AUTOMOTIVE ENGINEERING

POWERTRAIN, CHASSIS SYSTEM AND VEHICLE BODY

EDITED BY DAVID A. CROLLA

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Powertrain, Chassis System and Vehicle Body

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1.1

Piston-engine cycles of operation

Heinz Heisler

1.1.1 The internal-combustion engine

The piston engine is known as an internal-combustion heat-engine. The concept of the piston engine is that a supply of air-and-fuel mixture is fed to the inside of the cylinder where it is compressed and then burnt. This internal combustion releases heat energy which is then converted into useful mechanical work as the high gas pressures generated force the piston to move along its stroke in the cylinder. It can be said, therefore, that a heat-engine is merely an energy transformer.

To enable the piston movement to be harnessed, the driving thrust on the piston is transmitted by means of a connecting-rod to a crankshaft whose function is to convert the linear piston motion in the cylinder to a rotary crankshaft movement (Fig. 1.1-1). The piston can thus be made to repeat its movement to and fro, due to the constraints of the crankshaft crankpin's circular path and the guiding cylinder.

The backward-and-forward displacement of the piston is generally referred to as the *reciprocating* motion of the piston, so these power units are also known as reciprocating engines.

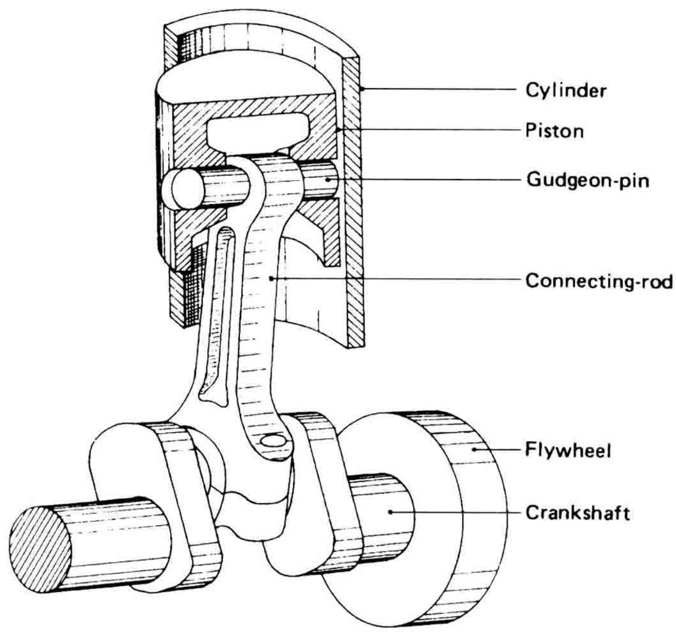

Fig. 1.1-1 Pictorial view of the basic engine.

1.1.1.1 Engine components and terms

The main problem in understanding the construction of the reciprocating piston engine is being able to identify and name the various parts making up the power unit. To this end, the following briefly describes the major components and the names given to them (Figs. 1.1-1 and 1.1-2).

Cylinder block This is a cast structure with cylindrical holes bored to guide and support the pistons and to harness the working gases. It also provides a jacket to contain a liquid coolant.

Cylinder head This casting encloses the combustion end of the cylinder block and houses both the inlet and exhaust poppet-valves and their ports to admit air–fuel mixture and to exhaust the combustion products.

Crankcase This is a cast rigid structure which supports and houses the crankshaft and bearings. It is usually cast as a mono-construction with the cylinder block.

Sump This is a pressed-steel or cast-aluminium-alloy container which encloses the bottom of the crankcase and provides a reservoir for the engine's lubricant.

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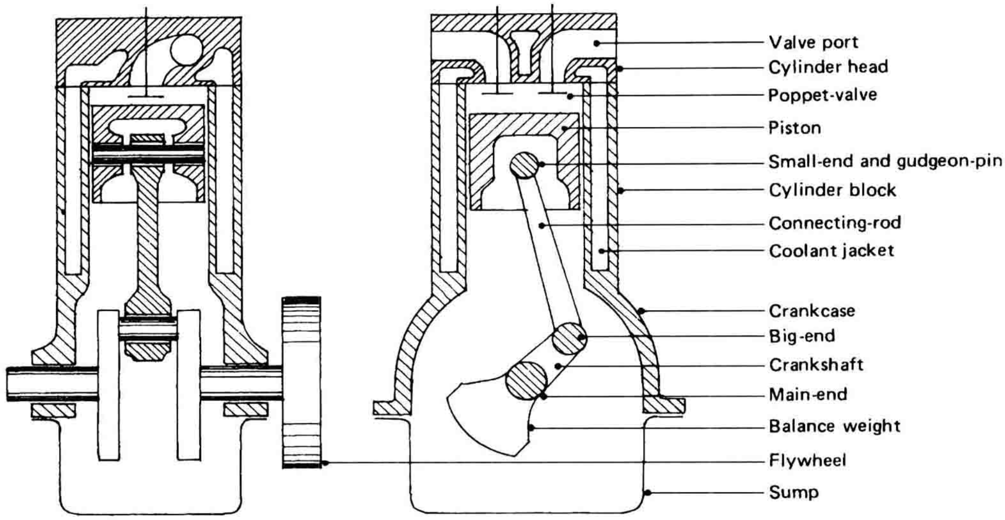

Fig. 1.1-2 Sectional view of the basic engine.

Piston This is a pressure-tight cylindrical plunger which is subjected to the expanding gas pressure. Its function is to convert the gas pressure from combustion into a concentrated driving thrust along the connecting-rod. It must therefore also act as a guide for the small-end of the connecting-rod.

Piston rings These are circular rings which seal the gaps made between the piston and the cylinder, their object being to prevent gas escaping and to control the amount of lubricant which is allowed to reach the top of the cylinder.

Gudgeon-pin This pin transfers the thrust from the piston to the connecting-rod small-end while permitting the rod to rock to and fro as the crankshaft rotates.

Connecting-rod This acts as both a strut and a tie link-rod. It transmits the linear pressure impulses acting on the piston to the crankshaft big-end journal, where they are converted into turning-effort.

Crankshaft A simple crankshaft consists of a circular-sectioned shaft which is bent or cranked to form two perpendicular crank-arms and an offset big-end journal. The unbent part of the shaft provides the main journals. The crankshaft is indirectly linked by the connecting-rod to the piston – this enables the straight-line motion of the piston to be transformed into a rotary motion at the crankshaft about the main-journal axis.

Crankshaft journals These are highly finished cylindrical pins machined parallel on both the centre axes and the offset axes of the crankshaft. When assembled, these journals rotate in plain bush-type bearings mounted in the crankcase (the main journals) and in one end of the connecting-rod (the big-end journal).

Small-end This refers to the hinged joint made by the gudgeon-pin between the piston and the connecting-rod so that the connecting-rod is free to oscillate relative to the cylinder axis as it moves to and fro in the cylinder.

Big-end This refers to the joint between the connecting-rod and the crankshaft big-end journal which provides the relative angular movement between the two components as the engine rotates.

Main-ends This refers to the rubbing pairs formed between the crankshaft main journals and their respective plain bearings mounted in the crankcase.

Line of stroke The centre path the piston is forced to follow due to the constraints of the cylinder is known as the line of stroke.

Inner and outer dead centres When the crankarm and the connecting-rod are aligned along the line of stroke, the piston will be in either one of its two extreme positions. If the piston is at its closest position to the cylinder head, the crank and piston are said to be at inner dead centre (IDC) or top dead centre (TDC). With the piston at its furthest position from the cylinder head, the crank and piston are said to be at outer dead centre (ODC) or bottom dead centre (BDC). These reference points are of considerable importance for valve-to-crankshaft timing and for either ignition or injection settings.

Clearance volume The space between the cylinder head and the piston crown at TDC is known as the clearance volume or the combustion-chamber space.

Crank-throw The distance from the centre of the crankshaft main journal to the centre of the big-end journal is known as the crank-throw. This radial length influences the leverage the gas pressure acting on the piston can apply in rotating the crankshaft.

Piston stroke The piston movement from IDC to ODC is known as the piston stroke and corresponds to the crankshaft rotating half a revolution or 180°. It is also equal to twice the crank-throw.

i.e. $L = 2R$
where L = piston stroke
and R = crank-throw

Thus a long or short stroke will enable a large or small turning-effort to be applied to the crankshaft respectively.

Cylinder bore The cylinder block is initially cast with sand cores occupying the cylinder spaces. After the sand cores have been removed, the rough holes are machined with a single-point cutting tool attached radially at the end of a rotating bar. The removal of the unwanted metal in the hole is commonly known as boring the cylinder to size. Thus the finished cylindrical hole is known as the cylinder bore, and its internal diameter simply as the bore or bore size.

1.1.1.2 The four-stroke-cycle spark-ignition (petrol) engine

The first internal-combustion engine to operate successfully on the four-stroke cycle used gas as a fuel and was built in 1876 by Nicolaus August Otto, a self-taught German engineer at the Gas-motoreufabrik Deutz factory near Cologne, for many years the largest manufacturer of internal-combustion engines in the world. It was one of Otto's associates – Gottlieb Daimler – who later developed an engine to run on petrol which was described in patent number 4315 of 1885. He also pioneered its application to the motor vehicle (Fig. 1.1-3).

Petrol engines take in a flammable mixture of air and petrol which is ignited by a timed spark when the charge is compressed. These engines are therefore sometimes called spark-ignition (S.I.) engines.

These engines require four piston strokes to complete one cycle: an air-and-fuel intake stroke moving outward from the cylinder head, an inward movement towards the cylinder head compressing the charge, an outward power stroke, and an inward exhaust stroke.

Induction stroke (Fig. 1.1-3(a)) The inlet valve is opened and the exhaust valve is closed. The piston descends, moving away from the cylinder head (Fig. 1.1-3(a)). The speed of the piston moving along the cylinder creates a pressure reduction or depression which reaches a maximum of about 0.3 bar below atmospheric pressure at one-third from the beginning of the stroke. The depression actually generated will depend on the speed and load experienced by the engine, but a typical average value might be 0.12 bar below atmospheric pressure. This depression induces (sucks in) a fresh charge of air and atomised petrol in proportions ranging from 10 to 17 parts of air to one part of petrol by weight.

An engine which induces fresh charge by means of a depression in the cylinder is said to be 'normally aspirated' or 'naturally aspirated'.

Compression stroke (Fig. 1.1-3(b)) Both the inlet and the exhaust valves are closed. The piston begins to ascend towards the cylinder head (Fig. 1.1-3(b)). The induced air-and-petrol charge is progressively compressed to something of the order of one-eighth to one-tenth of the cylinder's original volume at the piston's innermost position. This compression squeezes the air and atomised-petrol molecules closer together and not only increases the charge pressure in the cylinder but also raises the temperature. Typical maximum cylinder compression pressures will range between 8 and 14 bar with the throttle open and the engine running under load.

Power stroke (Fig. 1.1-3(c)) Both the inlet and the exhaust valves are closed and, just before the piston approaches the top of its stroke during compression, a spark-plug ignites the dense combustible charge (Fig. 1.1-3(c)). By the time the piston reaches the innermost point of its stroke, the charge mixture begins to burn, generates heat, and rapidly raises the pressure in the cylinder until the gas forces exceed the resisting load. The burning gases then expand and so change the piston's direction of motion and push it to its outermost position. The cylinder pressure then drops from a peak value of about 60 bar under full load down to maybe 4 bar near the outermost movement of the piston.

Exhaust stroke (Fig. 1.1-3(d)) At the end of the power stroke the inlet valve remains closed but the exhaust valve is opened. The piston changes its direction of motion and now moves from the outermost to the innermost position (Fig. 1.1-3(d)). Most of the burnt gases will be expelled by the existing pressure energy of the gas, but the returning piston will push the last of the spent gases out of the cylinder through the exhaust-valve port and to the atmosphere.

During the exhaust stroke, the gas pressure in the cylinder will fall from the exhaust-valve opening pressure (which may vary from 2 to 5 bar, depending on the engine speed and the throttle-opening position) to atmospheric pressure or even less as the piston nears the innermost position towards the cylinder head.

Cycle of events in a four-cylinder engine (Figs. 1.1-3(e)–(g)) Fig. 1.1-3(e) illustrates how the cycle of events – induction, compression, power, and exhaust – is phased in a four-cylinder engine. The relationship between cylinder pressure and piston stroke position over the four strokes is clearly shown in Figs. 1.1-3(f) and (g) and, by following the arrows, it can be seen that a figures of eight is repeatedly being traced.

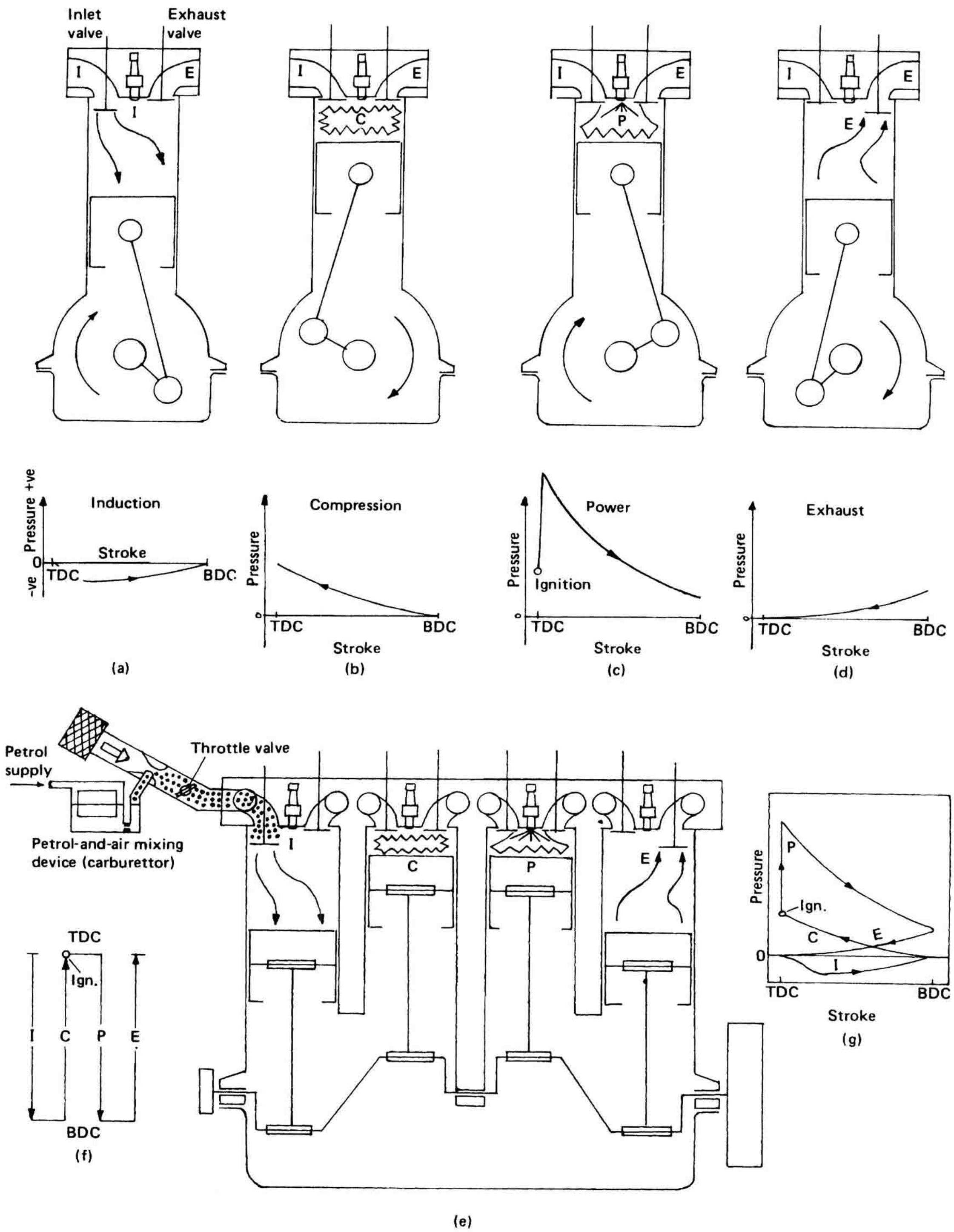

Fig. 1.1-3 Four-stroke-cycle petrol engine.

1.1.1.3 Valve timing diagrams

In practice, the events of the four-stroke cycle do not start and finish exactly at the two ends of the strokes – to improve the breathing and exhausting, the inlet valve is arranged to open before TDC and to close after BDC and the exhaust valve opens before BDC and closes after TDC. These early and late opening and closing events can be shown on a valve timing diagram such as Fig. 1.1-4.

Valve lead This is where a valve opens so many degrees of crankshaft rotation before either TDC or BDC.

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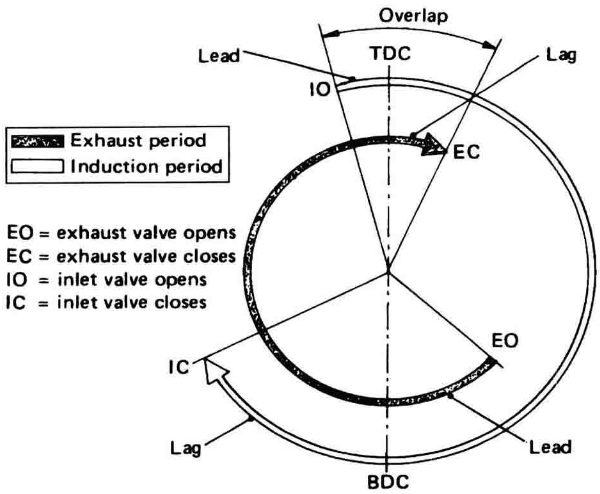

Fig. 1.1-4 Valve timing diagram.

Valve lag This is where a valve closes so many degrees of crankshaft rotation after TDC or BDC.

Valve overlap This is the condition when both the inlet and the exhaust valves are open at the same time during so many degrees of crankshaft rotation.

1.1.2 The two-stroke-cycle petrol engine

The first successful design of a three-port two-stroke engine was patented in 1889 by Joseph Day & Son of Bath. This employed the underside of the piston in conjunction with a sealed crank-case to form a scavenge pump ('scavenging' being the pushing-out of exhaust gas by the induction of fresh charge) (Fig. 1.1-5).

This engine completes the cycle of events – induction, compression, power, and exhaust – in one revolution of the crankshaft or two complete piston strokes.

Crankcase-to-cylinder mixture transfer (Fig. 1.1-5(a)) The piston moves down the cylinder and initially uncovers the exhaust port (E), releasing the burnt exhaust gases to the atmosphere. Simultaneously the downward movement of the underside of the piston compresses the previously filled mixture of air and atomised petrol in the crankcase (Fig. 1.1-5(a)). Further outward movement of the piston will uncover the transfer port (T), and the compressed mixture in the crankcase will then be transferred to the combustion-chamber side of the cylinder. The situation in the cylinder will then be such that the fresh charge entering the cylinder will push out any remaining burnt products of combustion – this process is generally referred to as cross-flow scavenging.

Cylinder compression and crankcase induction (Fig. 1.1-5(b)) The crankshaft rotates, moving the piston in the direction of the cylinder head. Initially the piston seals off the transfer port, and then a short time later the exhaust port will be completely closed. Further inward movement of the piston will compress the mixture of air and atomised petrol to about one-seventh to one-eighth of its original volume (Fig. 1.1-5(b)).

At the same time as the fresh charge is being compressed between the combustion chamber and the piston head, the inward movement of the piston increases the total volume in the crank-case so that a depression is created in this space. About half-way up the cylinder stroke, the lower part of the piston skirt will uncover the inlet port (I), and a fresh mixture of air and petrol prepared by the carburettor will be induced into the crank-case chamber (Fig. 1.1-5(b)).

Cylinder combustion and crankcase compression (Fig. 1.1-5(c)) Just before the piston reaches the top of its stroke, a spark-plug situated in the centre of the cylinder head will be timed to spark and ignite the dense mixture. The burning rate of the charge will rapidly raise the gas pressure to a maximum of about 50 bar under full load. The burning mixture then expands, forcing the piston back along its stroke with a corresponding reduction in cylinder pressure (Fig. 1.1-5(c)).

Considering the condition underneath the piston in the crankcase, with the piston initially at the top of its stroke, fresh mixture will have entered the crankcase through the inlet port. As the piston moves down its stroke, the piston skirt will cover the inlet port, and any further downward movement will compress the mixture in the crankcase in preparation for the next charge transfer into the cylinder and combustion-chamber space (Fig. 1.1-5(c)).

The combined cycle of events adapted to a three-cylinder engine is shown in Fig. 1.1-5(d). Figs. 1.1-5(e) and (f) show the complete cycle in terms of opening and closing events and cylinder volume and pressure changes respectively.

1.1.2.1 Reverse-flow (Schnuerle) scavenging

To improve scavenging efficiency, a loop-scavenging system which became known as the reverse-flow or (after its inventor, Dr E. Schnuerle) as the Schnuerle scavenging system was developed (Fig. 1.1-6). This layout has a transfer port on each side of the exhaust port, and these direct the scavenging charge mixture in a practically tangential direction towards the opposite cylinder wall. The two separate columns of the scavenging mixture meet and merge together at this wall to form one inward rising flow which turns under the cylinder head and then flows down on the entry side, thus forming a complete loop. With this form of porting, turbulence and intermixing of fresh fuel mixture with residual burnt gases will be minimal over a wide range of piston speeds.

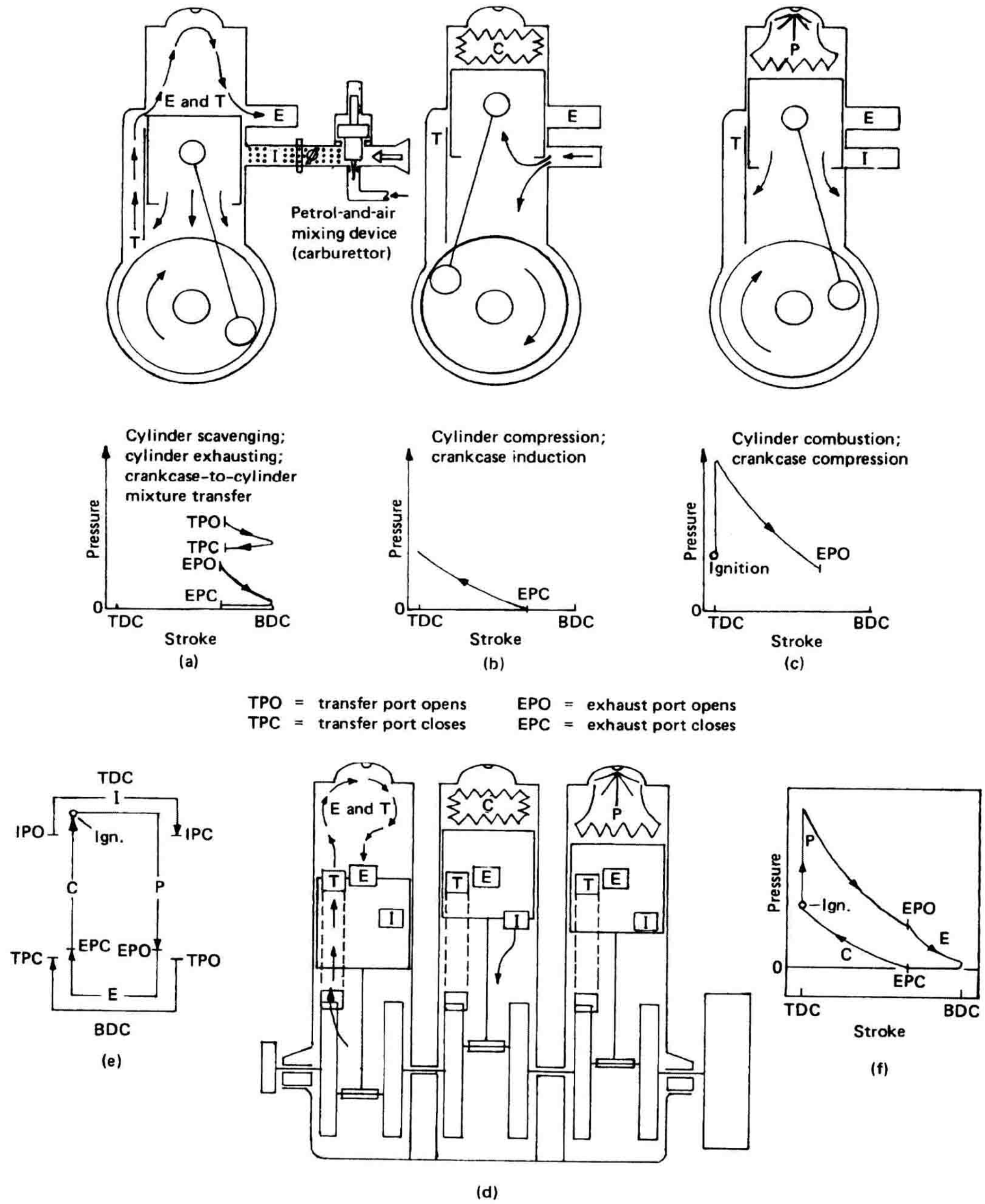

Fig. 1.1-5 Two-stroke-cycle petrol engine.

Note that in this particular design the charge mixture is transferred through ports formed in the piston skirt. Alternatively, extended transfer passages may be preferred so that the piston skirt plays no part in the timed transfer.

1.1.2.2 Crankcase disc-valve and reed-valve inlet charge control

An alternative to the piston-operated crankcase inlet port is to use a disc-valve attached to and driven by the crankshaft (Fig. 1.1-7(a)). This disc-valve is timed to open and close so that the fresh charge is induced to enter the crankcase as early as possible, and only at the point when the charge is about to be transferred into the cylinder is it closed. This method of controlling crankcase induction does not depend upon the piston displacement to uncover the port – it can therefore be so phased as to extend the filling period (Fig. 1.1-7).

A further method of improving crankcase filling is the use of reed-valves (Fig. 1.1-7(b)). These valves are not timed to open and close, but operate automatically when the pressure difference between the crankcase and the air intake is sufficient to deflect the reed-spring. In other

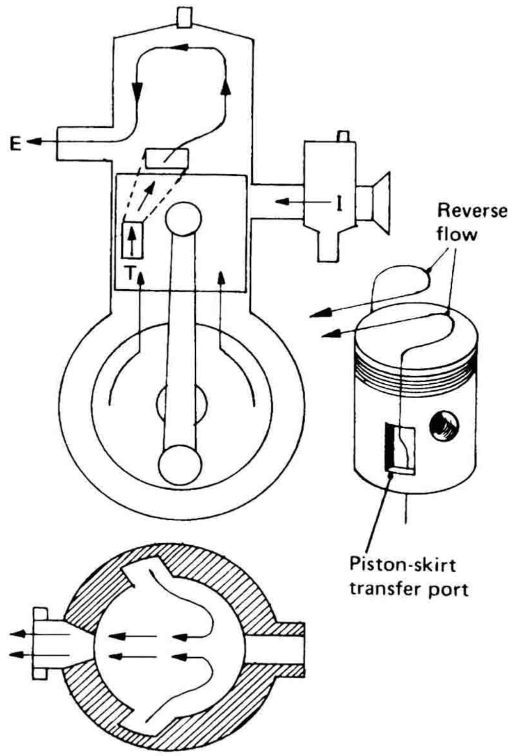

Fig. 1.1-6 Reverse flow or Schnuerle scavenging.

words, these valves sense the requirements of the crankcase and so adjust their opening and closing frequencies to match the demands of the engine.

1.1.2.3 Comparison of two- and four-stroke-cycle petrol engines

The following remarks compare the main points regarding the effectiveness of both engine cycles.

a) The two-stroke engine completes one cycle of events for every revolution of the crankshaft, compared with the two revolutions required for the four-stroke engine cycle.

b) Theoretically, the two-stroke engine should develop twice the power compared to a four-stroke engine of the same cylinder capacity.

c) In practice, the two-stroke engine's expelling of the exhaust gases and filling of the cylinder with fresh mixture brought in through the crankcase is far less effective than having separate exhaust and induction strokes. Thus the mean effective cylinder pressures in two-stroke units are far lower than in equivalent four-stroke engines.

d) With a power stroke every revolution instead of every second revolution, the two-stroke engine will run smoother than the four-stroke power unit for the same size of flywheel.

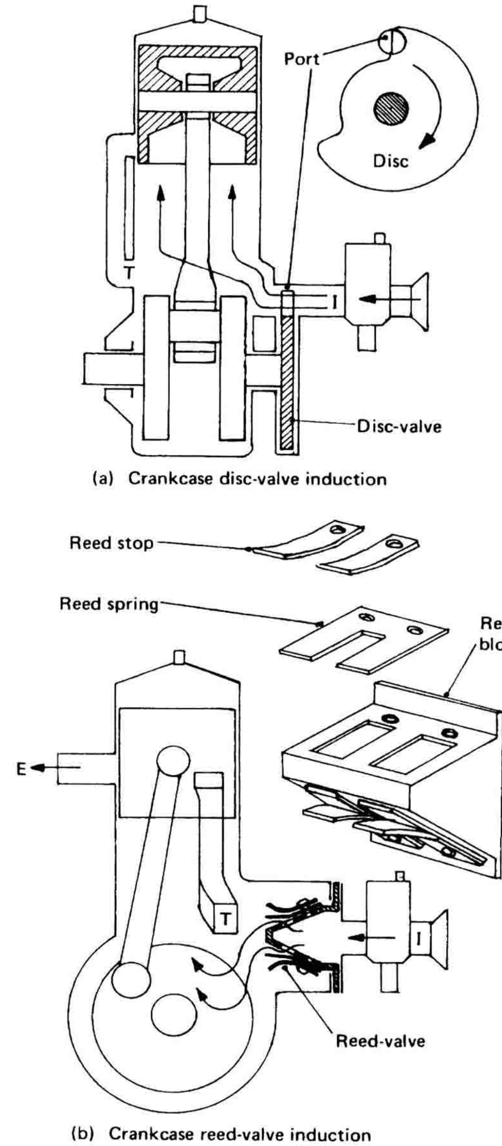

Fig. 1.1-7 Crankcase disc-valve and reed-valve induction.

e) Unlike the four-stroke engine, the two-stroke engine does not have the luxury of separate exhaust and induction strokes to cool both the cylinder and the piston between power strokes. There is therefore a tendency for the piston and small-end to overheat under heavy driving conditions.

f) Due to its inferior scavenging process, the two-stroke engine can suffer from the following:

- **i)** inadequate transfer of fresh mixture into the cylinder,
- **ii)** excessively large amounts of residual exhaust gas remaining in the cylinder,

iii) direct expulsion of fresh charge through the exhaust port.

These undesirable conditions may occur under different speed and load situations, which greatly influences both power and fuel consumption.

g) Far less maintenance is expected with the two-stroke engine compared with the four-stroke engine, but there can be a problem with the products of combustion carburising at the inlet, transfer, and exhaust ports.

h) Lubrication of the two-stroke engine is achieved by mixing small quantities of oil with petrol in proportions anywhere between 1:16 and 1:24 so that, when crankcase induction takes place, the various rotating and reciprocating components will be lubricated by a petroil-mixture mist. Clearly a continuous proportion of oil will be burnt in the cylinder and expelled into the atmosphere to add to unwanted exhaust emission.

i) There are fewer working parts in a two-stroke engine than in a four-stroke engine, so two-stroke engines are generally cheaper to manufacture.

1.1.3 Four-stroke-cycle compression-ignition (diesel) engine

Compression-ignition (C.I.) engines burn fuel oil which is injected into the combustion chamber when the air charge is fully compressed. Burning occurs when the compression temperature of the air is high enough to spontaneously ignite the finely atomised liquid fuel. In other words, burning is initiated by the self-generated heat of compression (Fig. 1.1-8).

Engines adopting this method of introducing and mixing the liquid fuel followed by self-ignition are also referred to as 'oil engines', due to the class of fuel burnt, or as 'diesel engines' after Rudolf Diesel, one of the many inventors and pioneers of the early C.I. engine. Note: in the United Kingdom fuel oil is known as 'DERV', which is the abbreviation of 'diesel-engine road vehicle'.

Just like the four-stroke-cycle petrol engine, the C.I. engine completes one cycle of events in two crankshaft revolutions or four piston strokes. The four phases of these strokes are (i) induction of fresh air, (ii) compression and heating of this air, (iii) injection of fuel and its burning and expansion, and (iv) expulsion of the products of combustion.

Induction stroke (Fig. 1.1-8(a)) With the inlet valve open and the exhaust valve closed, the piston moves away from the cylinder head (Fig. 1.1-8(a)).

The outward movement of the piston will establish a depression in the cylinder, its magnitude depending on the ratio of the cross-sectional areas of the cylinder and the inlet port and on the speed at which the piston is moving. The pressure difference established between the inside and outside of the cylinder will induce air at atmospheric pressure to enter and fill up the cylinder. Unlike the petrol engine, which requires a charge of air-and-petrol mixture to be drawn past a throttle valve, in the diesel-engine inlet system no restriction is necessary and only pure air is induced into the cylinder. A maximum depression of maybe 0.15 bar below atmospheric pressure will occur at about one-third of the distance along the piston's outward stroke, while the overall average pressure in the cylinder might be 0.1 bar or even less.

Compression stroke (Fig. 1.1-8(b)) With both the inlet and the exhaust valves closed, the piston moves towards the cylinder head (Fig. 1.1-8(b)).

The air enclosed in the cylinder will be compressed into a much smaller space of anything from 1/12 to 1/24 of its original volume. A typical ratio of maximum to minimum air-charge volume in the cylinder would be 16:1, but this largely depends on engine size and designed speed range.

During the compression stroke, the air charge initially at atmospheric pressure and temperature is reduced in volume until the cylinder pressure is raised to between 30 and 50 bar. This compression of the air generates heat which will increase the charge temperature to at least 600 °C under normal running conditions.

Power stroke (Fig. 1.1-8(c)) With both the inlet and the exhaust valves closed and the piston almost at the end of the compression stroke (Fig. 1.1-8(c)), diesel fuel oil is injected into the dense and heated air as a high-pressure spray of fine particles. Provided that they are properly atomised and distributed throughout the air charge, the heat of compression will then quickly vaporise and ignite the tiny droplets of liquid fuel. Within a very short time, the piston will have reached its innermost position and extensive burning then releases heat energy which is rapidly converted into pressure energy. Expansion then follows, pushing the piston away from the cylinder head, and the linear thrust acting on the piston end of the connecting-rod will then be changed to rotary movement of the crankshaft.

Exhaust stroke When the burning of the charge is near completion and the piston has reached the outermost position, the exhaust valve is opened. The piston then reverses its direction of motion and moves towards the cylinder head (Fig. 1.1-8(d)).

The sudden opening of the exhaust valve towards the end of the power stroke will release the still burning products of combustion to the atmosphere. The pressure energy of the gases at this point will accelerate their expulsion from the cylinder, and only towards the end of

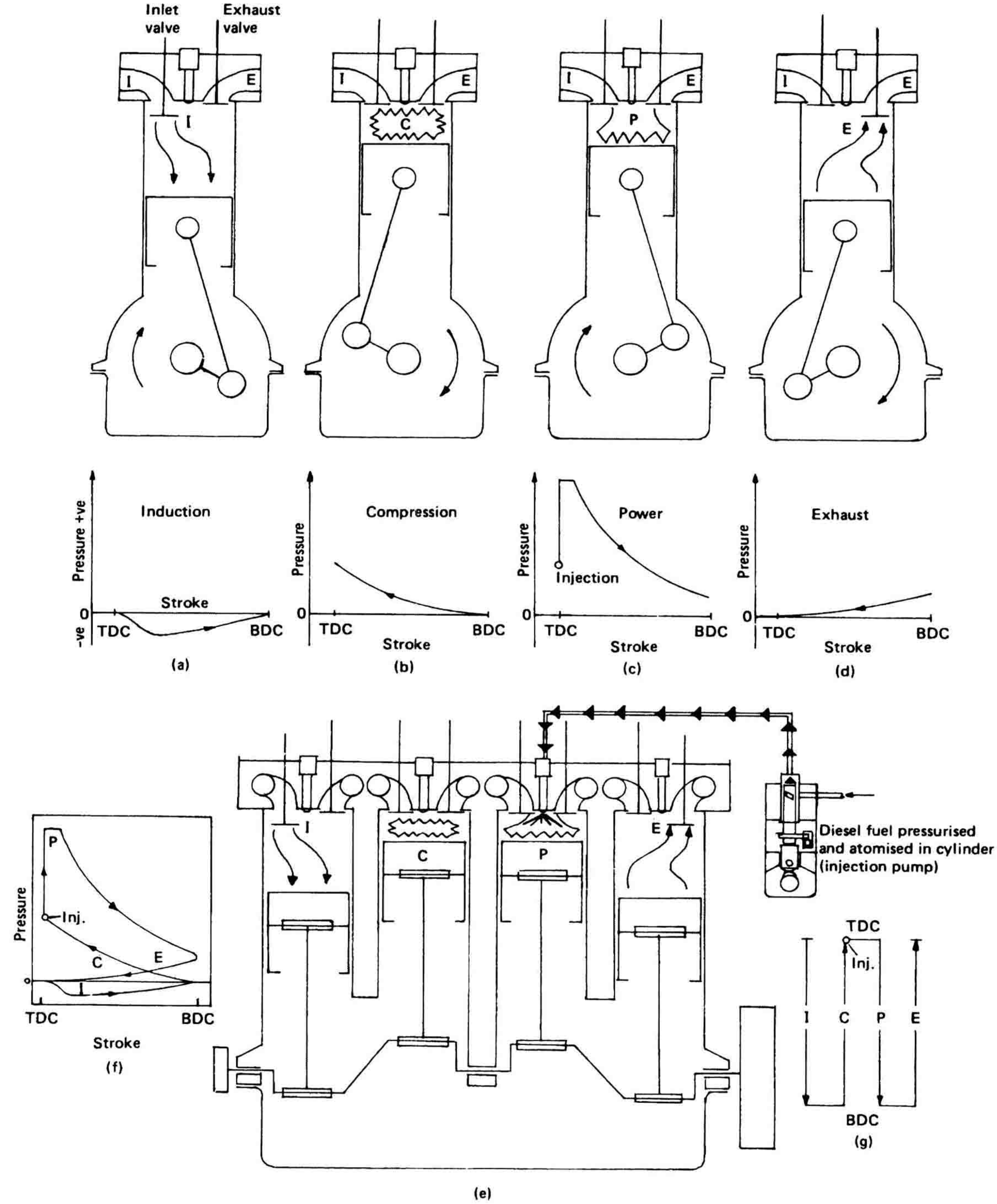

Fig. 1.1-8 Four-stroke-cycle diesel engine.

the piston's return stroke will the piston actually catch up with the tail-end of the outgoing gases.

Fig. 1.1-8(e) illustrates the sequence of the four operating strokes as applied to a four-cylinder engine, and the combined operating events expressed in terms of cylinder pressure and piston displacement are shown in Figs. 1.1-8(f) and (g).

1.1.3.1 Historical background to the C.I. engine

Credit for the origination of the C.I. engine is controversial, as eminent engineers cannot agree amongst themselves as to which of the patents by Herbert Akroyd-Stuart or Rudolf Diesel contributed most to the instigation and evolution of the high-speed C.I. engine burning heavy fuel oil. A brief summary of the background and achievements of these two pioneers is as follows.

Herbert Akroyd-Stuart, born 1864, was trained as an engineer in his father's works at Fenny Stratford, England. Between 1885 and 1890 he took out several patents for improvements to oil engines, and later, in conjunction with a Charles R. Binney of London, he took out patent number 7146 of 1890 describing the operation of his engine. Air alone was drawn into the cylinder and compressed into a separate combustion chamber (known as the vaporiser) through a contracted passage or bottleneck. A liquid fuel spray was then injected into the compressed air near the end of the compression stroke by means of a pump and a spraying nozzle. The combination of the hot chamber and the rise in temperature of the compressed air provided automatic ignition and rapid combustion at nearly constant volume – a feature of the C.I. engines of today.

These early engines were of low compression, the explosion taking place mainly due to the heat of the vaporiser chamber itself so that these engines became known as 'hot-bulb' or 'surface-ignition' engines. At starting, the separate combustion chamber was heated externally by an oil-lamp until the temperature attained was sufficient to ignite a few charges by compression. Then the chamber was maintained at a high enough temperature by the heat retained from the explosion together with the heat of the compressed air.

Rudolf Diesel was born in Paris in 1858, of German parents, and was educated at Augsburg and Munich. His works training was with Gebrü-der Sulzer in Winterthur. Dr Diesel's first English patent, number 7421, was dated 1892 and was for an engine working on the ideal Carnot cycle and burning all kinds of fuel – solid, liquid, and gas – but the practical difficulties of achieving this thermodynamic cycle proved to be far too much. A reliable diesel oil engine was built in 1897 after four years of experimental work in the Mashinen-fabrik Augsburg Nürnberg (MAN) workshops.

In this engine, air was drawn into the cylinder and was compressed to 35–40 bar. Towards the end of the compression stroke, an air blast was introduced into the combustion space at a much higher pressure, about 68–70 bar, thus causing turbulence in the combustion chamber. A three-stage compressor driven by the engine (and consuming about 10% of the engine's gross power) supplied compressed air which was stored in a reservoir. This compressed air served both for starting the engine and for air-injection into the compressed air already in the cylinder – that is, for blasting air to atomise the oil fuel by forcing it through perforated discs fitted around a fluted needle-valve injector. The resulting finely divided oil mist ignites at once when it contacts the hot compressed cylinder air, and the burning rate then tends to match the increasing cylinder volume as the piston moves outwards – expansion will therefore take place at something approaching constant pressure.

A summary of the combustion processes of Akroyd-Stuart and Diesel is that the former inventor used a low compression-ratio, employed airless liquid-fuel injection, and relied on the hot combustion chamber to vaporise and ignite the fuel; whereas Diesel employed a relatively high compression-ratio, adopted air-injection to atomise the fuel, and made the hot turbulent air initiate burning. It may be said that the modern high-speed C.I. engine embraces both approaches in producing sparkless automatic combustion – combustion taking place with a combined process of constant volume and constant pressure known as either the mixed or the dual cycle.

1.1.4 Two-stroke-cycle diesel engine

The pump scavenge two-stroke-cycle engine designed by Sir Dugald Clerk in 1879 was the first successful two-stroke engine; thus the two-stroke-cycle engine is sometimes called the Clerk engine. Uniflow scavenging took place – fresh charge entering the combustion chamber above the piston while the exhaust outflow occurred through ports uncovered by the piston at its outermost position.

Low- and medium-speed two-stroke marine diesels still use this system, but high-speed two-stroke diesels reverse the scavenging flow by blowing fresh charge through the bottom inlet ports, sweeping up through the cylinder and out of the exhaust ports in the cylinder head (Fig. 1.1-9(a)).

With the two-stroke-cycle engine, intake and exhaust phases take place during part of the compression and power stroke respectively, so that a cycle of operation is completed in one crankshaft revolution or two piston strokes. Since there are no separate intake and exhaust strokes, a blower is necessary to pump air into the cylinder for expelling the exhaust gases and to supply the cylinder with fresh air for combustion.

Scavenging (induction and exhaust) phase (Fig. 1.1-9(a)) The piston moves away from the cylinder head and, when it is about half-way down its stroke, the exhaust valves open. This allows the burnt gases to escape into the atmosphere. Near the end of the power stroke, a horizontal row of inlet air ports is uncovered by the piston lands (Fig. 1.1-9(a)). These ports admit pressurised air from the blower into the cylinder. The space above the piston is immediately filled with air, which now blows up the cylinder towards the exhaust valves in the cylinder head. The last remaining exhaust gases will thus be forced out of the cylinder into the exhaust system. This process

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