the smallest anti-knock property of all gasoline ingredients and its octane number is 0. The octane number of a fuel is indicated by the volume of iso-octane in it.

(B) Cetane number

In the fuel used for the diesel engine, ignition property exerts a great influence on the time of ignition lag. Therefore, cetane number is used as well as octane number of gasoline in order to show the ignition property quantitatively. The fuel with a larger cetane number has better ignition property and will cause less diesel knocking. The cetane numbers of the cetane which has a good ignition property and of the methyl naphthalene which has a bad ignition property are put at 100 and 0 respectively. The cetane number is shown by the percentage of cetane after both are mixed properly.