Vehicle Engine Technologies

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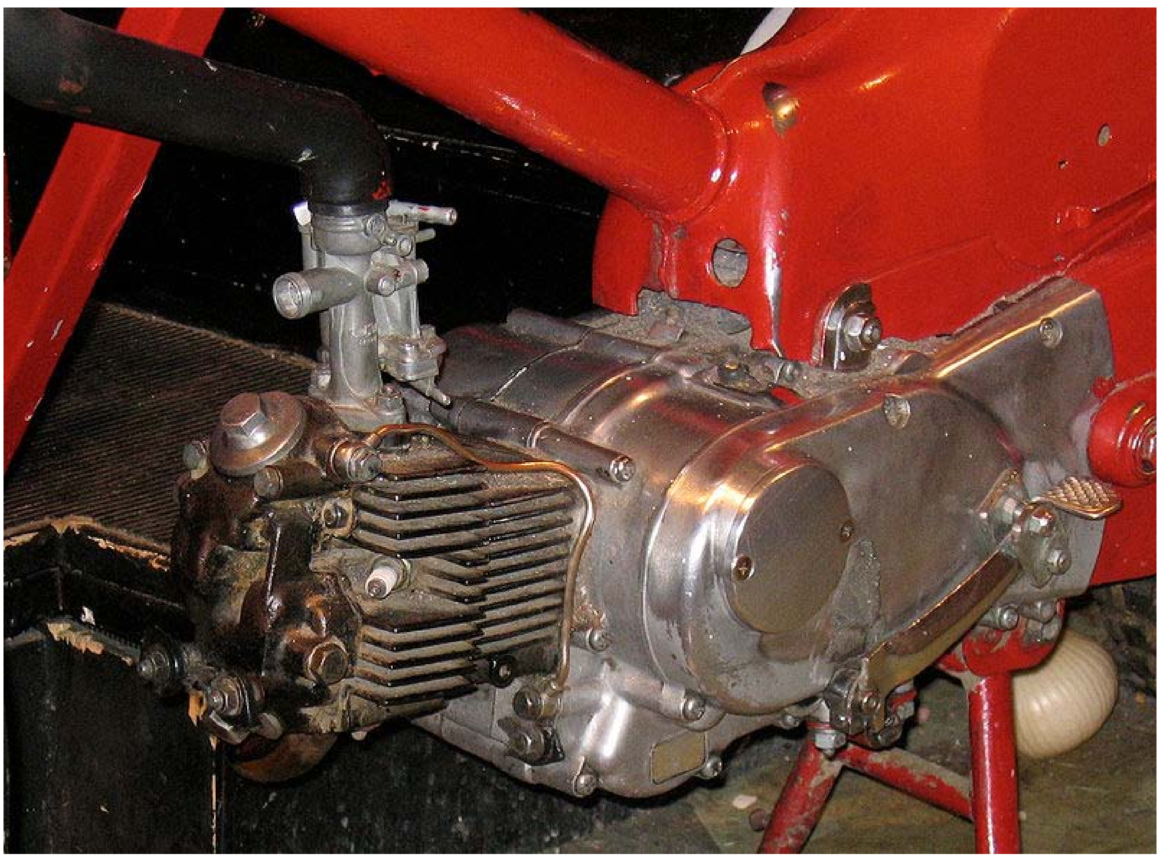
Motorcycle Engine



A Honda Super Cub engine. This 50 cc (3.1 cu in) horizontal single powers the most popular motorcycle in history, with over 60 million produced.

A **motorcycle engine** drives the rear wheel of a motorcycle and powers forward motion. Motorcycle engines vary in cylinder quantity, head design, displacement and layout.

Some motorcycle manufacturers have become strongly associated with one particular engine configuration. Modern Harley-Davidson motorcycles are exclusively transverse, narrow-angled V-twin engines, while Ducati and Moto Guzzi have specialised in 90° V-twins, the former transverse and the latter longitudinal with shaft drive. Longitudinal boxer twins are iconic of BMW motorcycles, although they now use a number of different engine layouts. British marques of the 1950s and 1960s were associated with parallel-twins even though they made other types as well. Japanese manufacturers vary greatly in layouts, and Honda in particular have produced almost every possible configuration and type.

History

Earliest motorcycle engine concept. This 1818 caricature was thought for many years to be entirely fanciful, until the Michaux-Perreaux, Roper and other steam cycles were rescued from obscurity, and the stories of the early steam cycle experiments were rediscovered. There were no steam motorcycles in 1818, but there soon would be.

The first motorcycles were powered by steam engines. The earliest example is the French Michaux-Perreaux steam velocipede of 1868. This was followed by the American Roper steam velocipede of 1869, and a number of other steam powered two and three wheelers, manufactured and sold to the public on through the early 20th century.

Using frames based both on the earlier boneshaker and the later—and in many ways completely modern—safety bicycle design, these early steam motorcycles experimented with a variety of engine placement strategies, as well as transmission and options. While today nearly every motorcycle has its engine in the center of the frame, this became standard only around 1900-1910 after nearly every possible engine location was tried. The modern scooter engine arrangement was arrived at in the 1940s and remains the same today.

The Otto cycle gasoline internal combustion engine was first used on an experimental two wheeler created by Gottlieb Daimler to test the practicality of such an engine in a vehicle. This motorcycle, the Daimler Reitwagen, is credited as the *world's first motorcycle* by many authorities, partially on the assumption that a motorcycle is defined not as any two wheel motor vehicle, but a two wheel *internal combustion engine* motor vehicle. The Oxford English Dictionary, for example, defines the word motorcycle this way. The steam cycles were also simply neglected and forgotten by many historians, even as the Michaux-Perreaux waited forty years on display in the National Motor Museum, Beaulieu.

In recent years, a surge in interest in clean energy has put many new electric powered two wheelers on the market, and they are registered as motorcycles or scooters, without the type of powerplant being an issue. Diesel motorcycles were also been experimented with briefly throughout the 20th century, and are again the subject of interest due to fuel economy and the needs of military logistics. The USMC has ordered a new diesel motorcycle, the M1030 M1, that can use the same fuel, JP-8, as the rest of their armored vehicles, aircraft, cars and trucks.

The overwhelming majority of the motorcycles produced and used in the world today have small displacement air-cooled single-cylinder engines, both two- and four-strokes. In the wealthier parts of the world, Europe and Japan, larger displacements and multiple cylinders are common alongside small-displacement bikes required by various licensing and rider experience requirements, and so a very diverse range of sizes, cylinder numbers, configurations, and cooling systems are seen on the road. Many developed countries have graduated licensing, where a rider is licensed for a period of time to ride only smaller-displacement motorcycles before being allowed to ride larger ones. In the United States, there are no such mandates, and so the mix is skewed even further to the largest displacements, consumer demand drives manufacturers to offer their largest motorcycles to that country, and to export far fewer sub-600 cc (37 cu in) models to the American market.

Types

Almost all commercially available motorcycles are driven by conventional gasoline internal combustion engines, increasingly four-strokes in all size ranges. Some are still air-cooled (forced with a fan in some cases) but water-cooling is more common. The mid-range and large two-strokes seen in the 1970s and 1980s have almost disappeared, particularly as emission laws were introduced. There are a few small scooter-type models using batteries and an electric motor. Van Veen, Hercules, Norton, and Suzuki produced quite small numbers of motorcycles propelled by Wankel rotary engines. The 2009 TT races included a new category 'TTX' for electric bikes using either fuel-cells or batteries

Most motorcycle engines have the primary working member or crankshaft across the frame (transverse mounting). Others are arranged to turn a shaft-drive to the rear wheel and the crankshaft is longitudinal, along the frame.

A sub-type of motorcycle, the scooter, has the engine as part of the rear suspension, so it is not fixed to the main frame. Such engines pivot to follow the road surface and are partly "unsprung weight". The final drive of scooters is much shorter than that of regular motorcycles and is contained within the engine casings in an oil-bath, a design that is only suitable for machines with small wheels, or is fully automatic using belts and expanding/contracting pulleys, ala DAF variomatic cars. The engines of the motorcycles known as underbones or "step-throughs" may be of either kind.

Two-stroke and four-stroke

Two-stroke engines have fewer moving parts than four-stroke engines, and produce twice the number of power strokes; consequently, two-stroke engines are more powerful for their mass. Two-strokes offer stronger acceleration, but similar top speed compared to a four-stroke engine. They are also easier to start. However, two-stroke engines have shorter life due to poorer piston lubrication, since lubrication comes from the fuel-oil mix.

Four-stroke engines are generally associated with a wider power band making for somewhat gentler power delivery, but technology such as reed valves and exhaust power-valve systems has improved ride-ability on two-strokes. Fuel economy is also better in four-strokes due to more complete combustion of the intake charge in four-stroke engines.

Nevertheless, two-strokes have been largely replaced on motorcycles in developed nations due to their environmental disadvantages. Cylinder lubrication is necessarily total-loss and this inevitably leads to a smokey exhaust, particularly on wide throttle openings. Two-stroke engined motorcycles continue to be made in large numbers, but mostly low power mopeds, small scooters and step-through underbones where they still compete strongly with four-strokes (including the highest selling motorcycle of all time, the 50 cc Honda Super Cub). The major markets of two-stroke motorcycles are in developing nations.

Heads

Motorcycle engine heads are the subject of a great deal of attention, due both to the critical role played by intake, exhaust and valve systems in the overall efficiency of an engine, but also because on a motorcycle the head is often the center of attention, aesthetically speaking. Harley-Davidsons, Moto Guzzis and BMWs are categorized by their heads, such as airhead, panhead, oilhead, and even knucklehead. The eras of Ducati production, and the camps or factions their enthusiasts gather in, are divided by head, whether they be pushrod, bevel heads, desmos, or chain- or belt-driven valves.

Valve control

Honda equipped the CBR400F with HYPER VTEC (or REV:Revolution-modulated valve control) in 1983. The system enabled to switch over the number of valve operations per cylinder between low and medium speed revolution range and high speed revolution range. In January 2002 HYPER VTEC evolved into Spec II and in December 2003 SPEC III was introduced.

Unit construction

Engines and gear-boxes were originally quite separate, with drive from one to the other by a chain (the 'primary'). Gradually these components were moved closer and closer together until they were eventually incorporated in the same case (actually, 2 compartments in one case).

Displacement

Engine displacement is defined as the total volume of air/fuel mixture an engine can draw in during one complete engine cycle. In a piston engine, this is the volume that is swept as the pistons are moved from top dead center to bottom dead center. This is the "size" of the engine. Motorcycle engines range from less than 50 cc, commonly found in many mopeds and small scooters, to a 6,000 cc engine used by Boss Hoss in its cruiser style motorcycle BHC-3 LS2. Many state laws in the U.S. define a motorcycle as having an engine larger than 50 cc, and a moped as a vehicle with an engine smaller than 60 cc.

Cylinders and configuration

Small motorcycles normally have a single cylinder, many smaller and mid-range motorcycles have twin cylinders and most medium to large motorcycles have four cylinders. However, no generalizations can be made, as there are a few large singles and twins. Three cylinders have been widely used and there have been some six-cylinder machines. Many different layouts have been used with vertical cylinders the most popular. There are some horizontally opposed and V layouts.

Single

1960 BSA Gold Star

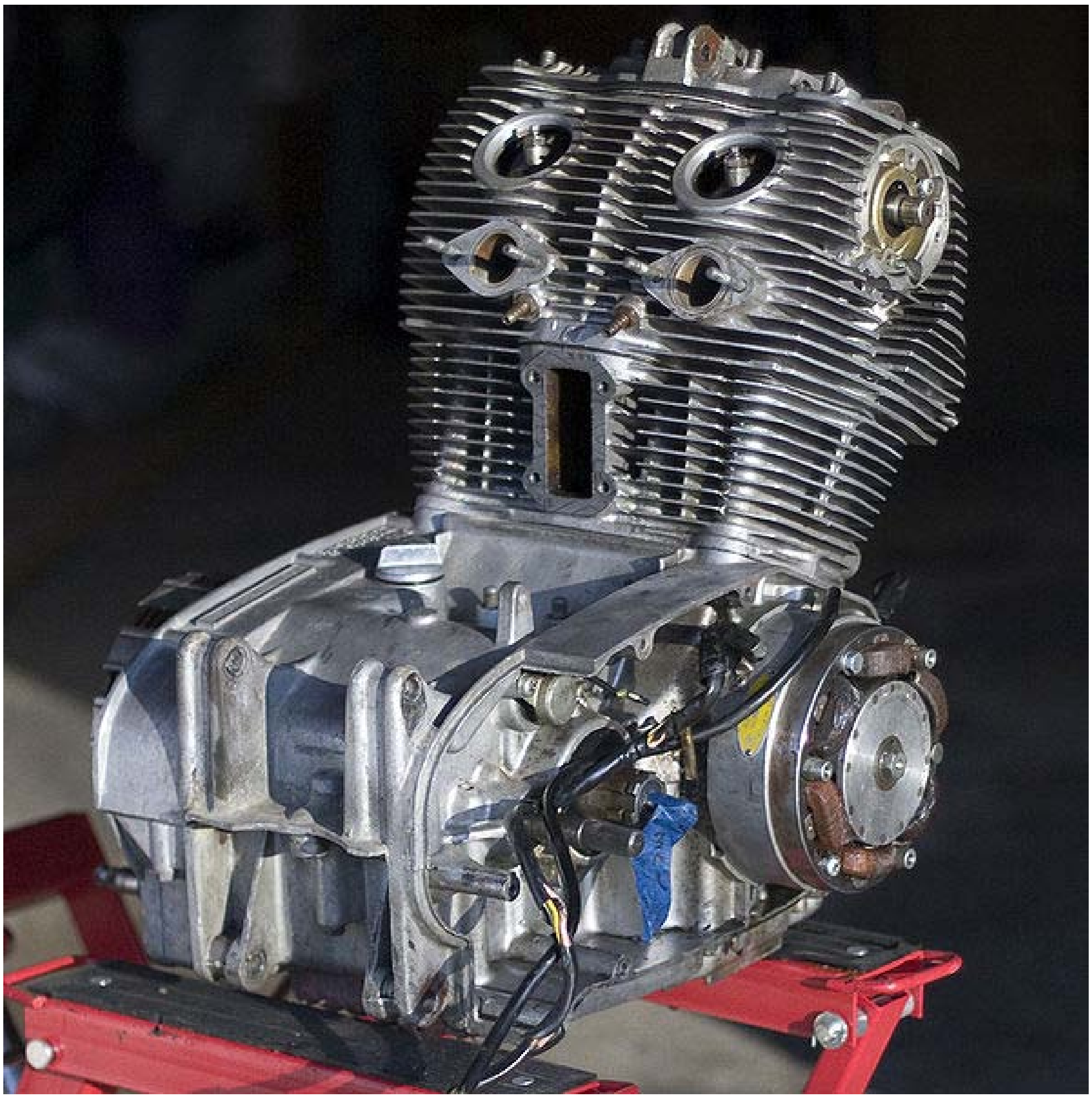
Single cylinder engines (known as "singles" or occasionally "thumpers") may have the cylinder vertical or horizontal, the latter particularly common in step-through or underbone motorcycles. Single cylinder engines require a larger flywheel, hindering ultimate performance but are a lot easier to maintain in almost every respect. In road motorcycles, single-cylinders tend to be associated with cheaper, utility motorcycles for daily transport. These motorcycle engines are tuned to give more power at lower engine revolutions, improving control, safety and engine longevity.

The need for the flywheel effect is less pronounced in all forms of competition motorcycles since they spend almost no time at tick-over speeds, all through the 1950s many of the fastest road racing motorcycles such as the Manx Norton were singlecylindered. The reduced weight and narrow width of single-cylinder motorcycles continue to make the layout well suited for the great majority of off road motorcycles, including those in top competition.

Split Single (a radical form of two-stroke) were used very successfully by DKW and Puch between and after the wars, losing out only to the loop-scavenging Japanese twin and triple machines of the 1970s.

Twin

Parallel-twin



1962 Honda CB77 Superhawk 305 cc (18.6 cu in) twin engine.

Two-cylinder engines are known as twins. The parallel twin as in most common British and many Japanese motorcycles. Engines of this design typically have the cylinders side by side vertically above the crankcase, with the exhaust ports pointing forward to maximize airflow cooling. Longitudinal twins include the 500 cc Sunbeam S7 and S8. The two crankpins can be timed simultaneously, with each side firing alternately every 360° (most British bikes), or timed with 1 piston at TDC and the other at BDC to fire 180° apart, followed by a long "dead" interval (many Hondas). Some Hondas have been made with both crankshaft types. Some engines, such as the Matchless 650, have had a 3rd center main bearing between the crankpins, but this was not successful.

The parallel-twin engine configuration was made famous by Edward Turner's Triumph Speed Twin design as used on the Bonneville 20 years later.

V-twin

Harley-Davidson Sportster V-twin

The V-twin engine where the cylinders form a "V" around the crankshaft, which is oriented longitudinally with the cylinders protruding left and right on models such as on the Honda CX500 and most Moto Guzzi motorcycles, or more typically transversely . V-twins can also be separated into three types, one having a shared crankpin (a normal con-rod is inserted between a forked con-rod thus sharing the single crankpin and keeping the cylinders in line, a single crankpin with side-by-side connecting rods and offset cylinders, or two crankpins, with the cylinders offset, which nearly every one else uses.

The angle in the V-twins varies from around 42° (Indian), 45° (Harley-Davidson), 60°, and up to 90°. Typical of the former are the Harley-Davidson and Vincent engines which because of their firing order tend to vibrate more. Ducati and Moto Guzzi make V-twins with cylinders arranged at a 90 degree angle to quell primary vibrations.

Flat twin

BMW's opposed twin

The opposed twin engine's cylinders normally protrude sideways into the cooling air stream, although some early motorcycles had them transversely mounted.

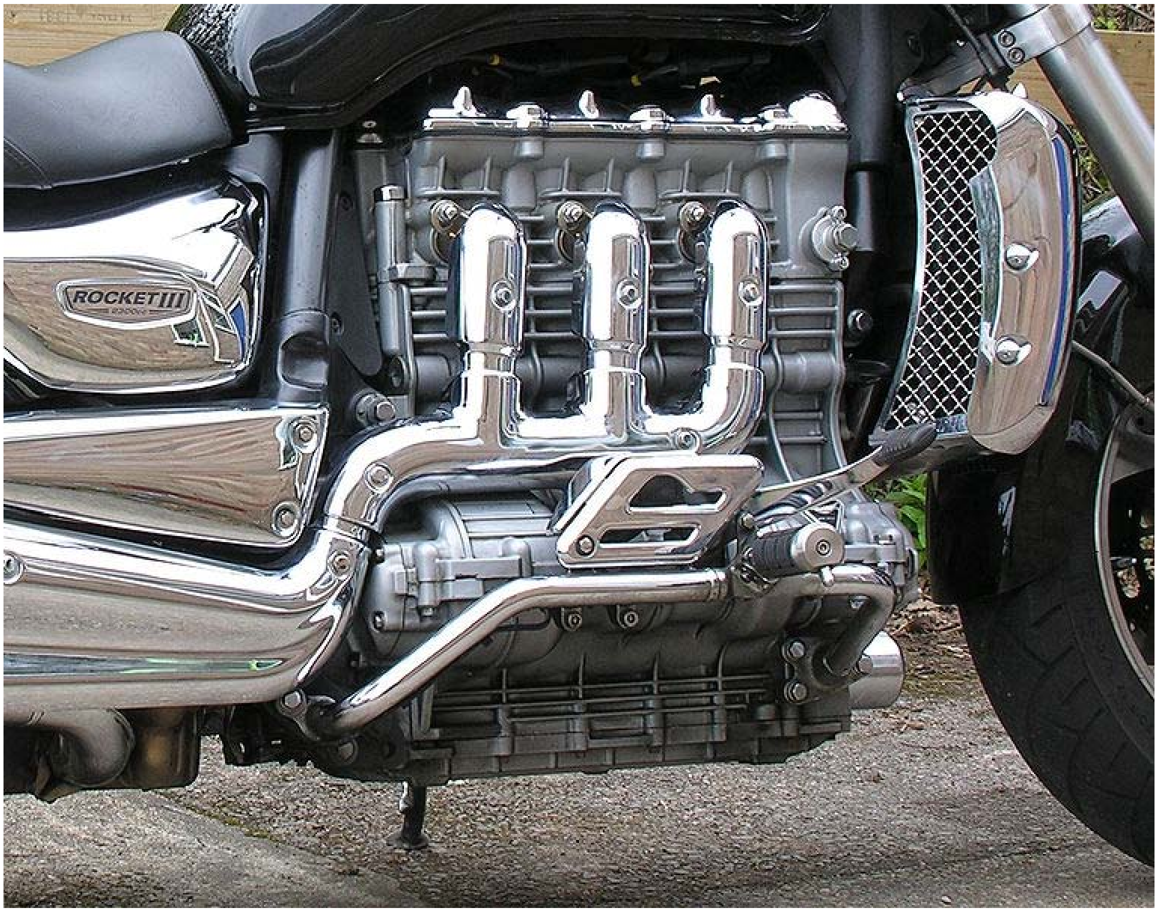
In the flat-twin (boxer) engine, which is used by BMW Motorrad, Ural, Harley-Davidson's WW2 "XA" model, Marusho, and historically by Douglas, the cylinders are horizontally opposed, protruding from either side of the frame. The boxer is the only twin-cylinder arrangement that has inherent primary balance without a rocking couple, producing very low vibration levels without the use of counterbalance shafts.

Tandem twin

The Tandem Twin where the cylinders are longitudinal, and have two cranks geared together such as Kawasaki's KR250 road bike and KR250 and KR350 GP Bikes.

Triple

Inline 3



Triumph Rocket III inline-3

Three-cylinder designs are referred to as "triples" and are normally inline triples in layout. The British Hinckley-built Triumph, mostly transverse but also the 2,300 cc longitudinal Rocket III, Italian Benelli and Japanese Yamaha XS750 are three motorcycle manufacturers who have used triples in their large displacement motorcycles. The Italian firm Laverda made a few 1,000 cc and 1,200 cc triples. BMW made the K75 longitudinal 750 cc triple with the cylinders parallel to the ground. BSA made the Rocket-3 transverse 750 cc and old Triumph the 750 cc Trident

Two-stroke triples were somewhat more common historically. The Kawasaki triples were produced with capacities of 250, 350, 400, 500, and 750 cc in the 1970s, while Suzuki produced 380, 550, and 750 triples (the last being water cooled). Motobecane made 350 cc and fuel injected 500 cc triples with 3 into 4 pipes in the early seventies. Honda produced the water cooled V-3 two-strokes MVX250 and NS400. There have been various race bike triples such as Kawasaki KR750, Suzuki TR750 transverse 3's, and Proton/Modenas KR3, Honda NS500 V-3s.

Four

Four-cylinder engines are most commonly found in a transverse-mounted inline four layout, although some are longitudinal (as in the earlier BMW K100). V-4 and boxer designs (as in the earlier Honda Gold Wing) have been produced. One of the more unusual designs was the Ariel Square Four, effectively two parallel-twin engines one in front of the other in a common crankcase – it had remarkably little vibration due to the contra-rotating crankshafts.

Inline 4

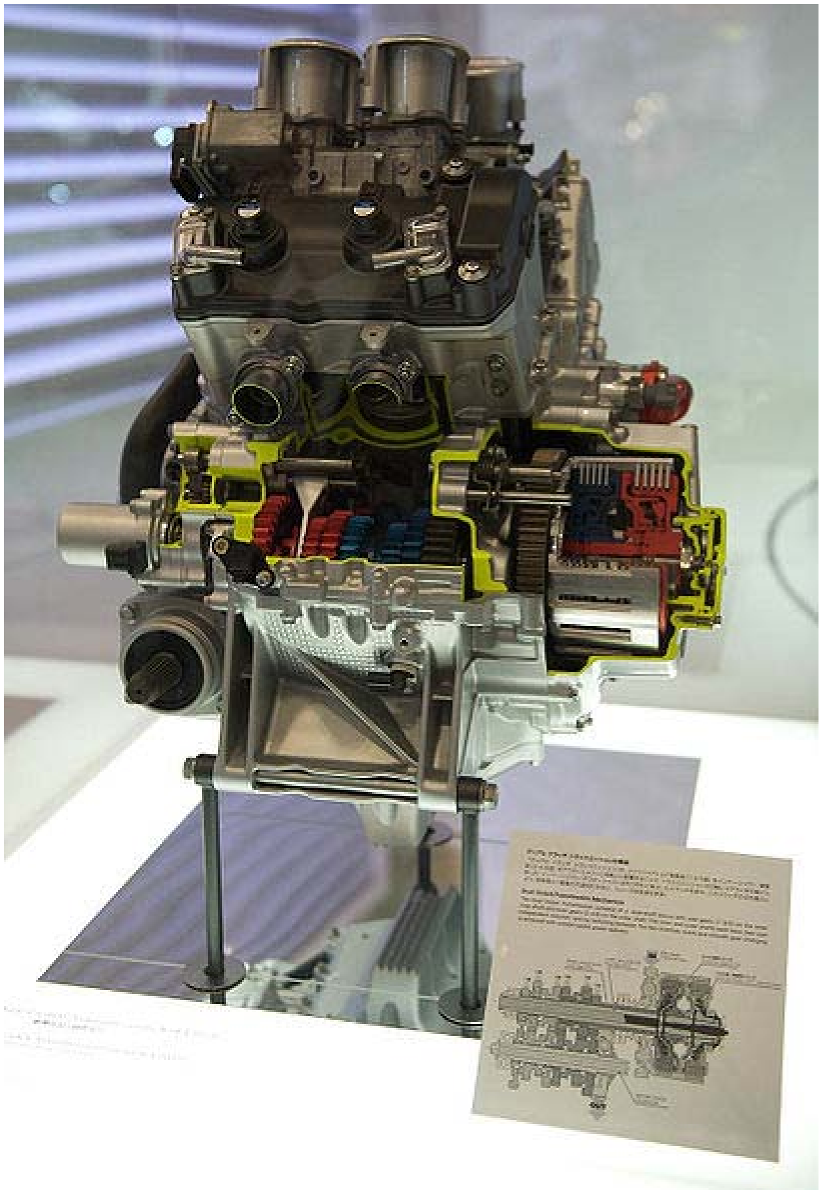
Honda CB750 transverse inline-4

Since the advent of the Honda CB750 straight-four engine, straight-fours have dominated the non-cruiser street motorcycle segments. The German manufacturer Münch based their motorcycles on four cylinder car engines (e.g. Mammut 2000 has a 2.0l with a turbo and cylinder heads by Cosworth).

Flat 4

The Honda GL1000 flat-four

V4



Honda VFR1200F engine with dual clutch transmission.

Honda uses V4 engines in the ST series and VFR series. As for two-stroke engines, there were four cylinders in the smaller classes such as Kawasaki's 125 cc KR3 square 4 and Yamaha's 250 cc RD500 V4 (RZ 500 in the US). Yamaha later raced transverse four TZ500/700/750's and virtually all the bikes in the last decade of the two-stroke GP500 era were fours (first squares then Vees) i.e. Honda, Kawasaki, Cagiva, Suzuki, Yamaha - Kawasaki also experimented with a trapezoidal four the 602S. Yamaha made the V4 RD500LC, and Suzuki the RG400 and RG500 square four road bikes.

Square 4

A square four is a U engine with two cylinders on each side. This configuration was used on the Ariel Square Four motorcycle from 1931 to 1959. This design was revived as a two-stroke version on some racing Suzuki models, and their subsequent road-going version the RG500. Although some racing success was achieved, the road bikes didn't sell in great numbers, and the design was phased out in favour of in-line, four-stroke designs, as at the time two stroke engines were quickly being superseded by more economical, reliable, and emissions-friendly four-strokes.

Five

V5

Honda V5 MotoGP engine

Honda has produced five-cylinder engines for racing, the RC211V 990 cc V5. No V5 engines are currently available in commercial production motorcycles.

Six

Inline 6

Benelli Sei inline-6

Six-cylinder engines are rare and found only on the biggest motorcycles. Two easily recognizable examples in recent times have been the Honda CBX and the Kawasaki KZ1300 and also Kawasakis Voyager XIII, Bennelli also made 750 cc and 900 cc Straight sixes known as the Sei. Honda made a 250 cc straight-six GP bike. Modern straight-six motorcycles include the BMW K1600GT and K1600GTL, which have a transverse-mounted 1,649 cc engine.

Flat 6

Honda Valkyrie flat-6

The six-cylinder engine is currently used by Honda in the boxer engine of the Rune, Valkyrie and Gold Wing.

V8

Moto Guzzi V8

Galbusera built a V8 in 1938, and Moto Guzzi experimented over a period of two years with its dual overhead cam 500 cc V8 (the Otto Cylindri) in the 1950s. Some custom and one-off motorcycles use more than six cylinders. For example, the Boss Hoss motorcycle uses (5,700 cc, 6,000 cc and 8,200 cc) Chevy V-8 crate motors. In the 1990s Daimler-Chrysler manufactured a limited number of Tomahawk concept bikes featuring a Dodge Viper's V-10 engine. Australian company Drysdale have built short runs of 750 cc V8 superbikes and 1L V8 roadgoing motorcycles, both with engines specifically developed for the purpose. No major motorcycle manufacturer has used eight or more cylinders although Honda made the 'almost' V8 oval piston NR750 road bike and NR500 GP bike (having eight connecting rods, for example) and Morbidelli has shown two V8 prototype road bikes, but has yet to get off the ground

Other types

Wankel rotary

Hercules (motorcycle), Norton Commando, ZF Sachs, Suzuki RE5

Oval pistons

Honda NR

Rotary engines

Megola, Killinger and Freund Motorcycle

Jet engines

MTT Turbine Superbike

Diesel

Only very small numbers of diesel engined motorcycles have ever been built. The improved fuel efficiency is offset by the increased weight, reduced acceleration and potential difficulty of starting, at least in colder climates. Enfield India built a few from 1965 onwards but is no longer doing so. In November 2006, the Dutch company E.V.A. Products BV Holland announced their first diesel-powered motorcycle, its Track T-800CDI, using an 800 cc three-cylinder Daimler Chrysler diesel engine.

Several armies are moving to an all-diesel engine fleet to reduce the fire risks of petrol and the need to provide two different fuels. This includes their despatch riders as well, encouraging the market for diesel motorcycles. Interest in biofuels is also likely to encourage future developments for small Diesels.

Diesels are also available in both two and four-stroke versions.

Engine cooling

Liquid

Liquid-cooled motorcycles have a radiator (similar to the radiator on a car) which is the primary way their heat is dispersed. Coolant is constantly circulated between this radiator and the cylinders when the engine is running. While most off-road motorcycles have no radiator fan and rely on air flowing over the radiators from the forward motion of the motorcycle, many road motorcycles have a small fan attached to the radiator which is controlled by a thermostat. Some off-road motorcycles are liquid cooled and anti-dirt protection is attached to the radiator. The cooling effect of this fan is enough to prevent the engine overheating in most conditions, so liquid-cooled bikes are safe to use in a city, where traffic may frequently be at a standstill.

Emissions regulations and the market demand for maximum power are driving the motorcycle industry to liquid-cooling for most motorcycles. Even Harley-Davidson, a strong advocate of air-cooled motors, has begun producing a Revolution liquid-cooled engine.

Air

Most air cooled motorcycles take advantage of air blowing past the cylinder and cylinder head while in motion to disperse heat. Frequent, sustained stationary periods may cause over-heating. Some models (mostly scooters) are equipped with fans that force the air to go past the cylinder block, which solves the problem of city driving. The cylinders on air cooled bikes are designed with fins (heat sinks) to aid in this process. Air cooled bikes are cheaper, simpler and lighter than their water-cooled counterparts.

Oil

The BMW R1150GS has an oil cooler below the headlights and fins for air cooling on the cylinders

Some manufacturers use a hybrid cooling method where engine oil is circulated between the engine case and a small radiator. Here the oil doubles as cooling liquid, prompting the name "oil-cooling." Suzuki has produced many "oil-cooled" motorcycles. Modern BMW R-series flat-twin motorcycles, such as the R1150GS, use air and oil cooling. Polaris's Victory motorcycles use oil/air cooling exclusively.

Other components

Fuel injection and computer engine management systems are now normal on middle range and larger motorcycles and are increasingly being incorporated onto the smaller machines, partly driven by better emission control and lower maintenance but mostly by manufacturing cost considerations. Ignition systems moved from magneto in the 1950s to battery-coil-contact breaker (points), and these were increasingly superseded by Capacitor Discharge Ignition (CDI) from the 1980s. Small, single cylinder motorcycles abandoned the flywheel magneto system with contact breakers to similar flywheel driven solid-state systems at about the same time.

Turbo and Superchargers. Superchargers (blowers) were common in the GP's, until they were banned (which didn't help the two-stokes, as pre Ernest Degners new technology, they needed the help against the four-strokes). The big four also made a turbo-ed bike, Honda made two......, mainly as an exercise in technical expertise and later discontinued for more conventional methods. Bolt on (well nearly) blowers are available to put on street bikes - and they are essential for drag bikes and land speed record streamliners etc. Most sports bikes now use some sort of 'ram-air' system where, as road speed increases, more and more air is forced through ducts in the fairing to pressurize the airbox.

Chapter 2

Big-Bang Firing Order

A **big bang engine** is an unconventional motorcycle engine designed so that most of the power strokes occur simultaneously or in close succession. This is achieved by changing the ignition timing; sometimes in combination with a change in crankpin angle. The goal is to change the power delivery characteristics of the engine or exhaust sound. A regular firing multi-cylinder engine fires at approximately even intervals, giving a smooth-running engine. Because of a big bang engine's power delivery imbalance, there exists more vibration and stress in the engine. This imbalance can overwhelm the rear tire, and generally makes a slide harder to catch. Until recently, this has limited their use to racing.

Twins and twingles

Engine	Crankshaft	Ignition timing	Graphical	Example
Single (2-stroke) Parallel twin Flat twin	360° 180°	360-360	1-0-0-0-1-0-0-0-	BSA, Triumph, Norton, AJS, Matchless and BMW F800S BMW R series
Single Parallel twingle Flat twingle	360° 180°	720	1-0-0-0-0-0-0-0- 2-0-0-0-0-0-0-0- 2-0-0-0-0-0-0-0-	
Parallel twin	180°	180-540	1-0-1-0-0-0-0-0-	1966 Honda “Black Bomber”, Yamaha TX500 and Kawasaki ER-6
Parallel twin 90° V twin	270° 360°	270-450	1-0-0-1-0-0-0-0-	Yamaha TRX850 and Triumph Thunderbird 1600 Ducati

45° V twin	360°	315-405	1-0-0-010-0-0-0-	Harley-Davidson
45° V twingle	360°	45-675	110-0-0-0-0-0-0-	Modified Harley-Davidson XR-750 for flat track racing

Parallel twins

The classic British parallel twins (BSA, Triumph, Norton, AJS & Matchless) had a 360° crankshaft that, compared to a single, gave twice as many ignition pulses, which were evenly spaced.

The early Japanese parallel twins, like the 1966 Honda “Black Bomber” and Yamaha TX500, adopted a 180° crank that gave an uneven firing pattern. This configuration has the best possible primary mechanical engine balance for a parallel twin; the uneven firing was a by-product of this design.

The Yamaha TRX850 had a 270° crank that allowed a more regular firing pattern than a 180° crank, and less regular than a 360° crank. This configuration has the best possible secondary engine balance for a parallel twin; its exhaust sound and power delivery is identical to a 90° V-twin.

Twingles

A twingle is a two-stroke twin cylinder engine with an altered firing order designed to give power pulses similar to a single cylinder four-stroke engine. It is well known that four-stroke singles "hook up" better than two-strokes in the dirt. This is because four-strokes have half as many power strokes per crankshaft revolutions as a two-stroke. This creates a recovery gap during which the rear tire regains traction.

Inline twins with a 360° crankpin offset and flat-twins can be easily converted into twingles by firing both of the cylinders at the same time. The Vintage Dirt Track Racing Association (VDTRA) 2010 Rules have banned vintage motorcycles from being setup as a twingle.

V twins

A narrow angle v-twin such as the 45° Harley-Davidson naturally has slightly uneven spaced power strokes. By changing the ignition timing on one of the cylinders by 360° the power strokes are very closely spaced. This will cause uneven fuel distribution in an engine with a single carburettor. The Harley-Davidson XR-750 with twin carburettors was a popular bike to twingle. It had great success in flattrack racing.

Four cylinder engines

Engine	Crankshaft	Ignition timing	Graphical	Example
I4	180°	180-180-180-180	1-0-1-0-1-0-1-0-	Honda CB750
I4 'Long bang'	180°	180-540	2-0-2-0-0-0-0-0-	Shinya Nakano's Kawasaki Ninja ZX-RR
I4 'Uneven bang'	crossplane	180-90-180-270	1-0-1-1-0-1-0-0-	2009 Yamaha YZF-R1
70° V4 90° V4	180°	180-70-180-290 180-90-180-270	1-0-1-1-0-1-0-0-	1985-2007 Yamaha V-Max Honda VFR800
90° V4 'Twin pulse'	70°	90-200-90-340	1-1-0-1-1-0-0-0-	Ducati Desmosedici RR
90° V4 'Droner'	360°	90-270-90-270	1-1-0-0-1-1-0-0-	Honda VF/RC30/RC45
112° V4 'Big bang' (2-stroke)	180°	68-292-68-292	2-2-0-0-2-2-0-0-	1990 Honda NSR500
90° V4 'Screamer' (2-stroke)	180°	90-90-90-90-90-90-90-90	1-1-1-1-1-1-1-1-	1984 Honda NSR500

Inline fours

A four-cylinder engine with a regular firing interval is sometimes referred to as a screamer. The regular delivery of power strokes can overwhelm the rear tire, and generally makes a slide harder to catch as well. A long bang fires both pairs of cylinders in quick succession; the power delivery is identical to a parallel twin with a 180° crank and similar to a v-twin. In 2005 Kawasaki experimented with this configuration on the ZX-RR MotoGP bike.

The 2009 Yamaha YZF-R1 has instead an uneven firing order. The power delivery is the same as a 90° V4 with a 180° crank, such as the Honda VFR800 and very similar to the Yamaha V-Max which has been lauded for its exhaust sound.

2-stroke V4

The Honda NSR500 began and ended its life as a screamer. However in 1990 Honda connected both of the pistons in one bank to the same crankpin and both of the other pistons to a crankpin offset 180°. This NSR500 was called a 'big bang'. Yamaha created a big bang YZR500 in 1992. The YZR500 had two crankshafts like a U engine and the angle between each pair of cylinders was 90°, like a V4.

In 1997 Mick Doohan wanted to run a 180° screamer engine. HRC crew chief Jerry Burgess explains why: "The 180 got back a direct relationship between the throttle and the rear wheel, When the tire spun I could roll off without losing drive. The big bang has a lot of engine braking, so it upsets the bike into corners, then when you open the throttle you get this sudden pulse of power, which again upsets the suspension. Mick's secret is corner speed, so he needs the bike to be smooth and the 180 is much smoother."

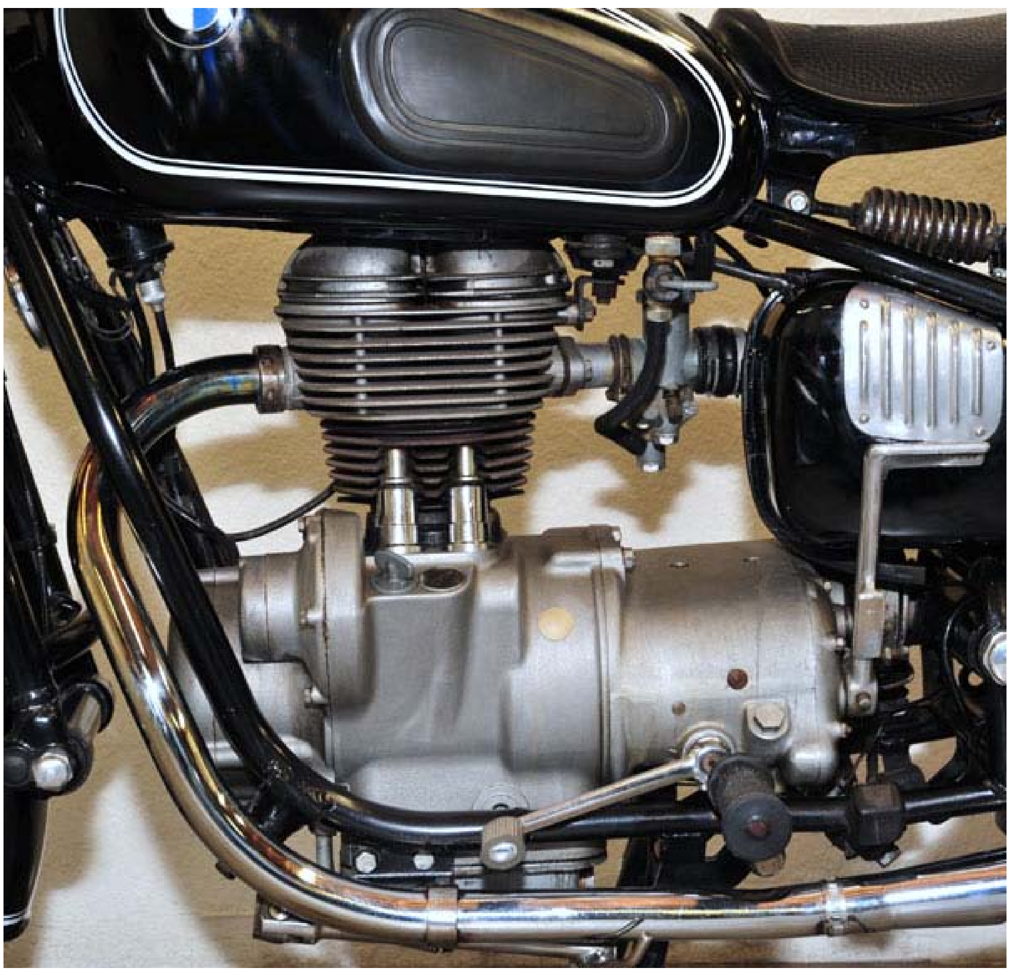
Chapter 3

Single Cylinder Engine and Straight-Three Engine

Single cylinder engine

A **single cylinder engine** is the most basic piston engine configuration of an internal combustion engine. It is often seen on motorcycles, Auto rickshaws, motor scooters, Mopeds, dirt bikes, go-karts, radio-controlled models and has many uses in portable tools and garden machinery. It has been used in cars and tractors.

Characteristics



BMW R27 single-cylinder motorcycle engine

Single cylinder engines are simple and compact, and will often deliver the maximum power possible within a given envelope. Cooling is simpler than with multiple cylinders, potentially saving further weight, especially if air-cooling can be used.

Single-cylinder engines require more flywheel effect than multi-cylinder engines and the rotating mass is relatively large, restricting acceleration and sharp changes of speed. In the basic arrangement they are prone to vibration - though in some cases it may be possible to control this with balance shafts.

Pros and Cons

Single cylinder engines are simple and economical in construction. The vibration they generate is acceptable in many applications while less acceptable in others. Counter-balance shafts and counterweights can be fitted but such complexities tend to counter the previously listed advantages.

Components such as the crankshaft of a single cylinder engine have to be nearly as strong as that in a multi-cylinder engine of the same capacity per cylinder, meaning that some parts are effectively four times heavier than they need to be for the total displacement of the engine. The single cylinder engine will almost inevitably develop a lower power to weight ratio than a multi-cylinder engine of similar technology. This can be a disadvantage in mobile operations, although it is of little significance in others and in most stationary applications.

Uses

Motorbike Horex "Regina" with one-cylinder-four-stroke-engine

Early motorcycles, automobiles and other applications such as marine engines all tended to be single cylinder. The configuration remains in widespread use in Auto rickshaws, motor scooters, Mopeds, dirt bikes, go-karts, radio-controlled models and is almost exclusively used in portable tools, along with garden machinery such as lawn mowers.

The bestselling motor-vehicle of the world, the Honda Super Cub, has a very fuel-efficient 49cc single cylinder engine and big-diameter 17inch-wheels (rolls smoother over obstacles).

Even big motorcycles with strong single-cylinder-engines are available today. There are Sport Bikes Like the KTM 690 Duke R which has 70hp-690cc-single-cylinder-engine and reaches 125mph (200km/h) with a curb weight of only 150kg. Or Dual-Sport Motorcycles like the BMW G650GS. And there are Classic motorcycles like the Royal-Enfield 500 Bullet with a classic long-stroke single-cylinder-engine.

Nearly all Auto rickshaws have very fuel-efficient single-cylinder-engines. Typical mileage for an Indian-made auto rickshaw is around 35 kilometers per liter of petrol (about 2.9 L per 100 km, or 82 miles per gallon [United States (wet measure), 100 miles per gallon Imperial (United Kingdom, Canada)].

Straight-three engine

Cylinder block of an inline three cylinder engine

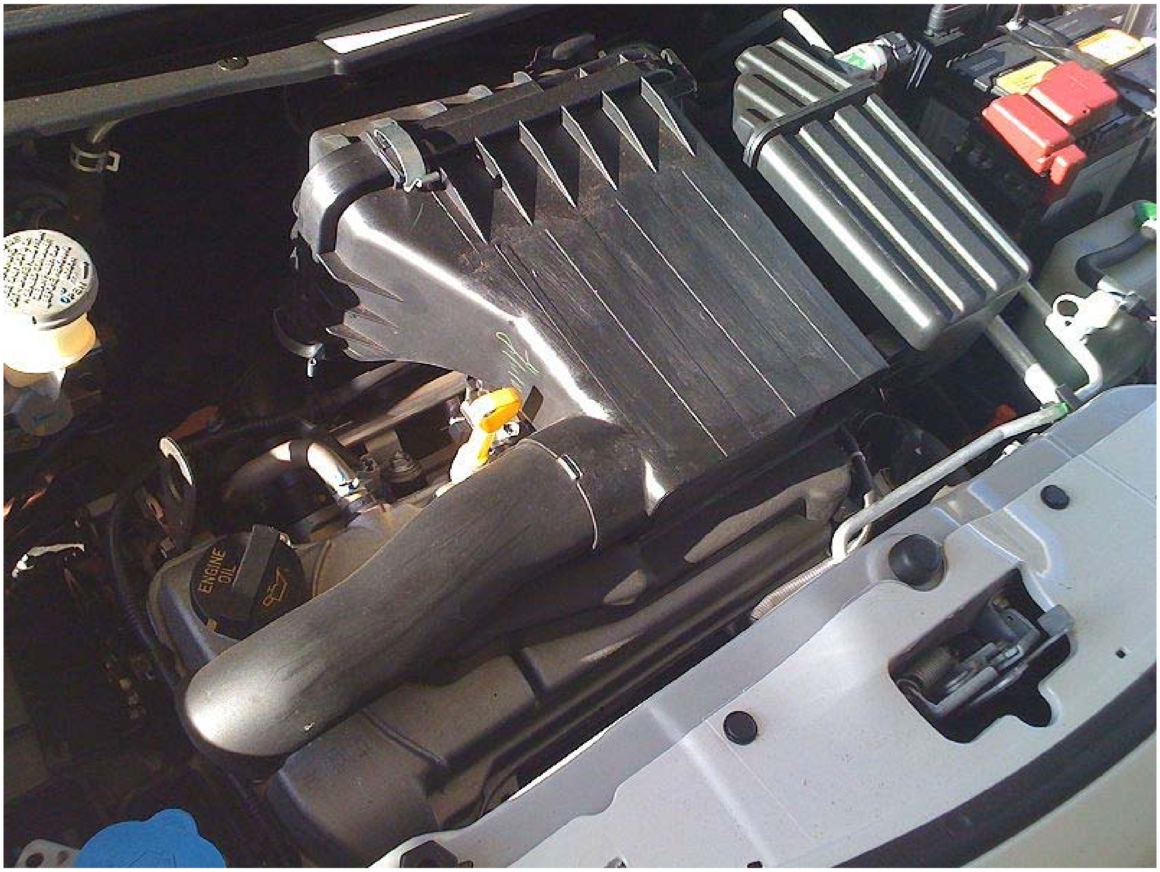
A **straight-three engine**, also known as **inline-three engine**, or a **triple**, (abbreviated **I3** or **R3**) is a reciprocating piston internal combustion engine with three cylinders arranged in a straight line or plane, side by side.

Most inline-three engines employ a crank angle of 120°, and are thus rotationally balanced; however, since the three cylinders are offset from each other, the firing of the end cylinders induces a rocking motion from end to end, since there is no opposing cylinder moving in the opposite direction as in a rotationally balanced straight-six engine. The use of a balance shaft in an antiphase to that vibration produces a smoothly running engine.

An exception to the 120° crankshaft can be found in some of the inline-three engines made by motorcycle manufacturer Laverda. In these engines (sometimes referred to as 180° triples), the outer pistons rise and fall together like a 360° straight-two engine. The inner cylinder is offset 180° from the outer cylinders. In these engines, cylinder #1 fires 180°. Later, cylinder #2 fires, and then 180° later cylinder #3 fires. There is no power stroke on the final 180° of rotation.

Automobile use

A tuned version of a Saab inline-three cylinder two-stroke engine



Suzuki K10B

The smallest inline-three, four-stroke automobile engine was the 543 cubic centimetres (33.1 cu in) Suzuki *F5A*, which was first used in the 1979 Suzuki Alto/Fronte. Smart currently produces a diminutive 799 cubic centimetres (48.8 cu in) inline-three diesel engine, the smallest automotive diesel engine yet. Most inline-three engines fall below 1.2 litres, with a 1,198 cubic centimetres (73.1 cu in) Volkswagen Group unit seen as the largest petrol engine. A 1,779 cubic centimetres (108.6 cu in) diesel engine was produced by VM Motori to the 1984 Alfa Romeo 33 *1.8 TD*, the largest inline-three produced for automotive use.

Basic versions of the Suzuki Swift/Forsa and related Geo/Chevy Metro used an inline-three.

Some Daihatsu cars use inline-three engines. The Charade and the Mira/Cuore used (or are still fitted with) this engine type. Three-cylinder 1.0 litre diesel and turbo diesel engines were also offered in Daihatsu Charades. Korean cars Daewoo Tico, based on the 1988 Suzuki Alto, and later base versions of Daewoo Matiz also used inline-three 796 cubic centimetres (48.6 cu in) 41 horsepower (31 kW; 42 PS) S-TEC petrol engine.

The Volkswagen Group is known for using three cylinder petrol- and diesel engines; in the Audi A2, Volkswagen Polo, Volkswagen Fox, SEAT Ibiza and Škoda Fabia. The engines in these cars ranges from 1.2 litre petrol with four valves per cylinder that deliver 47 to 65 kilowatts (64 to 88 PS; 63 to 87 bhp), to 1.4 TDI diesels= that deliver 51 to 66 kilowatts (69 to 90 PS; 68 to 89 bhp) and have turbos with variable vane geometry and deliver outstanding economy, this particular engine is used in small cars of all marques of the Volkswagen Group. The most innovative three cylinder engine the Volkswagen Group released was the 1.2 TDI diesel, it was one of the first all-aluminium diesel engines, and at the time of release it was the lightest and most economic engine in production. It won many awards and was used in the "3L" versions (from its diminutive fuel consumption of only 3 litres per 100 kilometres (94.2 mpg_{-imp}; 78.4 mpg_{-US})) of the Audi A2 and the Volkswagen Lupo.

Subaru also used an inline-three in the Subaru Justy and the export version of the Subaru Sambar, called the Subaru Sumo, using their Subaru EF engine.

Mitsubishi has also made extensive use of three cylinder engines.

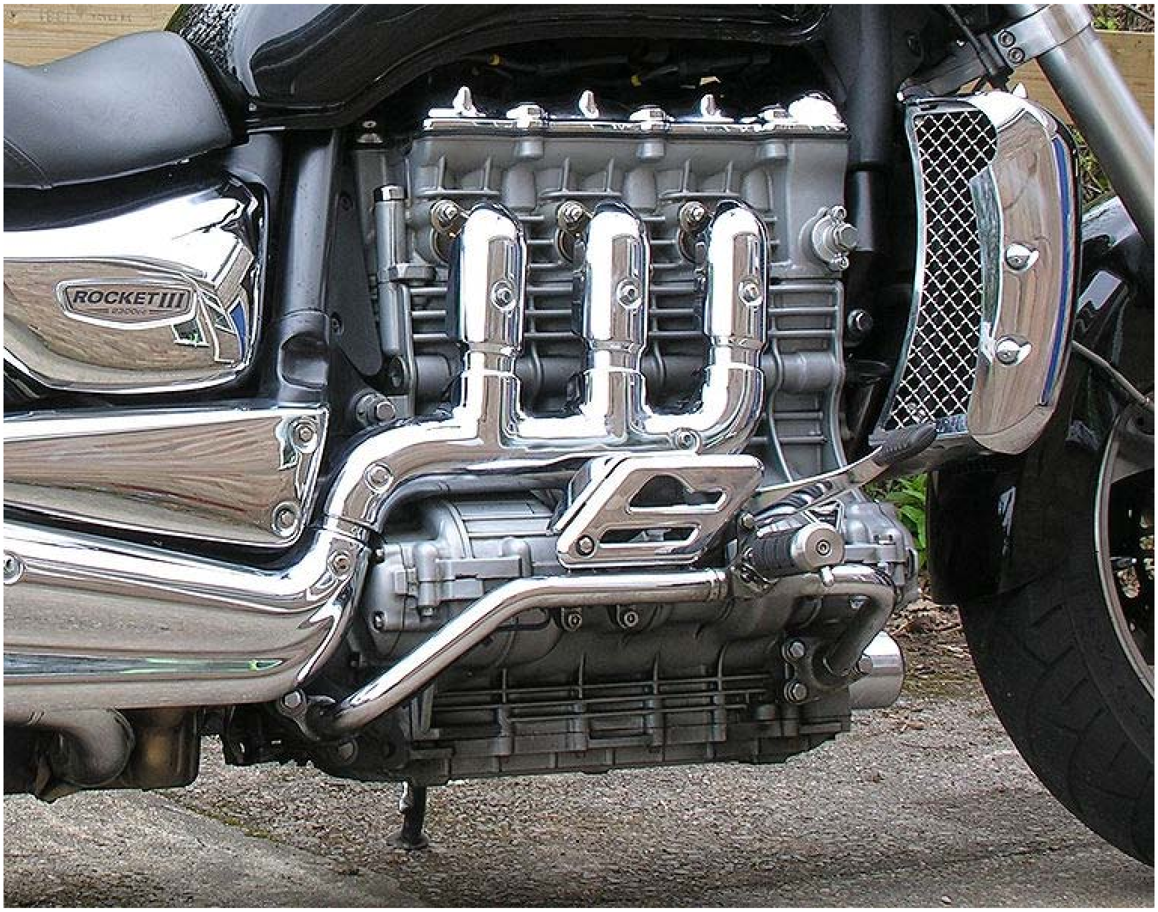
In the 1950s and 1960s, the Saab 93, Saab 95, Saab 96, and certain Dampf-Kraft-Wagen (DKW) automobiles were powered by inline-three-cylinder, two-stroke engines. Also, the Wartburg automobiles manufactured in Eastern Germany used this kind of engine.

The first-generation Honda Insight (2000–2006) used a 1.0 litre inline-three engine in conjunction with an electric motor in its hybrid system.

Toyota, Peugeot and Citroen are using a common inline-three-cylinder engine in models of Aygo, 107 and C1 respectively.

Currently, the only new three-cylinder car available in North America is the Smart fortwo.

Motorcycle use



Triumph Rocket III has a 2.3 L straight-three engine

Four-stroke

The four-stroke inline-three has been used by Aprilia, Laverda, Triumph, Yamaha, BMW, Benelli, Petronas, MV Agusta and BSA.

The Triumph Rocket III has a 2,294 cc (140.0 cu in) inline-three engine.

Two-stroke

Between 1972 and 1977, Suzuki made the inline-three water-cooled 750 cc GT750 and the air-cooled GT550 and GT380.

Between 1969 and 1978, Kawasaki triple motorcycles had inline-three air-cooled engines with capacities of 250 cc, 350 cc, 400 cc, 500 cc, and 750 cc.

Chapter 4

Variable Valve Timing

In internal combustion engines, **variable valve timing**, often abbreviated to **VVT**, is a generic term for an automobile piston engine technology. VVT allows the *lift*, *duration* or *timing* (in various combinations) of the intake and/or exhaust valves to be changed while the engine is in operation. Two-stroke engines use a power valve system to get similar results to VVT.

Overview

Piston engines normally use poppet valves for intake and exhaust. These are driven (directly or indirectly) by cams on a camshaft. The cams open the valves (*lift*) for a certain amount of time (*duration*) during each intake and exhaust cycle. The *timing* of the valve opening and closing is also important. The camshaft is driven by the crankshaft through timing belts, gears or chains.

The profile, or position and shape of the cam lobes on the shaft, is optimized for a certain engine revolutions per minute (RPM), and this tradeoff normally limits low-end torque, or high-end power. VVT allows the cam timing to change, which results in greater efficiency and power, over a wider range of engine RPMs.

An engine requires large amounts of air when operating at high speeds. However, the intake valves may close before enough air has entered each combustion chamber, reducing performance. On the other hand, if the camshaft keeps the valves open for longer periods of time, as with a racing cam, problems start to occur at the lower engine speeds. This will cause unburnt fuel to exit the engine since the valves are still open. This leads to lower engine performance and increased emissions. For this reason, pure racing engines which are designed to idle at speeds close to 2,000 rpm, cannot idle well at the lower speeds (around 800 rpm) expected of a road car.

Pressure to meet environmental goals and fuel efficiency standards is forcing car manufacturers to use VVT as a solution. Most simple VVT systems advance or retard the timing of the intake or exhaust valves. Others (like Honda's VTEC) switch between two sets of cam lobes at a certain engine RPM. Furthermore Honda's i-VTEC can alter intake valve timing continuously.

History

Steam engines

The first variable valve timing systems came into existence in the nineteenth century on steam engines. Stephenson valve gear, as used on early steam locomotives, supported variable cutoff, that is, changes to the time at which the admission of steam to the cylinders is cut off during the power stroke. Early approaches to variable cutoff coupled variations in admission cutoff with variations in exhaust cutoff. Admission and exhaust cutoff were decoupled with the development of the Corliss valve. These were widely used in constant speed variable load stationary engines, with admission cutoff, and therefore torque, mechanically controlled by a centrifugal governor and trip valves. As poppet valves came into use, simplified valve gear using a camshaft came into use. With such engines, variable cutoff could be achieved with variable profile cams that were shifted along the camshaft by the governor.this is now coming in system.

Aircraft

Some versions of the Bristol Jupiter radial engine of the early 1920s incorporated variable valve timing gear, mainly to vary the inlet valve timing in connection with higher compression ratios. The Lycoming R-7755 engine had a Variable Valve Timing system consisting of two cams that can be selected by the pilot. One for take off, pursuit and escape, the other for economical cruising.

Automotive use

In 1958 Porsche made application for a German Patent, also applied for and published as British Patent GB861369 in 1959. The Porsche patent used an oscillating cam driven via a push/pull rod from an eccentric shaft or swash plate. The cam was Desmodromic having opening and closing cam surfaces which operated the valve by a bifurcated rocker and ball joint. Being Desmodromic meant there was no valve spring. The cam pivot was adjustable for height, as the push/pull rod length was constant this rotated the cam so the lift and duration increased. A compensating link moved the rocker pivot to match the cam's position. The adjustment of the cam pivot could be by mechanical linkage to a screw thread, hydraulic from engine driven pump with spill valve or from a engine speed governor. At present it is unknown if any working prototype was ever made.

Fiat was the first auto manufacturer to patent a functional automotive variable valve timing system which included variable lift. Developed by Giovanni Torazza in the late 1960s, the system used hydraulic pressure to vary the fulcrum of the cam followers (US

Patent 3,641,988). The hydraulic pressure changed according to engine speed and intake pressure. The typical opening variation was 37%.

In September 1975, General Motors (GM) patented a system intended to vary valve lift. GM was interested in throttling the intake valves in order to reduce emissions. This was done by minimizing the amount of lift at low load to keep the intake velocity higher, thereby atomizing the intake charge. GM encountered problems running at very low lift, and abandoned the project.

Alfa Romeo was the first manufacturer to use a variable valve timing system in production cars (US Patent 4,231,330). The 1980 Alfa Romeo Spider 2.0 L had a mechanical VVT system in SPICA fuel injected cars sold in the United States. Later this was also used in the 1983 Alfetta 2.0 Quadrifoglio Oro models as well as other cars. The system was engineered by Ing Giampaolo Garcea in the 1970s.

Honda's REV motorcycle engine employed on the Japanese market-only Honda CBR400F in 1983 provided a technology base for VTEC.

In 1986, Nissan developed their own form of VVT with the VG30DE(TT) engine for their MID4 Concept. Nissan chose to focus their NVCS (Nissan Valve-Timing Control System) mainly on torque production at low to medium engine speeds, because, the vast majority of the time, automobile engines will not be operated at extremely high speeds. The NVCS system can produce a smooth idle and high amounts of torque at low to medium engine speeds. The VG30DE engine was first used in the 300ZX (Z31) 300ZR model in 1987. It was the first production car to use electronically controlled VVT technology. In 1987 Nissan also sold the Gloria, Leopard, and Cedric, all of which could come powered by the VG20DET engine which also utilized Nissans NVCS valve timing system.

The next step was taken in 1989 by Honda with the VTEC system. Honda had started production of a system that gives an engine the ability to operate on two completely different cam profiles, eliminating a major compromise in engine design. One profile designed to operate the valves at low engine speeds provides good road manners, low fuel consumption and low emissions output. The second is a high lift, long duration profile and comes into operation at high engine speeds to provide an increase in power output. The VTEC system was also further developed to provide other functions in engines designed primarily for low fuel consumption. The first VTEC engine Honda produced was the B16A which was installed in the Integra, CRX, and Civic hatchback available in Japan and Europe. In 1991 the Acura NSX powered by the C30A became the first VTEC equipped vehicle available in the US. VTEC can be considered the first "cam switching" system and is also one of only a few currently in production.

In 1991, Clemson University researchers patented the Clemson Camshaft which was designed to provide continuously variable valve timing independently for both the intake and exhaust valves on a single camshaft assembly. This ability makes it suitable for both pushrod and overhead cam engine applications.

In 1992, Porsche introduced VarioCam its 968 model which provided continuously variable valve timing for the intake valves.

In 1992, BMW introduced the VANOS system. Like the Nissan NVCS system it could provide timing variation for the intake cam in steps (or phases), the VANOS system differed in that it could provide one additional step for a total of three. Then in 1996 the Double Vanos system was introduced which significantly enhances emission management, increases output and torque, and offers better idling quality and fuel economy. Double Vanos was the first system which could provide electronically controlled, continuous timing variation for both the intake and exhaust valves.

Ford began using Variable Cam Timing in 1998 for the Ford Sigma engine and the Ford Zetec engine. Ford became the first manufacturer to use variable valve timing in a pickup-truck, with the top-selling Ford F-series in the 2004 model year. The engine used was the 5.4 L 3-valve Triton.

In 1999, Porsche introduced VarioCam Plus on its 911 Turbo which combined continuous valve timing and two stage valve lift on the intake valves.

In 2001, BMW introduced the Valvetronic system. The Valvetronic system can continuously and precisely vary intake valve lift, and in addition, the independent Double VANOS system can concurrently vary the timing for both the intake and exhaust valves. The precise control the system has over the intake valves allows for the intake charge to be controlled entirely by the intake valves, eliminating the need for a throttle valve and greatly reducing pumping loss. The reduction of pumping loss accounts for more than a 10% increase in power output and fuel economy.

In 2005, General Motors offered the first Variable Valve timing system for pushrod V6 engines, *LZE* and *LZ4*.

In 2007, DaimlerChrysler became the first manufacturer to produce a cam-in-block engine with independent control of exhaust cam timing relative to the intake. The 2008 Dodge Viper uses Mechadyne's concentric camshaft assembly to help boost power output to 600 bhp (450 kW).

In 2009, Fiat Powertrain Technologies introduced the Multiair system in Geneva Motor Show. The Multiair is a hydraulically-actuated variable valve timing system, which gives full control over valve lift and timing. The new technology is available in Alfa Romeo MiTo starting from September 2009.

In 2009, Porsche introduced an enhanced version of VarioCam Plus on its 911 GT3 including the previous variable valve timing and two stage valve lift on the intake valves but with additional variable timing of the exhaust valves.

Diesel engines

In 2010, Mitsubishi developed and started mass production of its 4N13 1.8 L DOHC I4 world's first passenger car diesel engine that features a variable valve timing system.

VVT implementations

- Aftermarket modifications — Conventional hydraulic tappet can be engineered to rapidly bleed-down for variable reduction of valve opening and duration.
- Alfa Romeo
  - Twin Cam — some versions are equipped with Variable Valve Timing technology.
  - Twin Spark — is equipped with Variable Valve Timing technology.
  - JTS — is equipped with Variable Valve Timing technology, both intake and exhaust.
  - Multiair continuously varies the timing of the inlet valve by changing oil pressure.
- BMW
  - Valvetronic — Provides continuously variable lift for the intake valves; used in conjunction with Double VANOS.
  - VANOS — Varies intake timing by rotating the camshaft in relation to the gear.
  - Double VANOS — Continuously varies the timing of the intake and exhaust valves.
- Daihatsu
  - DVVT — Daihatsu Variable Valve Timing. Continuously varies the timing of the intake camshaft, or both the intake and exhaust camshafts (depending on application).
- Fiat
  - "Twin Cam - VIS" engine - is equipped with Variable Valve Timing technology.
  - "StarJet" FIRE-based engine.
- Ford
  - VCT Variable Cam Timing — Varies valve timing by rotating the camshaft.
  - Ti-VCT Twin Independent Variable Camshaft with two fully variable camshafts used in Ford Sigma engine and Ford Duratec engine.
- Chrysler — Varies valve timing through the use of concentric camshafts developed by Mechadyne enabling dual-independent inlet/exhaust valve adjustment on the 2008 Dodge Viper.
- General Motors Corporation (GM)
  - VVT — Varies valve timing continuously throughout the RPM range for both intake and exhaust for improved performance in both overhead valve and overhead cam engine applications.

- DCVCP (Double Continuous Variable Cam Phasing) — Varies intake and exhaust camshaft timing continuously with hydraulic vane type phaser; available on Family 1, Family 0, and Family II engines.
    - Alloytec — Continuously variable camshaft phasing for inlet cams; continuously variable camshaft phasing for inlet cams and exhaust cams (High Output Alloytec).
- Honda
    - VTEC — Varies duration, timing and lift by switching between two different sets of cam lobes.
    - VTEC-E — This system is designed solely for the purpose of improving fuel economy. A variation of the VTEC mechanism is used to create an offset of lift between the two intake valves, one valve opening only slightly to prevent accumulation of fuel in the intake port. The asymmetrical opening of the intake valves creates a powerful swirl in the combustion chamber and allows for a very lean intake charge to be used under certain conditions. Under normal operation the two intake valve rocker arms are locked together and both valves follow the normal lift cam profile.
    - i-VTEC — In high-output DOHC 4 cylinder engines, the i-VTEC system adds continuous intake cam phasing (timing) to traditional VTEC. In economy-oriented SOHC and DOHC 4-cylinder engines the i-VTEC system increases engine efficiency by delaying the closure of the intake valves under certain conditions and by using an electronically controlled throttle valve to reduce pumping loss. In SOHC V6 engines the i-VTEC system is used to provide Variable Cylinder Management which deactivates one bank of three cylinders during low demand operation.
    - Advanced VTEC — This is the latest Honda VVT system and is the most unusual of all the VTEC systems. Rather than switching between cam lobes the Advanced VTEC system uses intermediate rocker arms with a variable fulcrum to continuously vary intake valve timing, duration and lift.
- Hyundai MPI CVVT — Varies power, torque, exhaust system, and engine response.
- Iran Khodro
    - CVVT-i - Continuous Variable Valve Timing Intelligence which is used for EF7 & EF4 engines of the IKCO EF engines family.
- Kawasaki — Varies position of cam by changing oil pressure thereby advancing and retarding the valve timing, 2008 Concours 14 (also known as the 1400GTR).
- Lexus VVT-iE — Continuously varies the intake camshaft timing using an electric actuator.
- Mazda S-VT — Continually varies intake timing and crank angle using an oil control valve actuated by the ECU to control oil pressure.
- Mitsubishi MIVEC — Varies valve timing, duration and lift by switching between two different sets of cam lobes.
    - The 4B1 engine series uses a different variant of MIVEC which varies timing (phase) of both intake and exhaust camshafts continuously.

    - The 4N1 engine family is the world's first to feature a variable valve timing system applied to passenger car diesel engines.
- Nissan
    - N-VCT — Varies the rotation of the cam(s) only, does not alter lift or duration of the valves.
    - VVL — Varies timing, duration, and lift of the intake and exhaust valves by using two different sets of cam lobes.
    - CVTCS - introduced with the HR15DE, HR16DE, MR18DE and MR20DE engines in September 2004 on the Nissan Tiida and North American version named Nissan Versa (in 2007); and finally the Nissan Sentra (in 2007). Also used on the new MR16DDT
    - VVEL - introduced with the VQ37VHR Nissan VQ engine engine in 2007 on the Infiniti G37.
- Porsche
    - VarioCam — Varies intake timing by adjusting tension of a cam chain.
    - VarioCam Plus — Varies intake valve timing by rotating the cam in relation to the cam sprocket as well as duration, timing and lift of the intake and exhaust valves by switching between two different sets of cam lobes.
- Proton
    - Campro CPS — Varies intake valve timing and lift by switching between two sets of cam lobes without using rocker arms as in most variable valve timing systems. Debuted in the 2008 Proton Gen-2 CPS and the 2008 Proton Waja CPS.
    - VVT introduced in the Waja 1.8's F4P renault engine (Toyota supplies the VVT to renault)
- PSA Peugeot Citroën CVVT — Continuous variable valve timing.
- Renault Clio Renault Sport 172, 172 Cup, 182, 182 Cup, Trophy, 197, 197 Cup, 200, and Clio V6 Mk2 VVT — Megane 1.6 vvt variable valve timing. Clio Mk4 Dynamique S 1.6 VVT. RS Twingo 133 1.6 VVT
- Rover VVC — Varies timing with an eccentric disc.
- Suzuki — VVT — Suzuki M engine
- Subaru
    - AVCS — Varies timing (phase) with hydraulic pressure, used on turbocharged and six-cylinder Subaru engines.
    - AVLS — Varies duration, timing and lift by switching between two different sets of cam lobes (similar to Honda VTEC). Used by non-turbocharged Subaru engines.
- Toyota
    - VVT — Toyota 4A-GE 20-Valve engine introduced VVT in the 1992 Corolla GT-versions.
    - VVT-i — Continuously varies the timing of the intake camshaft, or both the intake and exhaust camshafts (depending on application).
    - VVTL-i — Continuously varies the timing of the intake valves. Varies duration, timing and lift of the intake and exhaust valves by switching between two different sets of cam lobes.

    - Valvematic
- Vauxhall - VVT used in the facelift Vectra 1.8 engines, Astra's and Corsa's.
- Volkswagen Group — VVT introduced with later revisions of the 1.8t engine, and the 30-valve 2.8 L V6. Similar to VarioCam, the intake timing intentionally runs advanced and a retard point is calculated by the ECU. A hydraulic tensioner retards the intake timing. Most modern VW Group petrol engines now include VVT on either the inlet cam, or both inlet and exhaust cams, as in their V6, V8 and V10 engines.
- Volvo
    - CVVT — Continuous variable valve timing on intake and/or exhaust camshafts (depending on application).
    - CPS — Changes valve timing, duration and lift of the intake valves by switching between two different sets of cam lobes. Same basic technology as Porsches VarioCam Plus with switching direct-acting tappets. To date this is only used on Volvos short inline-6 (SI6) naturally-aspirated 3.2 L engine.
- Yamaha — VCT (Variable Cam Timing) Varies position of cam thereby advancing and retarding the valve timing.

Chapter 5

Gasoline Direct Injection

In internal combustion engines, **gasoline direct injection** (GDI), also known as **petrol direct injection** or **direct petrol injection**, is a variant of fuel injection employed in modern two-stroke and four-stroke gasoline engines. The gasoline is highly pressurized, and injected via a common rail fuel line directly into the combustion chamber of each cylinder, as opposed to conventional multi-point fuel injection that happens in the intake tract, or cylinder port.

In some applications, gasoline direct injection enables a stratified fuel charge (ultra lean burn) combustion for improved fuel efficiency, and reduced emission levels at low load.

Theory of operation

The major advantages of a GDI engine are increased fuel efficiency and high power output. In addition, the cooling effect of the injected fuel and the more evenly dispersed mixtures allow for more aggressive ignition timing curves. Emissions levels can also be more accurately controlled with the GDI system. The cited gains are achieved by the precise control over the amount of fuel and injection timings that are varied according to the load conditions. In addition, there are no throttling losses in some GDI engines, when compared to a conventional fuel injected or carbureted engine, which greatly improves efficiency, and reduces 'pumping losses' in engines without a throttle plate. Engine speed is controlled by the engine control unit/engine management system (EMS), which regulates fuel injection function and ignition timing, instead of having a throttle plate that restricts the incoming air supply. Adding this function to the EMS requires considerable enhancement of its processing and memory, as direct injection plus the engine speed management must have very precise algorithms for good performance and drivability.

The engine management system continually chooses among three combustion modes: ultra lean burn, stoichiometric, and full power output. Each mode is characterized by the air-fuel ratio. The stoichiometric air-fuel ratio for gasoline is 14.7:1 by weight, but ultra lean mode can involve ratios as high as 65:1 (or even higher in some engines, for very limited periods). These mixtures are much leaner than in a conventional engine and reduce fuel consumption considerably.

- **Ultra lean burn** mode is used for light-load running conditions, at constant or reducing road speeds, where no acceleration is required. The fuel is not injected at the intake stroke but rather at the latter stages of the compression stroke, so that the small amount of air-fuel mixture is optimally placed near the spark plug. This stratified charge is surrounded mostly by air, which keeps the fuel and the flame away from the cylinder walls for lowest emissions and heat losses. The combustion takes place in a toroidal (donut-shaped) cavity on the piston's surface. The cavity is displaced to one side of the piston, the side that has the fuel injector. This technique enables the use of ultra-lean mixtures that would be impossible with carburetors or conventional fuel injection.
- **Stoichiometric** mode is used for moderate load conditions. Fuel is injected during the intake stroke, creating a homogenous fuel-air mixture in the cylinder. From the stoichiometric ratio, an optimum burn results in a clean exhaust emission, further cleaned by the catalytic converter.
- **Full power** mode is used for rapid acceleration and heavy loads (as when climbing a hill). The air-fuel mixture is homogenous and the ratio is slightly richer than stoichiometric, which helps prevent knock (pinging). The fuel is injected during the intake stroke.

Direct injection may also be accompanied by other engine technologies such as variable valve timing (VVT) and tuned/multi path or variable length intake manifolding (VLIM, or VIM). Water injection or (more commonly) exhaust gas recirculation (EGR) may help reduce the high nitrogen oxides (NOx) emissions that can result from burning ultra lean mixtures.

It is also possible to inject more than once during a single cycle. After the first fuel charge has been ignited, it is possible to add fuel as the piston descends. The benefits are more power and economy, but certain octane fuels have been seen to cause exhaust valve erosion. For this reason, most companies have ceased to use the Fuel Stratified Injection (FSI) operation during normal running.

Tuning up an early generation FSI power plant to generate higher power is difficult, since the only time it is possible to inject fuel is during the induction phase. Conventional injection engines can inject throughout the 4-stroke sequence, as the injector squirts onto the back of a closed valve. A direct injection engine, where the injector injects directly into the cylinder, is limited to the suction stroke of the piston. As the RPM increases, the time available to inject fuel decreases. Newer FSI systems that have sufficient fuel pressure to inject even late in compression phase do not suffer to the same extent; however, they still do not inject during the exhaust cycle (they could but it would just waste fuel). Hence, all other factors being equal, an FSI engine needs higher-capacity injectors to achieve the same power as a conventional engine.

History

Early systems

The first use of direct gasoline injection was on the Hesselman engine invented by Swedish engineer Jonas Hesselman in 1925. Hesselman engines used the ultra lean burn principle and injected the fuel in the end of the compression stroke and then ignited it with a spark plug, it was often started on gasoline and then switched over to run on diesel or kerosene. The Hesselman engine was a low compression design constructed to run on heavy fuel oils. Direct gasoline injection was used on production aircraft during WWII, with German (Junkers Jumo 210, Daimler-Benz DB 601, both 1937), Soviet (Shvetsov ASh-82, 1943, Chemical Automatics Design Bureau - KB Khimavtomatika) and US (Wright R-3350, 1944) designs. The first automotive direct injection system used to run on gasoline was developed by Bosch, and was introduced by Goliath and Gutbrod in 1952. The 1955 Mercedes-Benz 300SL, the first sports car to use fuel injection, used direct injection. The Bosch fuel injectors were placed into the bores on the cylinder wall used by the spark plugs in other Mercedes-Benz six-cylinder engines (the spark plugs were relocated to the cylinder head). Later, more mainstream applications of fuel injection favored the less-expensive indirect injection methods.

In the early 1970s, research was conducted with the backing of American Motors Corporation (AMC) to develop a Straticharge Continuous Fuel-Injection (SCFI) system. The conventional spark ignited internal combustion I6 engine was a modified with a redesigned cylinder head. The system incorporated a mechanical device that automatically responded to the engine’s airflow and loading conditions with two separate fuel-control pressures supplied to two sets of continuous-flow injectors. Flexibility was designed into the SCFI system for trimming it to a particular engine. Prototype "straticharge" engine road testing was performed using a 1973 AMC Hornet, but the mechanical fuel controls had teething problems.

During the late 1970s, the Ford Motor Company developed a stratified-charge engine they called "ProCo" (programmed combustion), utilizing a unique high-pressure pump and direct injectors. One hundred Crown Victoria cars were built at Ford's Atlanta Assembly in Hapeville, Georgia using a ProCo V8 engine. The project was canceled for several reasons: electronic controls, a key element, were in their infancy; pump and injector costs were extremely high; and lean combustion produced nitrogen oxides in excess of near future United States Environmental Protection Agency (EPA) limits. The three-way catalytic converter proved to be a less expensive solution.

Later systems

In **1996** gasoline direct injection reappeared in the automotive market. Mitsubishi was the first with a **GDI** engine in the Japanese market with its Galant/Legnum's *4G93* 1.8 L inline-four. It was subsequently brought to Europe in 1997 in the Carisma, although Europe's then high-sulfur unleaded fuel led to emissions problems, and fuel efficiency was less than expected. It also developed the first six-cylinder GDI powerplant, the *6G74* 3.5 L V6, in 1997. Mitsubishi applied this technology widely, producing over one million GDI engines in four families by 2001.

In **1997** Nissan released the Leopard featuring the VQ30DD equipped with direct injection.

In **1998**, Toyota's D4 direct injection system first appeared on various Japanese market vehicles equipped with the *SZ* and *NZ* engines. Toyota later introduced its D4 system to European markets with the *1AZ-FSE* engine found in the 2001 Avensis. and US markets in 2005 with the *3GR-FSE* engine found in the Lexus GS 300. Toyota's *2GR-FSE* V6 uses a more advanced direct injection system, which combines both direct and indirect injection using two fuel injectors per cylinder, a traditional port fuel injector (low pressure) and a direct fuel injector (high-pressure) in a system known as D4-S.

In **1999**, Renault introduced the 2.0 IDE (Injection Direct Essence), first on the Megane. Rather than following the lean burn approach, Renault's design uses high ratios of exhaust gas recirculation to improve economy at low engine loads, with direct injection allowing the fuel to be concentrated around the spark. Later gasoline direct injection engines have been tuned and marketed for their high performance as well as increased fuel efficiency. PSA Peugeot Citroën, Hyundai and Volvo licensed Mitsubishi's GDI technology in 1999. Although other companies have since developed gasoline direct injection engines, the acronym 'GDI' (with an uppercase final "I") remains a registered trademark of Mitsubishi Motors.

In **2000**, the Volkswagen Group introduced its gasoline direct injection engine in the Volkswagen Lupo, a 1.4 L inline-four unit, under the product name "Fuel Stratified Injection" (FSI). The technology was adapted from Audi's Le Mans prototype race car R8. Volkswagen Group marques use direct injection in its 2.0 L FSI turbocharged and naturally-aspirated four-cylinder engines. Later, a 2.0 L inline-four unit was introduced in the model year 2003 Audi A4. PSA Peugeot Citroën introduced its first GDi (HPi) engine in 2000 in the Citroën C5 and Peugeot 406. It was a 2.0-liter 16-valve EW10 D unit with 140 hp (104 kW), the system was licensed from Mitsubishi.

In **2001**, Ford introduced its first European Ford engine to use direct injection technology, badged SCi (Smart Charge injection) for Direct-Injection-Spark-Ignition (DISI). The range will include some turbocharged derivatives, including the 1.1 L, three-cylinder turbocharged unit showcased at the 2002 Geneva Show. This new 1.8 L Duratec SCi naturally aspirated engine made its production debut in the Ford Mondeo in 2003.

In **2002**, the Alfa Romeo 156 with a direct-injection engine, the JTS (Jet Thrust Stoichiometric) went on sale and today the technology is used on almost every Alfa Romeo engine.

In **2003**, BMW introduced a low-pressure gasoline direct injection N73 V12. This initial BMW setup could not enter lean-burn mode, but the company introduced its second-generation High Precision Injection (HPI) system on the updated N52 straight-6 in 2006, which used high-pressure injectors. This system surpasses many others with a wider envelope of lean-burn time, increasing overall efficiency. PSA is cooperating with BMW on a new line of engines that made its first appearance in the 2007 MINI Cooper S. Honda released their own direct injection system on the Stream sold in Japan. Honda's fuel injector is placed directly atop the cylinder at a 90-degree angle rather than a slanted angle.

Since **2004**, General Motors has released three such direct injected engines: in 2004, a 155 hp (116 kW) version of the 2.2 L Ecotec used in the Opel/Vauxhall Vectra and Signum in 2005, a 2.0 L turbocharged Ecotec for the new Opel GT, Pontiac Solstice GXP, and the Saturn Sky Red Line, in 2007 the same engine was used in the Super Sport versions of the Chevrolet Cobalt and the HHR. Also in 2007, the 3.6 L LLT became available in the redesigned Cadillac CTS and STS. The 3.6 L was added to the 2009 model GMC Acadia, Chevrolet Traverse, Saturn Outlook, Buick Enclave, and the 2010 Chevy Camaro. In 2004 Isuzu produced the first GDi engine sold in a mainstream American vehicle, standard on the 2004 Axiom and optional on the 2004 Rodeo. Isuzu claimed the benefit of GDi is that the vaporizing fuel has a cooling effect, allowing a higher compression ratio (10.3:1 versus 9.1:1) that boosts output by 20 hp (15 kW), and that 0-to-60 mph times drop from 8.9 to just 7.5 seconds, with the quarter-mile being cut from 16.5 to 15.8 seconds.

In **2005**, Mazda began to use their own version of direct-injection in the Mazdaspeed6 and later on the CX-7 sport-utility, and the new Mazdaspeed3 in the US and European market. It is referred to as Direct Injection Spark Ignition (DISI).

In **2006**, BMW released the new N54 twin-turbo-charged direct injection inline-six engine for its 335i Coupe and later for the 335i Sedan, 535i series and the 135i models. Mercedes-Benz released its direct injection system (Charged Gasoline Injection, or "CGI") on the CLS 350 CGI featuring common rail, piezo-electric direct fuel injectors. The CLS 350 CGI offers 292 BHP versus 272 BHP for the CLS 350, with reduced carbon dioxide emissions and improved fuel economy.

In **2007**, Ford introduced its new Ford EcoBoost engine technology designed for a range of global vehicles (from small cars to large trucks). The engine first appeared in the 2007 Lincoln MKR Concept under the name *TwinForce*. The new global EcoBoost family of 4-cylinder and 6-cylinder engines features turbocharging and direct injection technology (GTDI - Gasoline Turbocharged Direct Injection). A 2.0 L version was unveiled in the 2008 Ford Explorer America Concept.

In **2008**, BMW released the X6 xDrive50i equipped with a direct injected twin turbo N63 V8 engine.

In **2009**, Ferrari began selling the front-engine California with a direct injection system, and announced that its new 458 Italia car will also feature a direct injection system, a first for Ferrari mid-rear engine setups. Porsche also began selling the 997 and Cayman equipped with direct injection. Ford produced the new generation Taurus SHO and Flex with a 3.5 L twin-turbo EcoBoost V-6 with direct injection. Holden has also added two direct injection engines as standard on the V6 variant Commodores under the name of SIDI or Spark Ignition Direct Injection. The Infiniti Essence concept car is powered by a direct injected twin turbo V6. The Jaguar Land Rover AJ-V8 Gen III 5.0 L engine (introduced in August 2009 for the 2010 model year) features spray-guided direct injection.

In **2010** Infiniti will produce the M56 which includes DI. Motus Motorcycles is developing, with Katech Engines, a direct-injected V4 engine named the KMV4 as the powertrain for their MST motorcycles. The Hyundai Sonata 2011 model will come with GDI engines. Hyundai's Theta I-4 engine family is a proprietary design, engineered in Namyang, Korea and currently in production for applications all over the world at volumes exceeding 2 million annually. The new Theta II 2.4L GDI engine is a derivative of the Theta with major upgrades in technology and architecture. It features a unique block, valvetrain, front-end accessory drive (FEAD), intake manifold, pistons, rods, crankshaft, variable induction system, and catalyst.

In two-stroke engines

The benefits of direct injection are even more pronounced in two-stroke engines, because it eliminates much of the pollution they cause. In conventional two-strokes, the exhaust and intake ports are both open at the same time, at the bottom of the piston stroke. A large portion of the fuel/air mixture entering the cylinder from the crankcase through the intake ports goes directly out, unburned, through the exhaust port. With direct injection, only air comes from the crankcase, and fuel is not injected until the piston rises and all ports are closed.

Some Goliath two stroke cars built in the early 1950s had direct injection, but their engines were soon superseded by four strokes.

Two types of GDi are used in two-strokes: low-pressure air-assisted, and high-pressure. The former, developed by Orbital Engine Corporation of Australia (now Orbital Corporation) injects a mixture of fuel and compressed air into the combustion chamber. When the air expands it atomizes the fuel. The Orbital system is used in motor scooters manufactured by Aprilia, Piaggio, Peugeot and Kymco, in outboard motors manufactured by Mercury and Tohatsu, and in personal watercraft manufactured by Bombardier Recreational Products (BRP).

In the early 1990s, Ficht GmbH of Kirchseeon, Germany developed a high-pressure direct injector for use with two stroke engines. Outboard Marine Corporation (OMC) licensed the technology in 1995 and introduced it on a production outboard engine in 1996. OMC purchased a controlling interest in Ficht in 1998. Beset by extensive warranty claims for its Ficht outboards and prior and concurrent management-financial problems, OMC declared bankruptcy in December 2000 and the engine manufacturing portion and brands (Evinrude Outboard Motors and Johnson Outboards), including the Ficht technology, were purchased by BRP in 2001.

Evinrude introduced the E-Tec system, an improvement to the Ficht fuel injection, in 2003, based on U.S. patent 6,398,511. In 2004, Evinrude received the EPA Clean Air Excellence Award for their outboards utilizing the E-Tec system. The E-Tec system has recently also been adapted for use in performance two-stroke snowmobiles.

Yamaha also has a high-pressure direct injection (HPDI) system for two-stroke outboards. It differs from the Ficht/E-Tec and Orbital direct injection systems because it uses a separate, belt driven, high-pressure, mechanical fuel pump to generate the pressure necessary for injection in a closed chamber. This is similar to most current 4-stroke automotive designs.

EnviroFit, a non-profit corporation sponsored by Colorado State University, has developed direct injection retrofit kits for two-stroke motorcycles in a project to reduce air pollution in Southeast Asia, using technology developed by Orbital Corporation of Australia. The World Health Organization says air pollution in Southeast Asia and the Pacific causes 537,000 premature deaths each year. The 100-million two-stroke taxis and motorcycles in that part of the world are a major cause.

Future

Twin-fuel engines

Code named Bobcat, the new twin-fuel engine from Ford is based on a 5.0L V8 engine block but uses E85 cylinder injection and gasoline port injection. The engine was co-developed with Ethanol Boosting Systems, LLC of Cambridge, Massachusetts, which calls its trademarked process DI Octane Boost. The direct injection of ethanol increases the octane of regular gasoline from 88-91 octane to more than 150 octane. The Bobcat project was unveiled to the United States Department of Energy and the SAE International in April 2009.

Formula One

As part of the rule changes under discussion for the 2013 season, GDI has been mentioned as a potential technology of interest by Ferrari.

Chapter 6

VTEC

VTEC (**Variable Valve Timing and Lift Electronic Control**) is a valvetrain system developed by Honda to improve the volumetric efficiency of a four-stroke internal combustion engine. This system uses two camshaft profiles and electronically selects between the profiles. This was the first system of its kind. Different types of variable valve timing and lift control systems have also been produced by other manufacturers (MIVEC from Mitsubishi, AVCS from Subaru, VVTL-i from Toyota, VarioCam Plus from Porsche, VVC from Rover Group, VVL from Nissan, etc.). It was invented by Honda R&D engineer Ikuo Kajitani.

History

VTEC, the original Honda variable valve control system, originated from REV (Revolution-modulated valve control) introduced on the CBR400 in 1983 known as HYPER VTEC. In the regular four-stroke automobile engine, the intake and exhaust valves are actuated by lobes on a camshaft. The shape of the lobes determines the timing, lift and duration of each valve. Timing refers to an angle measurement of when a valve is opened or closed with respect to the piston position (BTDC or ATDC). Lift refers to how much the valve is opened. Duration refers to how long the valve is kept open. Due to the behavior of the working fluid (air and fuel mixture) before and after combustion, which have physical limitations on their flow, as well as their interaction with the ignition spark, the optimal valve timing, lift and duration settings under low RPM engine operations are very different from those under high RPM. Optimal low RPM valve timing, lift and duration settings would result in insufficient filling of the cylinder with fuel and air at high RPM, thus greatly limiting engine power output. Conversely, optimal high RPM valve timing, lift and duration settings would result in very rough low RPM operation and difficult idling. The ideal engine would have fully variable valve timing, lift and duration, in which the valves would always open at exactly the right point, lift high enough and stay open just the right amount of time for the engine speed in use.

VTEC was initially designed to increase the power output of an engine to 100 PS/liter or more while maintaining practicality for use in mass production vehicles. Some later variations of the system were designed solely to provide improvements in fuel efficiency, or increased power output. In practice, a fully variable valve timing engine is difficult to design and implement.

The opposite approach to variable timing is to produce a camshaft which is better suited to high RPM operation. This approach means that the vehicle will run very poorly at low RPM (where most automobiles spend much of their time) and much better at high RPM. VTEC is the result of an effort to marry high RPM performance with low RPM stability.

Additionally, Japan has a tax on engine displacement, requiring Japanese auto manufacturers to make higher-performing engines with lower displacement. In cars such as the Toyota Supra and Nissan 300ZX, this was accomplished with a turbocharger. In the case of the Mazda RX-7 and RX-8, a rotary engine was used. VTEC serves as yet another method to derive very high specific output (power/unit displacement) from smaller-displacement engines.

DOHC VTEC

The VTEC system is a simple method of endowing the engine with multiple camshaft profiles optimized for low and high RPM operations. Instead of one cam lobe actuating each valve, there are two: one optimized for low-RPM stability & fuel efficiency; the other designed to maximize high-RPM power output. Switching between the two cam lobes is controlled by the ECU which takes account of engine oil pressure, engine temperature, vehicle speed, engine speed and throttle position. Using these inputs, the ECU is programmed to switch from the low lift to the high lift cam lobes when the conditions mean that engine output will be improved. At the switch point a solenoid is actuated which allows oil pressure from a spool valve to operate a locking pin which binds the high RPM cam follower to the low RPM ones. From this point on, the poppet valve opens and closes according to the high-lift profile, which opens the valve further and for a longer time. The switch-over point is variable, between a minimum and maximum point, and is determined by engine load. The switch back from high to low RPM cams is set to occur at a lower engine speed than the up-switch (hysteresis) to avoid a situation in which the engine is asked to operate continuously at or around the switch-over point.

Introduced as a DOHC system in the 1989 Honda Integra and Civic CRX SiR (Japan) and 1.6i-VT (Europe) models, which used a 150 bhp (110 kW) variant of the B16A engine (B16A1). The US market saw the first VTEC system with the introduction of the 1991 Acura NSX, which used a 3 liter DOHC VTEC V6 with 280 bhp (210 kW). DOHC VTEC engines soon appeared in other vehicles, such as the 1992 Acura Integra GS-R (B17A1 1.7 liter engine), and later in the 1992 Honda Prelude VTEC (H22A 2.2 liter engine with 195 hp) and Honda Del Sol VTEC (B16A2 1.6 liter engine). The Integra Type R (1997–2001) available in the Japanese market produces 200 bhp (149 kW; 203

PS) using a B18C5 1.8 liter engine. Honda has also continued to develop other varieties and today offers several varieties of VTEC, such as i-VTEC and i-VTEC Hybrid.

SOHC VTEC

As popularity and marketing value of the VTEC system grew, Honda applied the system to SOHC (Single Over Head Cam) engines, which share a common camshaft for both intake and exhaust valves. The trade-off was that Honda's SOHC engines only benefitted from the VTEC mechanism on the intake valves. This is because VTEC requires a third center rocker arm and cam lobe (for each intake and exhaust side), and in the SOHC engine, the spark plugs are situated between the two exhaust rocker arms, leaving no room for the VTEC rocker arm. Additionally, the center lobe on the camshaft can only be utilized by either the intake or the exhaust, limiting the VTEC feature to one side.

However, beginning with the J37A4 3.7L SOHC V6 engine introduced on all 2009 Acura TL SH-AWD models, SOHC VTEC was incorporated for use with intake and exhaust valves. The intake and exhaust rocker shafts contain primary and secondary intake and exhaust rocker arms, respectively. The primary rocker arm contains the VTEC switching piston, while the secondary rocker arm contains the return spring. The term "primary" does not refer to which rocker arm forces the valve down during low-RPM engine operation. Rather, it refers to the rocker arm which contains the VTEC switching piston and receives oil from the rocker shaft.

The primary exhaust rocker arm contacts a low-profile camshaft lobe during low-RPM engine operation. Once VTEC engagement occurs, the oil pressure flowing from the exhaust rocker shaft into the primary exhaust rocker arm forces the VTEC switching piston into the secondary exhaust rocker arm, thus locking both exhaust rocker arms together. The high-profile camshaft lobe which normally contacts the secondary exhaust rocker arm alone during low-RPM engine operation is able to move both exhaust rocker arms together which are locked as a unit.

The secondary intake rocker arm contacts a low-profile camshaft lobe during low-RPM engine operation. Once VTEC engagement occurs, the oil pressure flowing from the intake rocker shaft into the primary intake rocker arm forces the VTEC switching piston into the secondary intake rocker arm, thus locking both intake rocker arms together. The high-profile camshaft lobe which normally contacts the primary intake rocker alone during low-RPM engine operation is able to move both intake rocker arms together which are locked as a unit.

The difficulty of incorporating VTEC for both the intake and exhaust valves in a SOHC engine has been removed on the J37A4 by a novel design of the intake rocker arm. Each exhaust valve on the J37A4 corresponds to one primary and one secondary exhaust rocker arm. Therefore, there are a total of twelve primary exhaust rocker arms and twelve secondary exhaust rocker arms.

However, each secondary intake rocker arm is shaped similar to a "Y" which allows it to contact two intake valves at once. One primary intake rocker arm corresponds to each secondary intake rocker arm. As a result of this design, there are only six primary intake rocker arms and six secondary intake rocker arms.

VTEC-E

It is a version of SOHC VTEC, which was used to increase efficiency at low RPM. At low RPM, one of the two intake valves is only allowed to open a very small amount, increasing the fuel/air atomization in the cylinder and thus allowing a leaner mixture to be used. As the engine's speed increases, both valves are needed to supply sufficient mixture. A sliding pin, which is pressured by oil, as in the regular VTEC, is used to connect both valves together and allows the full opening of the second valve.

3-Stage VTEC

It is a version of VTEC using 3 different cam profiles to control intake valve timing and lift. Due to this version of VTEC being on a SOHC valve head, space was limited and so VTEC can only modify the opening and closing of the intake valves. This version of VTEC combines the fuel economy benefits of VTEC-E and the performance of VTEC. From idle to 2500-3000RPM, depending on load conditions, one intake valve fully opens while the other just slightly, enough to prevent pooling of fuel behind the valve, also called 12 valve mode. This 12 Valve mode results in swirl of the intake charge which increases combustion efficiency resulting in improved low end torque and better fuel economy. At 3000-5400 RPM, depending on load, one of the VTEC solenoids engages which causes the 2nd valve (the one that barely opened before) to lock onto the first valve's camshaft lobe so now both valves share the same camshaft profile, with this mode also being called 4 valve mode, lending itself to improved mid-range power. At 5500-7000 RPM, the second VTEC solenoid engages (both solenoids now engaged) so that both intake valves are using a middle, third camshaft lobe. This camshaft lobe is a high performance lobe which is used to provide peak power at the top end of the RPM range.

i-VTEC

(intelligent-VTEC) introduced continuously variable camshaft phasing on the intake cam of DOHC VTEC engines. The technology first appeared on Honda's K-series four cylinder engine family in 2001 (2002 in the U.S.). In the United States, Honda first debuted the technology on the 2003 Honda Civic Si EP3 with the economy version.

Valve lift and duration are still limited to distinct low- and high-RPM profiles, but the intake camshaft is now capable of advancing between 25 and 50 degrees (depending upon engine configuration) during operation. Phase changes are implemented by a computer controlled, oil driven adjustable cam gear. Phasing is determined by a combination of engine load and rpm, ranging from fully retarded at idle to somewhat advanced at full throttle and low RPM. The effect is further optimization of torque output, especially at low and midrange RPM.

K-series

The K-Series motors have two different types of i-VTEC systems implemented. The first is for the performance motors like in the RSX Type S or the Civic Si and the other is for economy motors found in the CR-V or Accord. The performance i-VTEC system is basically the same as the DOHC VTEC system of the B16A's; both intake and exhaust have 3 cam lobes per cylinder. However the valvetrain has the added benefit of roller rockers and continuously variable intake cam timing. Performance i-VTEC is a combination of conventional DOHC VTEC with VTC.

The economy i-VTEC is more like the SOHC VTEC-E in that the intake cam has only two lobes, one very small and one larger, as well as no VTEC on the exhaust cam. The two types of motor are easily distinguishable by the factory rated power output: the performance motors make around 200 hp (150 kW) or more in stock form and the economy motors do not make much more than 160 hp (120 kW) from the factory.

R-series

The new SOHC i-VTEC implementation is an entirely new implementation that was first introduced on the 2006 Honda Civic's R-series four cylinder SOHC engines. This implementation uses the so-called "fuel economy cam" and "high output cam" on one of the two intake valves of each cylinder (another intake valve is fixed). The "fuel economy cams" are designed to retard the closure of one intake valve and are activated between 1000-3500 RPM and under low load conditions. When "fuel economy cams" are activated, the intake valve closes well after the piston has started moving upwards in the compression stroke. During this time, the drive-by-wire throttle valve is open wider than normal. Due to the delayed closing of intake valve, a part of the intake mixture that has entered the combustion chamber is forced out again into the intake manifold. That way, the engine "emulates" a lower displacement than its actual one (its operation is also similar to an Atkinson cycle engine, with uneven compression and combustion strokes), which reduces pumping losses thus reducing fuel consumption and increases its efficiency. VTEC-off on the R18A means it can be considered to be running "high output cams". When the right conditions are achieved for fuel economy, VTEC engages the 2nd set, the 'low' or 'economy' cams. Thus VTEC-on on the R18A means it is running low cams.

According to Honda, this measure alone can reduce pumping losses by 16%. Under heavier loads, the engine switches back into its "high output cams", and it operates like a regular 4 stroke Otto cycle engine. This implementation of i-VTEC was initially introduced in the R18A1 engine found under the hood of the 8th generation Civic, with a displacement of 1.8 L and an output of 140 PS (100 kW; 140 hp). Recently, another variant was released, the 2.0 L R20A2 with an output of 150 PS (110 kW; 150 hp), which powers the EUDM version of the all-new CRV. SOHC i-VTEC

With the continued introduction of vastly different i-VTEC systems, one may assume that the term is now a catch-all for creative valve control technologies from Honda.

i-VTEC with Variable Cylinder Management (VCM)

In 2003, Honda introduced an i-VTEC V6 (an update of the J-series) that includes Honda's cylinder deactivation technology which closes the valves on one bank of (3) cylinders during light load and low speed (below 80 km/h (50 mph)) operation. According to Honda "VCM technology works on the principle that a vehicle only requires a fraction of its power output at cruising speeds. The system electronically deactivates cylinders to reduce fuel consumption. The engine is able to run on 3,4, or all 6 cylinders based on the power requirement. Essentially getting the best of both worlds. V6 power when accelerating or climbing, as well as the efficiency of a smaller engine when cruising." The technology was originally introduced to the US on the Honda Odyssey minivan, and can now be found on the Honda Accord Hybrid, the 2006 Honda Pilot, and the 2008 Honda Accord. Example: EPA estimates for the 2011 (271hp SOHC 3.5L) V6 Accord are 24mpg combined vs. 27 in the two 4 cylinder equipped models.

i-VTEC VCM was also used in 1.3L 4-cylinder engines used in Honda Civic Hybrid.

i-VTEC i

It is a version of i-VTEC with direct injection.

It was first used in 2003 Honda Stream.

AVTEC

The AVTEC (Advanced VTEC) engine was first announced in 2006. It combines continuously variable valve lift and timing control with continuously variable phase control. Honda originally planned to produce vehicles with AVTEC engines within next 3 years.

Although it was speculated that it would first be used in 2008 Honda Accord, the vehicle instead utilizes the existing i-VTEC system.

A related US patent (6,968,819) was filed in 2005-01-05.

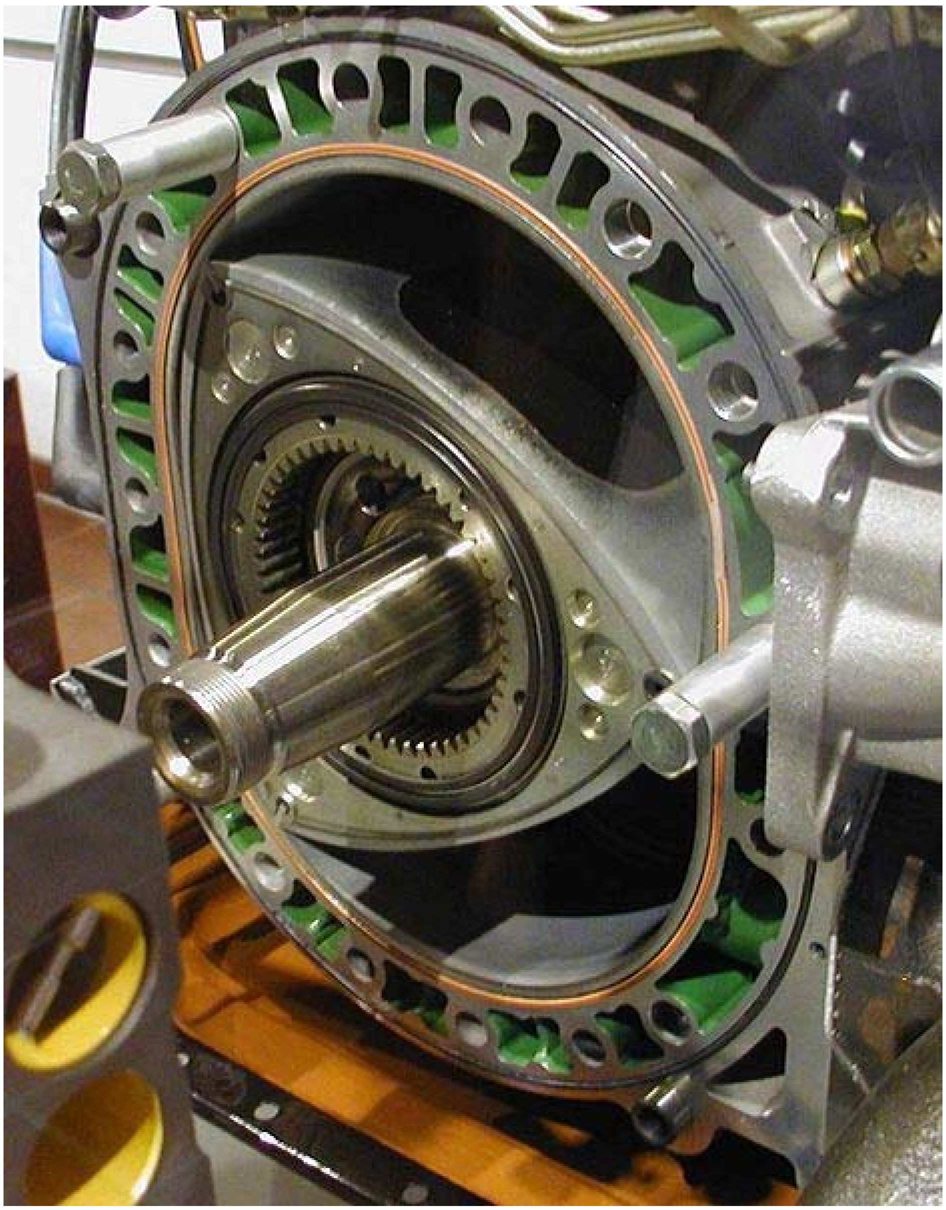
VTEC in motorcycles

Apart from the Japanese market-only Honda CB400SF Super Four HYPER VTEC, introduced in 1983, the first worldwide implementation of VTEC technology in a motorcycle occurred with the introduction of Honda's VFR800 sportbike in 2002. Similar to the SOHC VTEC-E style, one intake valve remains closed until a threshold of 7000 rpm is reached, then the second valve is opened by an oil-pressure actuated pin. The dwell of the valves remains unchanged, as in the automobile VTEC-E, and little extra power is produced but with a smoothing-out of the torque curve. Critics maintain that VTEC adds little to the VFR experience while increasing the engine's complexity. Honda seem to agree: their VFR1200, a model announced in October 2009 to replace the

VFR800, abandons the V-TEC concept in favour of a large capacity narrow-vee "unicam" (i.e. sohc) motor.

Chapter 7

Wankel Engine



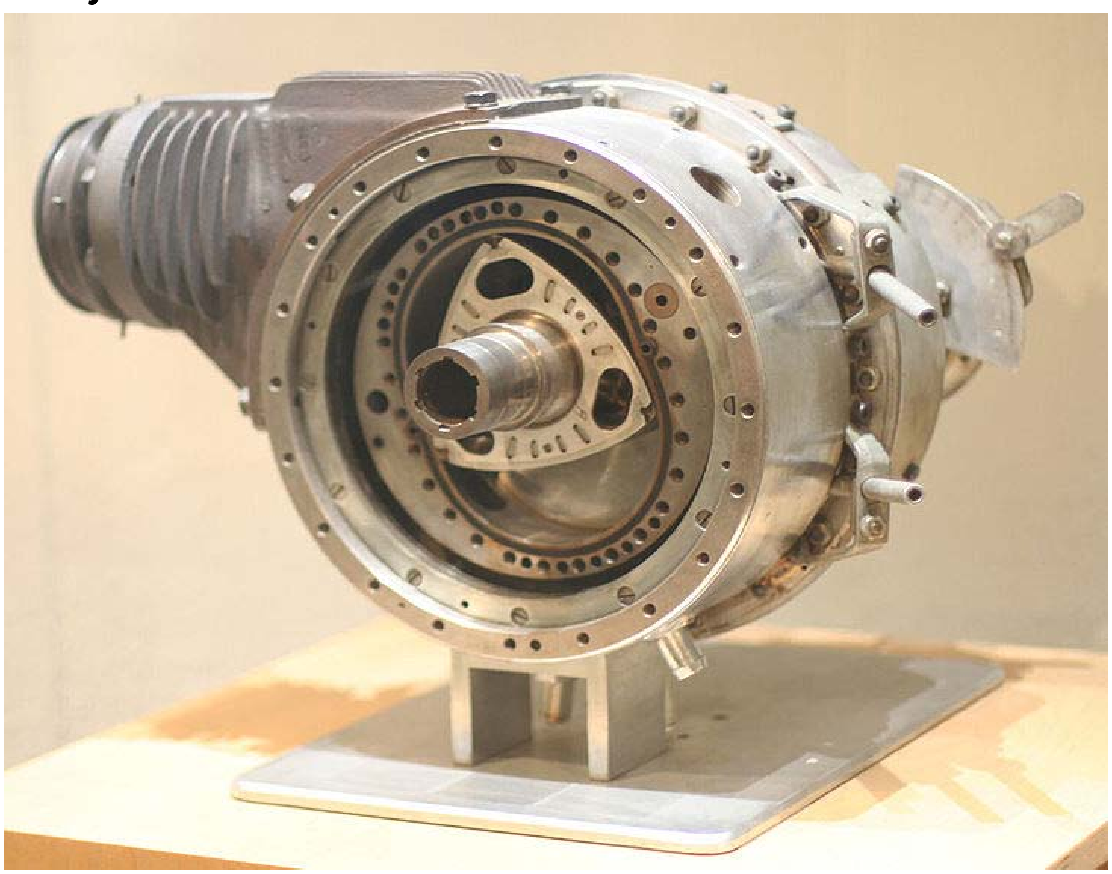
A Wankel engine in Deutsches Museum in Munich, Germany

The **Wankel engine** is a type of internal combustion engine that uses a rotary design to convert pressure into a rotating motion instead of using reciprocating pistons. Its four-stroke cycle takes place in a space between the inside of an oval-like epitrochoid-shaped housing and a rotor that is similar in shape to a Reuleaux triangle but with sides that are somewhat flatter. This design delivers smooth high-rpm power from a compact size. It is the only internal combustion engine invented in the twentieth century to go into production. Since its introduction the engine has been commonly referred to as the **rotary engine**, though this name is also applied to several completely different designs.

The engine was invented by German engineer Felix Wankel. He received his first patent for the engine in 1929, began development in the early 1950s at NSU Motorenwerke AG (NSU), and completed a working prototype in 1957. NSU then licensed the concept to companies around the world, which have continued to improve the design.

Because of their compact design, Wankel rotary engines have been installed in a variety of vehicles and devices such as automobiles (including racing cars), along with aircraft, go-karts, personal water craft, chain saws, and auxiliary power units. The most extensive automotive use of the Wankel engine has been by the Japanese company Mazda.

History



First DKM Wankel Engine DKM 54 (*Drehkolbenmotor*), at the Deutsches Museum in Bonn, Germany

First KKM Wankel Engine NSU KKM 57P (*Kreiskolbenmotor*), at Autovision und Forum, Germany

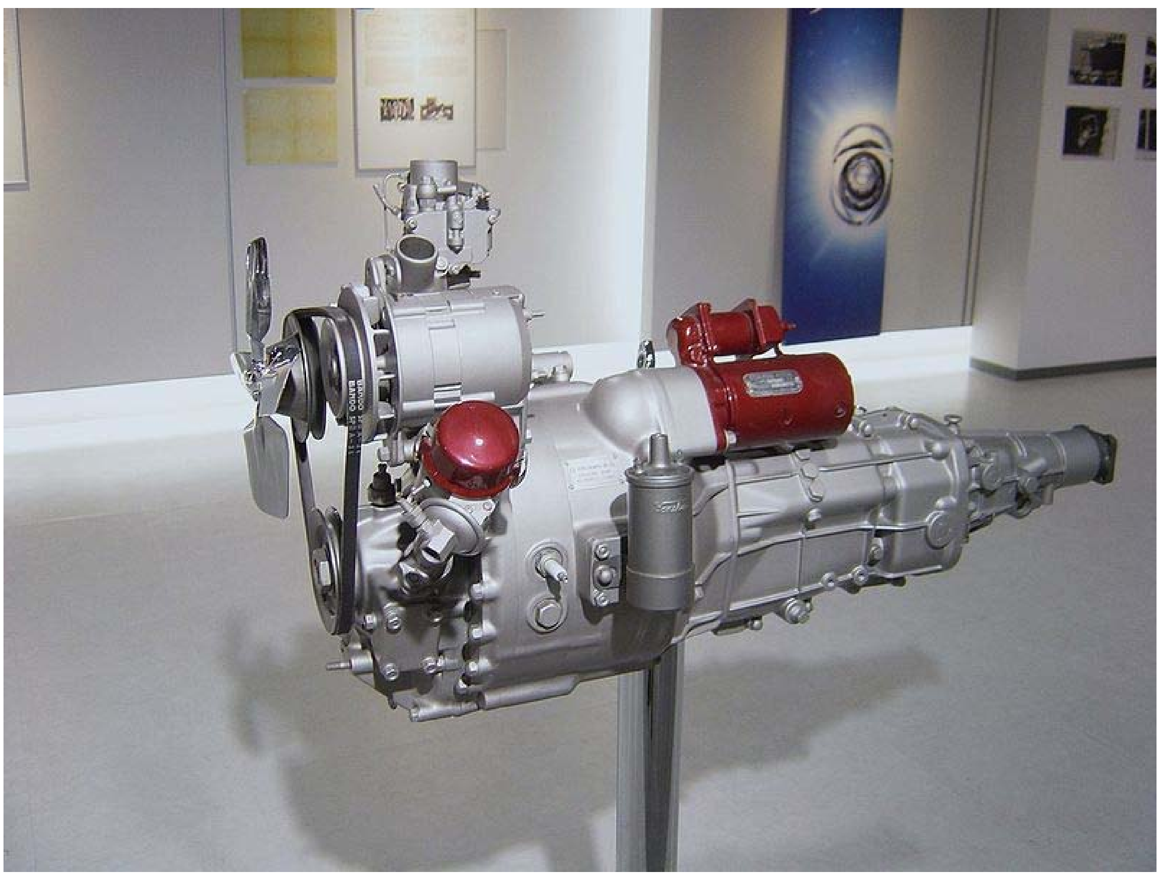
In 1951, the German engineer Felix Wankel began development of the engine at NSU Motorenwerke AG, where he first conceived his rotary engine in 1954 (DKM 54, *Drehkolbenmotor*). The so-called KKM 57 (the Wankel rotary engine, *Kreiskolbenmotor*) was constructed by NSU engineer Hanns Dieter Paschke in 1957 without the knowledge of Felix Wankel, who remarked "*you've turned my race horse into a plow mare*". The first working prototype DKM 54 was running on February 1, 1957 at the NSU research and development department *Versuchsabteilung TX*. It produced 21 horsepower; unlike modern Wankel engines, both the rotor and the housing rotated.

Considerable effort went into designing rotary engines in the 1950s and 1960s. They were of particular interest because they were smooth and quiet running, and because of the reliability resulting from their simplicity. An early problem of buildup of cracks in the epitrochoid surface was solved by installing the spark plugs in a separate metal piece instead of screwing them directly into the block.

Among the manufacturers signing licensing agreements to develop Wankel engines were Alfa Romeo, American Motors, Citroen, Ford, General Motors, Mercedes-Benz, Nissan, Porsche, Rolls-Royce, Suzuki, and Toyota. In the United States, in 1959 under license from NSU, Curtiss-Wright pioneered minor improvements in the basic engine design. In Britain, in the 1960s, Rolls Royce Motor Car Division pioneered a two-stage diesel version of the Wankel engine.

Also in Britain, Norton Motorcycles developed a Wankel rotary engine for motorcycles, based on the Sachs air cooled Wankel that powered the DKW/Hercules W-2000 motorcycle, which was included in their Commander and F1; Suzuki also made a production motorcycle with a Wankel engine, the RE-5, where they used ferrotic alloy apex seals and an NSU rotor in a successful attempt to prolong the engine's life. In 1971 and 1972 Arctic Cat produced snowmobiles powered by 303 cc Wankel rotary engines manufactured by Sachs in Germany. Deere & Company designed a version that was capable of using a variety of fuels. The design was proposed as the power source for United States Marine Corps combat vehicles and other equipment in the late 1980s.

Mazda and NSU signed a study contract to develop the Wankel engine in 1961 and competed to bring the first Wankel powered automobile to market. Although Mazda produced an experimental Wankel that year, NSU was first with a Wankel automobile on sale, the sporty NSU Spider in 1964; Mazda countered with a display of two and four rotor Wankel engines at that year's Tokyo Motor Show. In 1967, NSU began production of a Wankel engined luxury car, the Ro 80. However, problems with apex seal wear led to frequent engine failure, which led to large warranty costs for NSU, and curtailed further Wankel engine development.



Mazda's first Wankel engine, at the Mazda Museum in Hiroshima, Japan

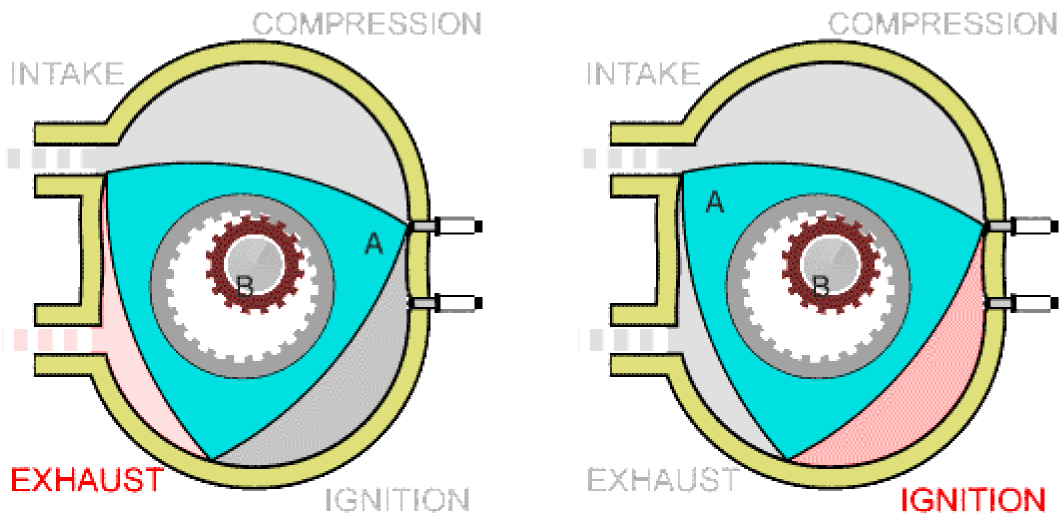
Mazda, however, claimed to have solved the apex seal problem, and was able to run test engines at high speed for 300 hours without failure. After years of development, Mazda's first Wankel engine car was the 1967 Cosmo 110S. The company followed with a number of Wankel ("rotary" in the company's terminology) vehicles, including a bus and a pickup truck. Customers often cited the cars' smoothness of operation. However, Mazda chose a method to comply with hydrocarbon emission standards that, while less expensive to produce, increased fuel consumption, just before a sharp rise in fuel prices. Mazda later abandoned the Wankel in most of their automotive designs, but continued using it in their RX-7 sports car until August 2002 (RX-7 importation for Canada ceased with only the 1993 year being sold. The USA ended with the 1994 model year with remaining unsold stock being carried over as the '1995' year.). The company normally used two-rotor designs, but the 1991 Eunos Cosmo used a twin-turbo three-rotor engine. In 2003, Mazda introduced the Renesis engine with the RX-8. The Renesis engine relocated the ports for exhaust and intake from the periphery of the rotary housing to the sides, allowing for larger overall ports, better airflow, and further power gains. Early Wankel engines had also side intake and exhaust ports, but the concept was abandoned because of carbon buildup in ports and side of rotor. The Renesis engine solved the problem by using a keystone scraper side seal. The Renesis is capable of delivering 238 hp (177 kW) with better fuel economy, reliability, and environmental friendliness than previous Mazda rotary engines, all from its 1.3 L displacement.

In 1961, the Soviet research organization of NATI, NAMI and VNIImotoprom started experimental development, and created experimental engines with different technologies.

Soviet automobile manufacturer AvtoVAZ also experimented with the use of Wankel engines in cars but without the benefit of a license. In 1974 they created a special engine design bureau, which in 1978 designed an engine designated as VAZ-311. In 1980, the company started delivering Wankel-powered VAZ-2106s (VAZ-411 engine with two-rotors) and Ladas, mostly to security services, of which about 200 were made. The next models were the VAZ-4132 and VAZ-415. Aviadvigatel, the Soviet aircraft engine design bureau, is known to have produced Wankel engines with electronic injection for aircraft and helicopters, though little specific information has surfaced.

Although many manufacturers licensed the design, including Citroën with their M35 and GS Birotor, using engines produced by Comotor, General Motors, which seems to have concluded that the Wankel engine was slightly more expensive to build than an equivalent reciprocating engine, and Mercedes-Benz which used it for their C111 concept car, only Mazda has produced Wankel engines in large numbers. American Motors (AMC) was so convinced "...that the rotary engine will play an important role as a powerplant for cars and trucks of the future...", according to Chairman Roy D. Chapin Jr., that the smallest U.S. automaker signed an agreement in February 1973, after a year's negotiations, to build Wankels for both passenger cars and Jeeps, as well as the right to sell any rotary engines it produces to other companies. It even designed the unique Pacer around the engine, even though by then, AMC had decided to buy the Wankel engines from GM instead of building them itself. However, GM's engines had not reached production when the Pacer was to hit the showrooms. Part of the demise of this feature was the 1973 oil crisis with rising fuel prices, and also concerns about proposed US emission standards legislation. General Motors' Wankel did not comply with those emission standards, so in 1974 the company canceled its development, although GM claimed having solved the fuel consumption problem; unfortunately, they never published the results of their research. This meant the Pacer had to be reconfigured to house AMC's venerable AMC Straight-6 engine with rear-wheel drive

Design



The Wankel cycle. The "A" marks one of the three apexes of the rotor. The "B" marks the eccentric shaft and the white portion is the lobe of the eccentric shaft. The shaft turns three times for each rotation of the rotor around the lobe and once for each orbital revolution around the eccentric shaft.

In the Wankel engine, the four strokes of a typical Otto cycle occur in the space between a three-sided symmetric rotor and the inside of a housing, although the Wankel cycle differs from Otto cycle in the duration of the expansion part of cycle, that is much longer. In the basic single-rotor Wankel engine, the oval-like epitrochoid-shaped housing surrounds a rotor which is triangular with bow-shaped flanks (often confused with a Reuleaux triangle, a three-pointed curve of constant width, but with the bulge in the middle of each side a bit more flattened). The theoretical shape of the rotor between the fixed corners is the result of a minimization of the volume of the geometric combustion chamber and a maximization of the compression ratio, respectively. The symmetric curve connecting two arbitrary apexes of the rotor is maximized in the direction of the inner housing shape with the constraint not to touch the housing at any angle of rotation (an arc is not a solution of this optimization problem).

The central drive shaft, called the eccentric shaft or E-shaft, passes through the center of the rotor and is supported by fixed bearings. The rotors ride on eccentrics (analogous to cranks) integral with the eccentric shaft (analogous to a crankshaft). The rotors both rotate around the eccentrics and make orbital revolutions around the eccentric shaft. Seals at the corners of the rotor seal against the periphery of the housing, dividing it into three moving combustion chambers. The rotation of each rotor on its own axis is caused and controlled by a pair of synchronizing gears A fixed gear mounted on one side of the rotor housing engages a ring gear attached to the rotor and ensures the rotor moves exactly 1/3 turn for each turn of the eccentric shaft. The power output of the engine is not transmitted through the synchronizing gears. The force of gas pressure on the rotor (to a first approximation) goes directly to the center of the eccentric, part of the output shaft.

The best way to visualize the action of the engine in the animation at left is to look not at the rotor itself, but the cavity created between it and the housing. The Wankel engine is actually a variable-volume progressing-cavity system. Thus there are 3 cavities per housing, all repeating the same cycle. Note as well that points A and B on the rotor and e-shaft turn at different speed, point B moves 3 times faster than point A, so that one full orbit of the rotor equates to 3 turns of the e-shaft.

As the rotor rotates and orbitally revolves, each side of the rotor gets closer and farther from the wall of the housing, compressing and expanding the combustion chamber similarly to the strokes of a piston in a reciprocating engine. The power vector of the combustion stage goes through the center of the offset lobe.

While a four-stroke piston engine makes one combustion stroke per cylinder for every two rotations of the crankshaft (that is, one-half power stroke per crankshaft rotation per cylinder), each combustion chamber in the Wankel generates one combustion stroke per each driveshaft rotation, i.e. one power stroke per rotor orbital revolution and three power strokes per rotor rotation. Thus, power output of a Wankel engine is generally higher than that of a four-stroke piston engine of similar engine displacement in a similar state of tune; and higher than that of a four-stroke piston engine of similar physical dimensions and weight.

Wankel engines also generally have a much higher redline than a reciprocating engine of similar power output, in part because the smoothness inherent in circular motion, but especially because they do not have highly stressed parts such as a crankshaft or connecting rods. Eccentric shafts do not have the stress-raising internal corners of crankshafts. The redline of a rotary engine is limited by wear of the synchronizing gears. Hardened steel gears are used for extended operation above 7000 or 8000 rpm. Mazda Wankel engines in auto racing are operated above 10,000 rpm. In aircraft they are used conservatively, up to 6500 or 7500 rpm. However, as gas pressure participates in seal efficiency, running a Wankel engine at high rpm under no load conditions can destroy the engine.

National agencies that tax automobiles according to displacement and regulatory bodies in automobile racing variously consider the Wankel engine to be equivalent to a four-stroke engine of 1.5 to 2 times the displacement; some racing series ban it altogether.

Engineering

Apex seals, left NSU Ro80 Serie and Research and right Mazda 12A and 13B

Left Mazda old L10A Camber axial cooling, middle Audi NSU EA871 axial water cooling only hot bow, right Diamond Engines Wankel radial cooling only in the hot bow

Felix Wankel managed to overcome most of the problems that made previous rotary engines fail by developing a configuration with vane seals that could be made of more durable materials than piston ring metal that led to the failure of previous rotary designs.

Rotary engines have a thermodynamic problem not found in reciprocating four-stroke engines in that their "cylinder block" operates at steady state, with intake, compression, combustion, and exhaust occurring at fixed housing locations for all "cylinders". In contrast, reciprocating engines perform these four strokes in one chamber, so that extremes of "freezing" intake and "flaming" exhaust are averaged and shielded by a boundary layer from overheating working parts.

The boundary layer shields and the oil film act as thermal insulation, leading to a low temperature of the lubricating film (max. ~200 °C/400 °F) on a water-cooled Wankel engine. This gives a more constant surface temperature. The temperature around the spark plug is about the same as the temperature in the combustion chamber of a reciprocating engine. With circumferential or axial flow cooling, the temperature difference remains tolerable.

Four-stroke reciprocating engines are less suitable for hydrogen. The hydrogen can misfire on hot parts like the exhaust valve and spark plugs. Another problem concerns the hydrogenate attack on the lubricating film in reciprocating engines. In a Wankel engine, this problem is circumvented by using a ceramic apex seal against a ceramic surface: there is no oil film to suffer hydrogenate attack. Since ceramic piston rings are not available as of 2009, the problem remains with the reciprocating engine. The piston shell must be lubricated and cooled with oil. This substantially increases the lubricating oil consumption in a four-stroke hydrogen engine.

Materials

Unlike a piston engine, where the cylinder is cooled by the incoming charge after being heated by combustion, Wankel rotor housings are constantly heated on one side and cooled on the other, leading to high local temperatures and unequal thermal expansion. While this places high demands on the materials used, the simplicity of the Wankel makes it easier to use alternative materials like exotic alloys and ceramics. With water cooling in a radial or axial flow direction, with the hot water from the hot bow heating the cold bow, the thermal expansion remains tolerable.

Sealing

Early engine designs had a high incidence of sealing loss, both between the rotor and the housing and also between the various pieces making up the housing. Also, in earlier model Wankel engines carbon particles could become trapped between the seal and the casing, jamming the engine and requiring a partial rebuild. It was common for very early Mazda engines to require rebuilding after 50,000 miles (80,000 km). Further sealing problems arise from the uneven thermal distribution within the housings causing distortion and loss of sealing and compression. This thermal distortion also causes uneven wear between the apex seal and the rotor housing, quite evident on higher mileage engines. The problem is exacerbated when the engine is stressed before reaching operating temperature. However, Mazda Wankel engines have solved these problems. Current engines have nearly 100 seal-related parts.

Fuel consumption and emissions

Just as the shape of the Wankel combustion chamber is resistant to preignition and will run on lower-octane rating gasoline than a comparable piston engine, it also leads to relatively incomplete combustion of the air-fuel charge, with a larger amount of unburned hydrocarbons released into the exhaust. The exhaust is, however, relatively low in NOx emissions; this allowed Mazda to meet the United States Clean Air Act of 1970 in 1973 with a simple and inexpensive 'thermal reactor' (an enlarged open chamber in the exhaust manifold) by paradoxically enriching the air-fuel ratio to the point where the unburned hydrocarbons (HC) in the exhaust would support complete combustion in the thermal reactor; while piston-engine cars required expensive catalytic converters to deal with both unburned hydrocarbons and NOx emissions. This raised fuel consumption, however, (already a weak point for the Wankel engine) at the same time that the oil crisis of 1973 raised the price of gasoline. Mazda was able to improve the fuel efficiency of the thermal reactor system by 40% by the time of introduction of the RX-7 in 1978, but eventually shifted to the catalytic converter system. According to the Curtiss-Wright research, the extreme that controls the amount of unburned HC in the exhaust is the rotor surface temperature, higher temperatures producing less HC. They showed also that the rotor can be widened. Quenching is the dominant source of HC at high speeds, and leakage at low speeds. The shape and positioning of rotor recess-combustion chamber- influences emissions and fuel use, the MDR being chosen as a compromise.

In Mazda's RX-8 with the Renesis engine, fuel consumption is now within normal limits while passing California State emissions requirements, including California's Low Emissions Vehicle or LEV standards. The exhaust ports, which in earlier Mazda rotaries were located in the rotor housings, were moved to the sides of the combustion chamber. This approach allowed Mazda to eliminate overlap between intake and exhaust port openings, while simultaneously increasing exhaust port area. The side port trapped the unburned fuel in the chamber decreased the oil consumption and improved the combustion stability in the low-speed and light load range. The HC emissions from the side exhaust port Wankel engine is 35 to 50 percent less than those from the peripheral exhaust port Wankel engine.

Advantages

NSU Wankel Spider, the first line of cars sold with a rotor Wankel engine

Mazda Cosmo, the first series two rotor Wankel engine sports car

Wankel engines are considerably simpler, lighter, and contain far fewer moving parts than piston engines of equivalent power output. For instance, because valving is accomplished by simple ports cut into the walls of the rotor housing, they have no valves or complex valve trains; in addition, since the rotor rides directly on a large bearing on the output shaft, there are no connecting rods and there is no crankshaft. The elimination of reciprocating mass and the elimination of the most highly stressed and failure prone parts of piston engines gives the Wankel engine high reliability, a smoother flow of power, and a high power-to-weight ratio.

The surface/volume-ratio problem is so complex that one cannot make a direct comparison between a reciprocating piston engine and a Wankel engine in terms of the surface/volume-ratio. The flow velocity and the heat losses behave quite differently. Surface temperatures behave absolutely differently; the film of oil in the Wankel engine acts as insulation. Engines with a higher compression ratio have a worse surface/volume-ratio. The surface/volume-ratio of a Diesel engine is much worse than a gasoline engine, but Diesel engines are well known for a higher efficiency factor than gasoline engines. Thus, engines with equal power should be compared: a naturally aspirated 1.3-liter Wankel engine with a naturally aspirated 1.3-liter four-stroke reciprocating piston engine with equal power. But such a four-stroke engine is not possible and needs twice the displacement for the same power as a Wankel engine. The extra or "empty" stroke(s) should not be ignored, as a 4-stroke cylinder produces a power stroke only every other rotation of the crankshaft. In actuality, this doubles the real surface/volume-ratio for the four-stroke reciprocating piston engine and the demand of displacement. The Wankel, therefore, has higher volumetric efficiency and a lower pumping loss through the absence of choking valves. Because of the quasi-overlap of the power strokes that cause the smoothness of the engine and the avoidance of the 4-stroke cycle in a reciprocating engine, the Wankel engine is very quick to react to throttle changes and is able to quickly deliver a surge of power when the demand arises, especially at higher rpm. This difference is more pronounced when compared to four-cylinder reciprocating engines and less pronounced when compared to higher cylinder counts.

In addition to the removal of internal reciprocating stresses by virtue of the complete removal of reciprocating internal parts typically found in a piston engine, the Wankel engine is constructed with an iron rotor within a housing made of aluminium, which has a greater coefficient of thermal expansion. This ensures that even a severely overheated Wankel engine cannot seize, as would be likely to occur in an overheated piston engine. This is a substantial safety benefit of use in aircraft. In addition, valves and valve trains that don't exist can't burn out, jam, break, or malfunction in any way, again increasing safety.

A further advantage of the Wankel engine for use in aircraft is the fact that a Wankel engine generally has a smaller frontal area than a piston engine of equivalent power, allowing a more aerodynamic nose to be designed around it. The simplicity of design and smaller size of the Wankel engine also allows for savings in construction costs, compared to piston engines of comparable power output.

Wankel engines that operate within their original design parameters are almost immune to catastrophic failure. A Wankel engine that loses compression, cooling or oil pressure will lose a large amount of power, and will die over a short period of time; however, it will usually continue to produce some power during that time. Piston engines under the same circumstances are prone to seizing or breaking parts that almost certainly results in major internal damage of the engine and an instant loss of power. For this reason, Wankel engines are very well suited to snowmobiles and aircraft, which often take users into remote places where a failure could result in frostbite or death.

Due to a 50% longer stroke duration compared to a four-cycle engine, there is more time to complete the combustion. This leads to greater suitability for direct injection. A Wankel rotary engine has stronger flows of air-fuel mixture and a longer operating cycle than a reciprocating engine, so it realizes concomitantly thorough mixing of hydrogen and air. The result is a homogeneous mixture, which is crucial for hydrogen combustion.

Disadvantages

Rolls Royce R6 two stage Wankel Diesel engine

Although in two dimensions the seal system of a Wankel looks to be even simpler than that of a corresponding multi-cylinder piston engine, in three dimensions the opposite is true. As well as the rotor apex seals evident in the conceptual diagram, the rotor must also seal against the chamber ends.

Piston rings are not perfect seals: each has a gap to allow for expansion. The sealing at the Wankel apexes is less critical, as leakage is between adjacent chambers on adjacent strokes of the cycle, rather than to the crankcase. However, the less effective sealing of the Wankel is one factor reducing its efficiency, limiting its use mainly to applications such as racing engines and sports vehicles where neither efficiency nor long engine life are major considerations. Comparison tests have shown that the Mazda rotary powered RX-8 uses more fuel than a heavier vehicle powered by larger displacement V-8 engine for similar performance results.

The time available for fuel to be port-injected into a Wankel engine is significantly shorter, compared to four-stroke piston engines, due to the way the three chambers rotate. The fuel-air mixture cannot be pre-stored as there is no intake valve. Also the Wankel engine, compared to a piston engine, has 50% longer stroke duration. The four Otto cycles last 1080° for a Wankel engine versus 720° for a four-stroke reciprocating piston engine.

There are various methods of calculating the engine displacement of a Wankel. The Japanese regulations for calculating displacements for engine ratings use the volume displacement of one rotor face only, and the auto industry commonly accepts this method as the standard for calculating the displacement of a rotary. However, when compared on the basis of specific output, the convention results in large imbalances in favor of the Wankel motor.

For comparison purposes between a Wankel Rotary engine and a piston engine, displacement and corresponding power output can more accurately be compared on the basis of displacement per revolution of the eccentric shaft. A calculation of this form dictates that a two rotor Wankel displacing 654 cc per face will have a displacement of 1.3 liters per every rotation of the eccentric shaft (only two total faces, one face per rotor going through a full power stroke) and 2.6 liters after two revolutions (four total faces, two faces per rotor going through a full power stroke). The results are directly comparable to a 2.6-liter piston engine with an even number of cylinders in a conventional firing order, which will likewise displace 1.3 liters through its power stroke after one revolution of the crankshaft, and 2.6 liters through its power strokes after two revolutions of the crankshaft. A Wankel Rotary engine is still a 4-stroke engine and pumping losses from non-power strokes still apply, but the absence of throttling valves and a 50% longer stroke duration result in a significantly lower pumping loss compared against a four-stroke reciprocating piston engine. Measuring a Wankel rotary engine in this way more accurately explains its specific output, as the volume of its air fuel mixture put through a complete power stroke per revolution is directly responsible for torque and thus power produced.

The trailing side of the rotary engine's combustion chamber develops a squeeze stream which pushes back the flamefront. With the conventional two-spark-plug or one-spark-plug system and homogenous mixture, this squeeze stream prevents the flame from propagating to the combustion chamber's trailing side in the mid and high engine speed ranges. This is why there can be more carbon monoxide and unburnt hydrocarbons in a Wankel's exhaust stream. A side-port exhaust, as is used in the Renesis, avoids this because the unburned mixture cannot escape. The Mazda 26B avoided this issue through a 3-spark plug ignition system. (As a result, at the Le Mans 24 hour endurance race in 1991, the 26B had significantly lower fuel consumption than the competing reciprocating piston engines. All competitors had only the same amount of fuel available, because of the Le Mans 24 h limited fuel quantity rule.) A peripheral intake port gives the highest MEP, however, side intake porting produces a more steady idle.

All Mazda-made Wankel rotaries, including the new Renesis found in the RX-8, burn a small quantity of oil by design; it is metered into the combustion chamber to preserve the apex seals. Owners must periodically add small amounts of oil, marginally increasing running costs — though it is still reasonable and comparable in some instances when compared to many reciprocating piston engines.

Applications

Automobile racing

Mazda 787B

In the racing world, Mazda has had substantial success with two-rotor, three-rotor, and four-rotor cars. Private racers have also had considerable success with stock and modified Mazda Wankel-engine cars.

The Sigma MC74 powered by a Mazda 12A engine was the first engine and only team from outside Western Europe or the United States to finish the entire 24 hours of the 24 Hours of Le Mans race, in 1974. Mazda is the only team from outside Western Europe or the United States to have won Le Mans outright and the only non-piston engine ever to win Le Mans, which the company accomplished in 1991 with their four-rotor 787B (2,622 cc/160 cu in—actual displacement, rated by FIA formula at 4,708 cc/287 cu in). The following year, a planned rule change at Le Mans made the Mazda 787B ineligible to race anymore due to weight advantages.

The Mazda RX-7 has won more IMSA races in its class than any other model of automobile, with its one hundredth victory on September 2, 1990. Following that, the RX-7 won its class in the IMSA 24 Hours of Daytona race ten years in a row, starting in 1982. The RX7 won the IMSA Grand Touring Under Two Liter (GTU) championship each year from 1980 through 1987, inclusive.

Formula Mazda Racing features open-wheel race cars with Mazda Wankel engines, adaptable to both oval tracks and road courses, on several levels of competition. Since 1991, the professionally organized Star Mazda Series has been the most popular format for sponsors, spectators, and upward bound drivers. The engines are all built by one engine builder, certified to produce the prescribed power, and sealed to discourage tampering. They are in a relatively mild state of racing tune, so that they are extremely reliable and can go years between motor rebuilds.

The Malibu Grand Prix chain, similar in concept to commercial recreational kart racing tracks, operates several venues in the United States where a customer can purchase several laps around a track in a vehicle very similar to open wheel racing vehicles, but powered by a small Curtiss-Wright rotary engine.

In engines having more than two rotors, or two rotor race engines intended for high-rpm use, a multi-piece eccentric shaft may be used, allowing additional bearings between rotors. While this approach does increase the complexity of the eccentric shaft design, it has been used successfully in the Mazda's production three-rotor 20B-REW engine, as well as many low volume production race engines. (The C-111-2 4 Rotor Mercedes-Benz eccentric shaft for the KE Serie 70, Typ DB M950 KE409 is made in one piece. Mercedes-Benz used split bearings.)

Motorcycle engines

Norton Interpol2 prototype

From 1974 to 1977 Hercules produced a limited number of motorcycles powered by Wankel engines. The motor tooling and blank apex seals were later used by Norton to produce the Norton Commander model in the early 1980s.

The Suzuki RE5 was a Wankel-powered motorcycle produced in 1975 and 1976. It was touted as the future of motorcycling, however, other problems and a lack of parts interchangeability meant low sales.

Dutch motorcycle importer and manufacturer van Veen produced small quantities of their dual rotor Wankel-engined OCR-1000 between 1978 and 1980, using surplus Comotor engines.

However, from the 1980s onwards, rotary engines have not been produced for sale to the general public for road use. Norton has used a Wankel engine in several models including the F1, F1 Sports, RC588, RCW588, NRS588, most notably Steve Hislop riding to various victories on Norton's F1 in the TT in 1992. Norton now makes a 588cc twin-rotor model called the NRV588 and is in the process of making a 700cc version called the NRV700.

Aircraft engines

Diamond DA20 with Diamond Engines Wankel

Sikorsky Cypher UAV powered with a UEL AR801 Wankel engine

The first Wankel rotary-engine aircraft was the experimental Lockheed Q-Star civilian version of the United States Army's reconnaissance QT-2, basically a powered Schweizer sailplane, in 1968 or 1969. It was powered by a 185 hp (138 kW) Curtiss-Wright RC2-60 Wankel rotary engine.

Aircraft Wankels have made something of a comeback in recent years. None of their advantages have been lost in comparison to other engines. They are increasingly being found in roles where their compact size and quiet operation is important, notably in drones, or UAVs. Many companies and hobbyists adapt Mazda rotary engines (taken from automobiles) to aircraft use; others, including Wankel GmbH itself, manufacture Wankel rotary engines dedicated for the purpose. One such use are the "Rotapower" engines in the Moller Skycar M400.

Wankel engines are also becoming increasingly popular in homebuilt experimental aircraft. Most are Mazda 12A and 13B automobile engines, converted to aviation use. This is a very cost-effective alternative to certified aircraft engines, providing engines ranging from 100 to 300 horsepower (220 kW) at a fraction of the cost of traditional engines. These conversions first took place in the early 1970s. With a number of these engines mounted on aircraft, as of 10 December 2006 the National Transportation Safety Board has only seven reports of incidents involving aircraft with Mazda engines, and none of these were a failure due to design or manufacturing flaws.

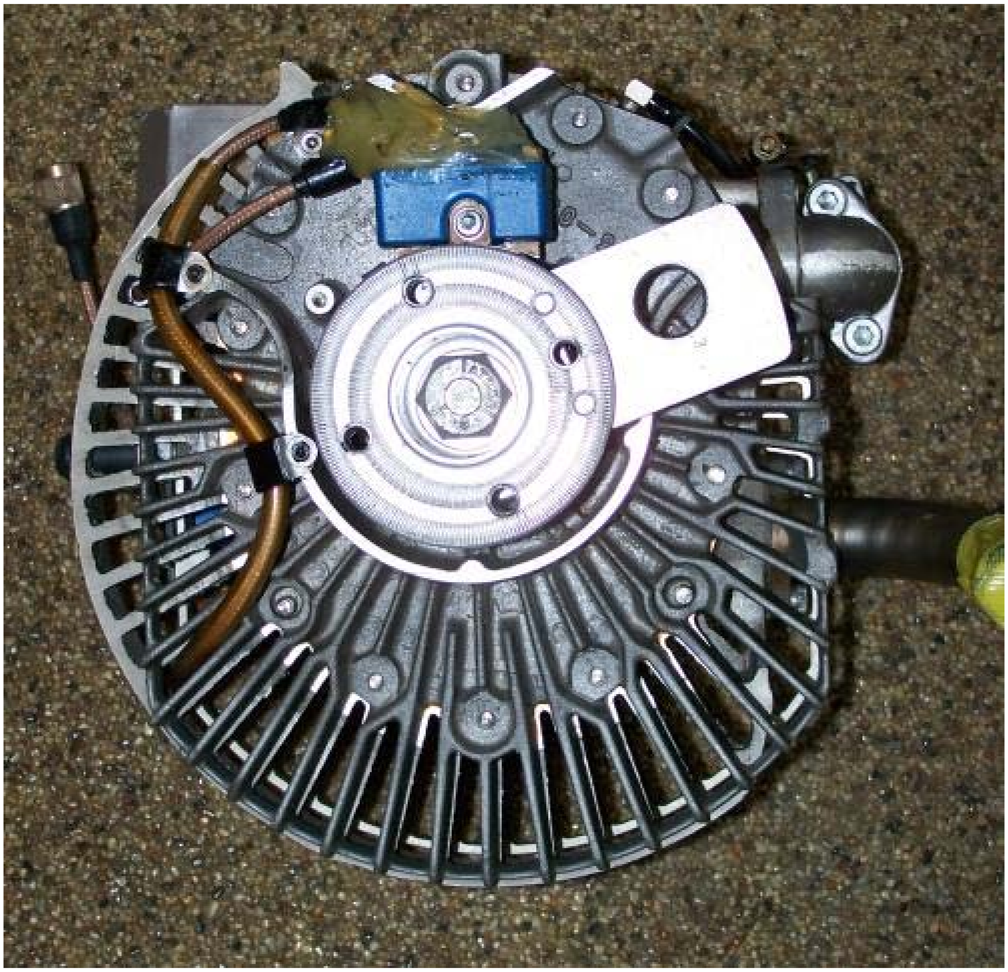
Peter Garrison, Contributing Editor for *Flying* magazine, has said that "the most promising engine for aviation use is the Mazda rotary." Mazdas have indeed worked well when converted for use in homebuilt aircraft. However, the real challenge in aviation is producing FAA-certified alternatives to the standard reciprocating engines that power most small general aviation aircraft. Mistral Engines, based in Switzerland, developed purpose-built rotaries for factory and retro-fit installations on certified production aircraft. The G-190 and G-230-TS rotary engines were already flying in the experimental market, and Mistral Engines hoped for FAA and JAA certification by 2011. As of June 2010, G-300 rotary engine development ceased, with the company citing a need for cash flow to complete development.

Mistral claims to have overcome the challenges of fuel consumption inherent in the rotary, at least to the extent that the engines are demonstrating specific fuel consumption within a few points of reciprocating engines of similar displacement. While fuel burn is still marginally higher than traditional engines, it is outweighed by other beneficial factors.

Since Wankel engines operate at a relatively high rotational speed with relatively low torque, propeller aircraft must use a Propeller Speed Reduction Unit (PSRU) to keep conventional propellers within the proper speed range. There are many experimental aircraft flying with this arrangement.

Pratt & Whitney Rocketdyne have been commissioned by DARPA to develop a diesel wankel engine for use in a prototype VTOL flying car called the "Transformer". The engine, based on an earlier UAV diesel wankel concept called 'EnduroCORE', will utilize wankel rotors of varying sizes on a shared eccentric shaft to increase efficiency. The engine is claimed to be a 'full-compression, full-expansion, diesel-cycle engine', which sets it apart from the earlier Rolls-Royce prototype that required an external air compressor to achieve high enough compression for diesel-cycle combustion.

Other uses



UEL UAV-741 Wankel engine for a UAV

Small Wankel engines are being found increasingly in other roles, such as go-karts, personal water craft and auxiliary power units for aircraft. The Graupner/O.S. 49-PI is a 1.27 hp (947 W) 5 cc Wankel engine for model airplane use which has been in production essentially unchanged since 1970; even with a large muffler, the entire package weighs only 380 grams (13.4 ounces).

The simplicity of the Wankel makes it well-suited for mini, micro, and micro-mini engine designs. The Microelectromechanical systems (MEMS) Rotary Engine Lab at the University of California, Berkeley has been developing Wankel engines of down to 1 mm in diameter with displacements less than 0.1 cc. Materials include silicon and motive power includes compressed air. The goal is to eventually develop an internal combustion engine that will deliver 100 milliwatts of electrical power; the engine itself will serve as the rotor of the generator, with magnets built into the engine rotor itself.

The largest Wankel engine was built by Ingersoll-Rand; available in 550 hp (410 kW) one rotor and 1,100 hp (820 kW) two rotor versions, displacing 41 liters per rotor with a rotor approximately one meter in diameter, it was available between 1975 and 1985. It was derived from a previous, unsuccessful Curtiss-Wright design, which failed because of a well-known problem with all internal combustion engines: the fixed speed at which the flame front travels limits the distance combustion can travel from the point of ignition in a given time, and thereby limiting the maximum size of the cylinder or rotor chamber which can be used. This problem was solved by limiting the engine speed to only 1200 rpm and the use of natural gas as fuel; this was particularly well chosen, since one of the major uses of the engine was to drive compressors on natural gas pipelines. Yanmar Diesel of Japan, produced some small, charge cooled rotor rotary engines for uses such as chainsaws and outboard engines, some of their contributions are that the LDR (rotor recess in the leading edge of combustion chamber) engines had better exhaust emissions profiles, and that reed-valve controlled intake ports improve part-load and low RPM performance.(Kojiro Yamaoka & Hiroshi Tado, SAE paper 720466, 1972)

In 2010 Audi revealed that in their electric car the A1 e-tron they would have a small 250 cc Wankel engine running at 5,000 rpm that would recharge the car's batteries as needed.

Non-internal combustion

In addition for use as an internal combustion engine, the basic Wankel design has also been utilized for gas compressors, and superchargers for internal combustion engines, but in these cases, although the design still offers advantages in reliability, the basic advantages of the Wankel in size and weight over the four-stroke internal combustion engine are irrelevant. In a design using a Wankel supercharger on a Wankel engine, the supercharger is twice the size of the engine.

The Wankel design is used in the seat belt pre-tensioner system of some Mercedes-Benz and Volkswagen cars. When the deceleration sensors sense a potential crash, small explosive cartridges are triggered electrically and the resulting pressurized gas feeds into tiny Wankel engines which rotate to take up the slack in the seat belt systems, anchoring the driver and passengers firmly in the seat before a collision.

Chapter 8

Two-Stroke Engine

Brons two-stroke V8 Diesel engine driving a Heemaf generator.

A **two-stroke** engine is an internal combustion engine that completes the process cycle in one revolution of the crank shaft (an up stroke and a down stroke of the piston, compared to twice that number for a four-stroke engine). This is accomplished by using the beginning of the compression stroke and the end of the combustion stroke to perform simultaneously the intake and exhaust (or scavenging) functions. In this way two-stroke engines often provide strikingly high specific power, at least in a narrow range of rotations speeds. The functions of some or all of the valves required by a four-stroke engine are usually served in a two-stroke engine by ports that are opened and closed by the motion of the pistons, greatly reducing the number of moving parts. Gasoline (spark ignition) versions are particularly useful in lightweight (portable) applications such as chainsaws and the concept is also used in diesel compression ignition engines in large and non-weight sensitive applications such as ships and locomotives.

Invention of the two-stroke cycle is attributed to Scottish engineer Dugald Clerk who in 1881 patented his design, his engine having a separate charging cylinder. The crankcase-scavenged engine, employing the area below the piston as a charging pump, is generally credited to Englishman Joseph Day (and Frederick Cock for the piston-controlled inlet port).

Applications

A two-stroke minibike.

Lateral view of a two-stroke Forty series British Seagull outboard engine. The serial number dates it to 1954/1955

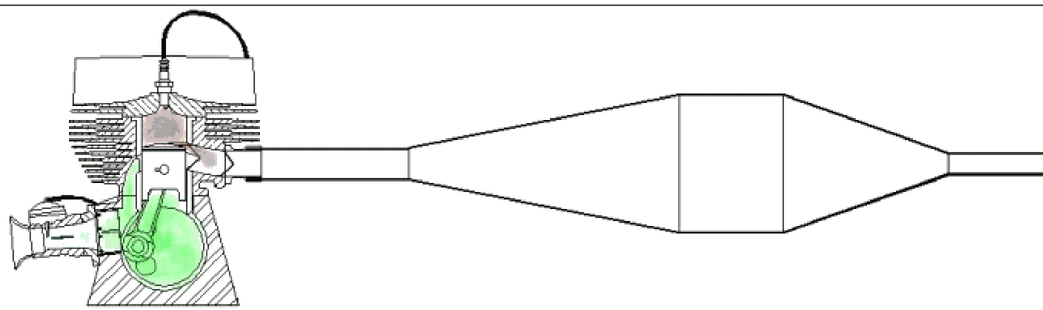
The two-stroke engine was very popular throughout the 20th century in motorcycles, small engined devices such as chainsaws and outboard motors and was also used in some cars, a few tractors and many ships. Part of their appeal was due to their simple design (and resulting low cost) and often high power-to-weight ratio. Many designs use total-loss lubrication, with the oil being burnt in the combustion chamber, causing "blue smoke" and other types of exhaust pollution. This is a major reason for two-stroke engines losing out to and being replaced by four-stroke engines in many applications.

Two-stroke engines continue to be commonly used in high-power, handheld applications such as string trimmers and chainsaws. The light overall weight, and light-weight spinning parts give important operational and even safety advantages. Only a two-stroke running on a gasoline-oil mixture can power a chainsaw running in any position.

These engines are still used for small, portable, or specialized machine applications such as outboard motors, high-performance, small-capacity motorcycles, mopeds, underbones, scooters, tuk-tuks, snowmobiles, karts, ultralights, model airplanes (and other model vehicles) and lawnmowers. The two-stroke cycle is used in many diesel engines, most notably large industrial and marine engines, as well as some trucks and heavy machinery.

A number of mainstream automobile manufacturers have used two-stroke engines in the past, including the Swedish Saab and German manufacturers DKW and Auto-Union. The Japanese manufacturer Suzuki did the same in the 1970s. Production of two-stroke cars ended in the 1980s in the West, but Eastern Bloc countries continued until around 1991, with the Trabant and Wartburg in East Germany. Lotus of Norfolk, UK, has a prototype direct-injection two-stroke engine intended for alcohol fuels called the Omnivore which it is demonstrating in a version of the Exige.

Different two-stroke design types



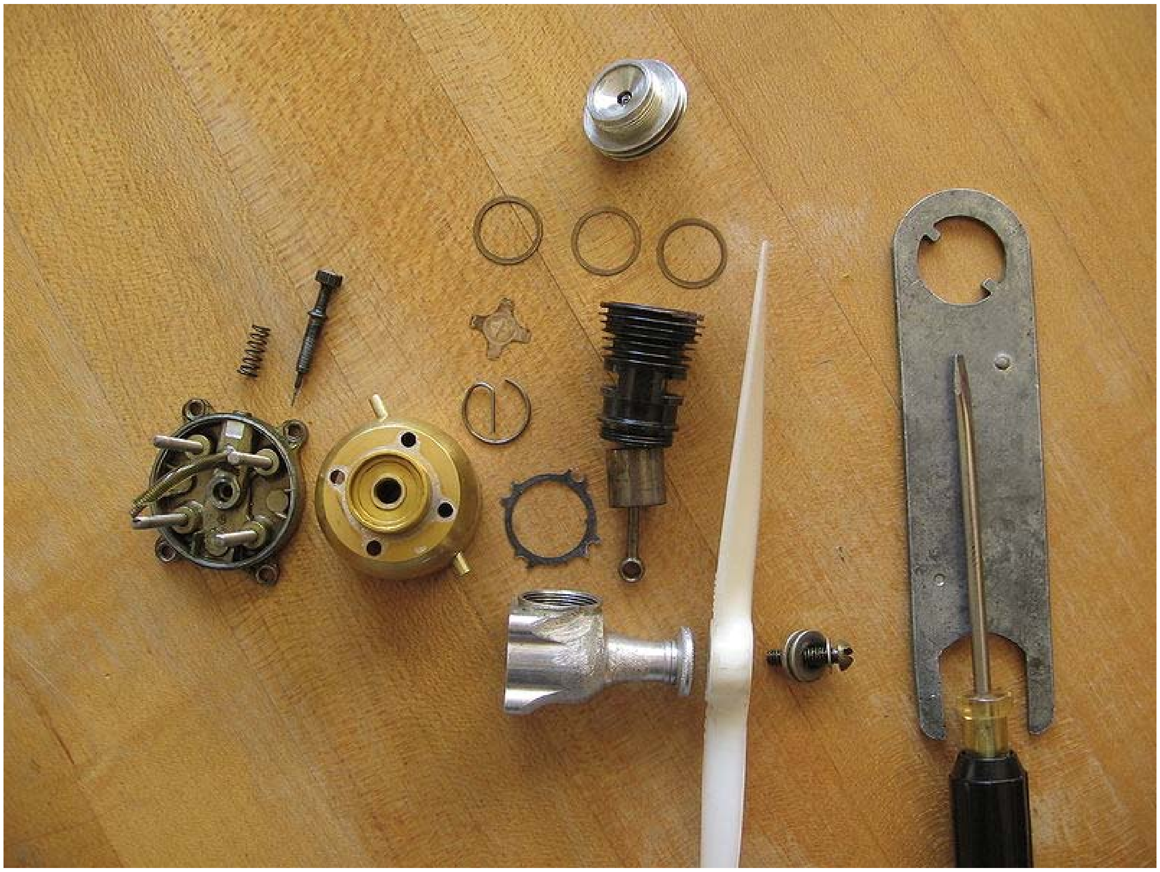
A two-stroke engine, in this case with a tuned expansion pipe illustrating the effect of a reflected pressure wave on the fuel charge. This feature is essential for maximum charge pressure (volumetric efficiency) and fuel efficiency. It is used on most high-performance engine designs.

Although the principles remain the same, the mechanical details of various two-stroke engines differ depending on the type. The design types of the two-stroke engine vary according to the method of introducing the charge to the cylinder, the method of scavenging the cylinder (exchanging burnt exhaust for fresh mixture) and the method of exhausting the cylinder.

Piston controlled inlet port

Piston port is the simplest of the designs. All functions are controlled solely by the piston covering and uncovering the ports as it moves up and down in the cylinder. A fundamental difference from typical four-stroke engines is that the crankcase is sealed and forms part of the induction process in gasoline and hot bulb engines. Diesel engines have mostly a roots blower or piston pump for scavenging.

Reed inlet valve



A Cox Babe Bee 0.049 cubic inch (0.8 cubic cm.) reed valve engine disassembled. It uses glow plug ignition. The mass is 64 grams.

The reed valve is a simple but highly effective form of check valve commonly fitted in the intake tract of the piston-controlled port. They allow asymmetric intake of the fuel-charge, improving power and economy, while widening the power band. They are widely used in ATVs, and marine outboard engines.

Rotary inlet valve

The intake pathway is opened and closed by a rotating member. A familiar type sometimes seen on small motorcycles is a slotted disk attached to the crankshaft which covers and uncovers an opening in the end of the crankcase, allowing charge to enter during one portion of the cycle.

Another form of rotary inlet valve used on two-stroke engines employs two cylindrical members with suitable cutouts arranged to rotate one within the other - the inlet pipe having passage to the crankcase only when the two cutouts coincide. The crankshaft itself may form one of the members, as in most Glowplug model engines. In another embodiment, the crank disc is arranged to be a close-clearance fit in the crankcase and is provided with a cutout which lines up with an inlet passage in the crankcase wall at the appropriate time, as in the Vespa motor scooter.

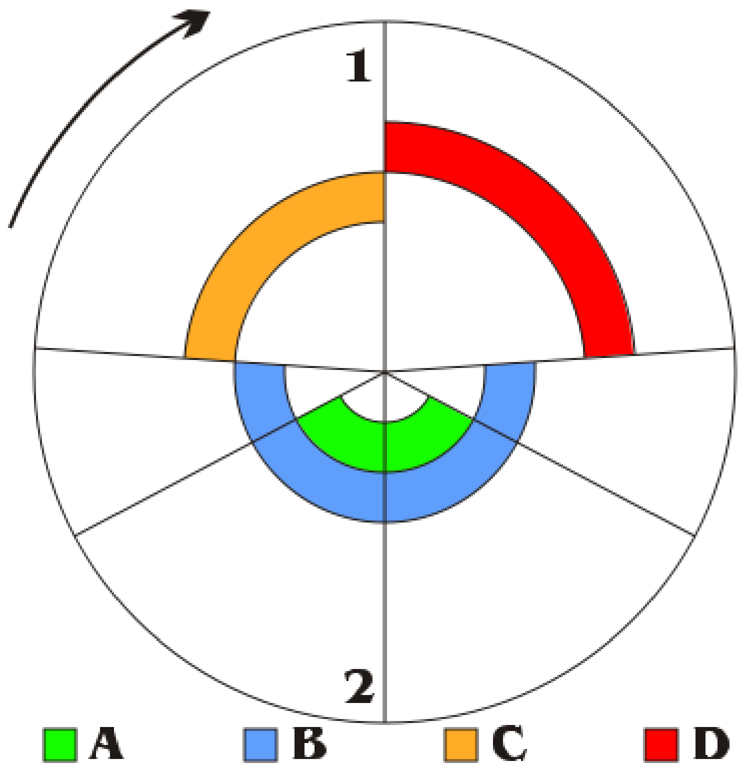
The advantage of a rotary valve is that it enables the two-stroke engine's intake timing to be asymmetrical which is not possible with two-stroke piston port type engines. The two-stroke piston port type engine's intake timing opens and closes before and after top dead center at the same crank angle making it symmetrical whereas the rotary valve allows the opening to begin earlier and close earlier.

Rotary valve engines can be tailored to deliver power over a wider speed range or higher power over a narrower speed range than either piston port or reed valve engine. Where a portion of the rotary-valve is a portion of the crankcase itself it is particularly important that no wear is allowed to take place.

Crossflow-scavenged

In a crossflow engine the transfer ports and exhaust ports are on opposite sides of the cylinder and a deflector on the top of the piston directs the fresh intake charge into the upper part of the cylinder pushing the residual exhaust gas down the other side of the deflector and out of the exhaust port. The deflector increases piston's weight and its exposed surface area, and also makes it difficult to achieve an efficient combustion chamber shape. This design has been largely superseded by loop scavenging method (below), although for smaller or slower engines the crossflow-scavenged design can be an acceptable approach.

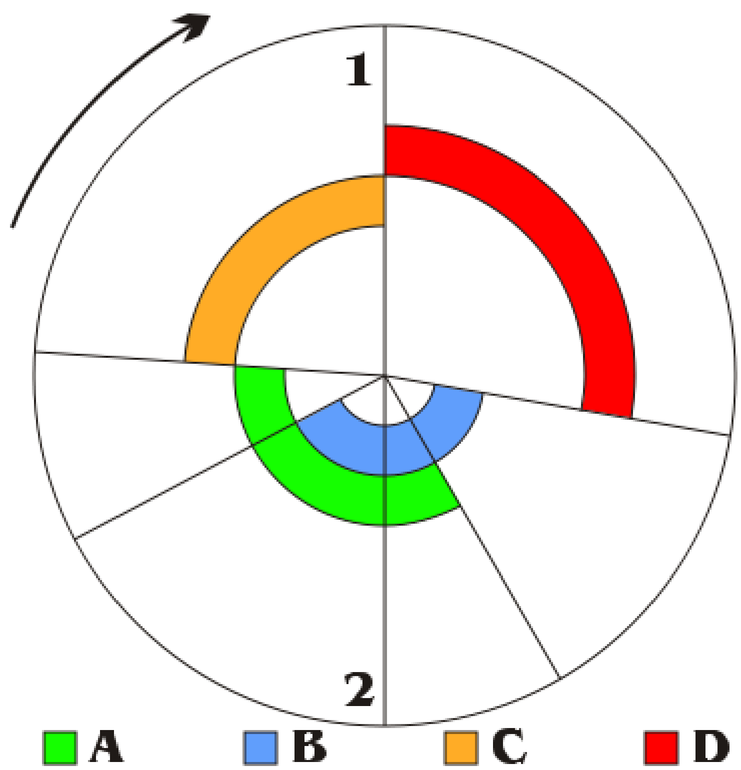
Loop-scavenged



The Two-stroke cycle
1=TDC
2=BDC
A: intake/scavenging
B: Exhaust
C: Compression
D: Expansion(power)

This method of scavenging uses carefully shaped and positioned transfer ports to direct the flow of fresh mixture toward the combustion chamber as it enters the cylinder. The fuel/air mixture strikes the cylinder head then follows the curvature of the combustion chamber then is deflected downward. This not only prevents the fuel/air mixture from traveling directly out the exhaust port but creates a swirling turbulence which improves combustion efficiency, power and economy. Usually a piston deflector is not required, so this approach has a distinct advantage over the cross flow scheme (above). Often referred to as "Schnuerle" (or "Schnürl") loop scavenging after the German inventor of an early form in the mid 1920s, it became widely adopted in that country during the 1930s and spread further afield after World War II. Loop scavenging is the most common type of fuel/air mixture transfer used on modern two stroke engines. Suzuki was one of the first manufacturers outside of Europe to adopt loop scavenged two stroke engines. This operational feature was used in conjunction with the expansion chamber exhaust developed by German motorcycle manufacturer, MZ and Walter Kaaden. Loop scavenging, disc valves and expansion chambers worked in a highly coordinated way that saw a significant increase in the power output of two-stroke engines, particularly from the Japanese manufacturers Suzuki, Yamaha and Kawasaki. Suzuki and Yamaha enjoyed success in grand Prix motorcycle racing in the 1960s due in no small way to the increased power afforded by loop scavenging. An additional benefit of loop scavenging was that the piston could be made nearly flat or slightly dome shaped. This enabled the piston to be appreciably lighter and stronger and consequently tolerated higher engine speeds. The "flat top" piston also has better thermal properties and is less prone to uneven heating, expansion, piston seizures, dimensional changes and compression losses.

Uniflow-scavenged



The Uniflow Two-stroke cycle
1=TDCdg
2=Bbb
A: Intake(effective scavenging ≈140°-250°)
B: Exhaust
C: Compression
D: Expansion(power)

In a uniflow engine the mixture, or air in the case of a diesel, enters at one end of the cylinder controlled by the piston and the exhaust exits at the other end controlled by an exhaust valve or piston. The scavenging gas-flow is therefore in one direction only, hence the name uniflow. The valved arrangement is common in diesel locomotives (Electro-

Motive Diesel) and large marine two-stroke engines (Wärtsilä). Ported types are represented by the opposed piston design in which there are two pistons in each cylinder, working in opposite directions such as the Junkers Jumo and Napier Deltic. The once-popular split-single design falls into this class being effectively a folded uniflow. With advanced angle exhaust timing uniflow engines can be supercharged with a crankshaft driven (piston or Roots) blower.

In Japan. Nissan Diesel Motor was manufacturing **Uniflow Two-stroke Diesel Engine**(ja:ユニフロー掃気ディーゼルエンジン) from General Motors from under a license of Detroit Diesel Series 71.

The latest invention, called the Reversed Uniflow two-stroke engine, has a large intake valve for compressed intake air without fuel-oil mixture. Direct fuel injection is to be used for gasoline or diesel fuel, pending intake air pressure. This engine will work on the Miller cycle. US Patent #6889636.

Stepped piston engine

The piston of this engine is "top-hat" shaped, the upper section forming the regular cylinder. and the lower section performing a scavenging function. The units run in pairs, the lower half of one piston charging an adjacent combustion chamber.

This system is still partially dependent on total loss lubrication (for the upper part of the piston), the other parts being sump lubricated with cleanliness and reliability benefits. The piston weight is only about 20% heavier than a loop-scavenged piston because skirt thicknesses can be less. The patents on this design are held by Bernard Hooper Engineering Ltd (BHE).

Power valve systems

Many modern two-stroke engines employ a power valve system. The valves are normally in or around the exhaust ports. They work in one of two ways: either they alter the exhaust port by closing off the top part of the port which alters port timing such as Ski-doo R.A.V.E, Yamaha YPVS, Honda RC-Valve, Cagiva C.T.S., Suzuki AETC system or by altering the volume of the exhaust which changes the resonant frequency of the expansion chamber, such as Honda V-TACS system. The result is an engine with better low-speed power without sacrificing high-speed power.

Direct injection

Direct injection has considerable advantages in two-stroke engines, eliminating some of the waste and pollution caused by carbureted two-strokes where a proportion of the fuel/air mixture entering the cylinder goes directly out, unburned, through the exhaust port. Two systems are in use, low-pressure air-assisted injection, and high pressure injection.

Since the fuel does not pass through the crank case, a separate source of lubrication is needed.

Two-stroke diesel engines

Diesel engines rely solely on the heat of compression for ignition. In the case of Schnuerle ported and loop-scavenged engines, intake and exhaust happens via piston-controlled ports. A uniflow diesel engine takes in air via scavenge ports, and exhaust gases exit through an overhead poppet valve. Two-stroke diesels are all scavenged by forced induction. Some designs utilize a mechanically driven Roots blower, whilst marine diesel engines normally use exhaust-driven turbochargers, with electrically-driven auxiliary blowers for low-speed operation when exhaust turbochargers are unable to deliver enough air.

Marine two-stroke diesel engines directly coupled to the propeller are able to start and run in either direction as required. The fuel injection and valve timing is mechanically readjusted by using a different set of cams on the camshaft. Thus the engine can be run in reverse to move the vessel backwards.

Lubrication

Most small petrol two-stroke engines cannot be lubricated by oil contained in their crankcase and sump, since the crankcase is already being used to pump fuel-air mixture into the cylinder. Traditionally the moving parts (both rotating crankshaft and sliding piston) were lubricated by a pre-mixed fuel-oil mixture (at a ratio between 16:1 and 50:1). As late as the 1960s petrol stations would often have a separate pump that would deliver such a pre-mix fuel to motorcycles. Even then, in many cases the rider would carry a bottle of his own two-stroke oil. Taking care to close the fuel-tap first, he or she would meter in a little oil (using the cap of the bottle) and then put in the petrol, this action mixing the two liquids.

Modern two-stroke engines pump lubrication from a separate tank of oil. This is still a total-loss system with the oil being burnt the same as in the older system, but at a lower and more economical rate. It is also cleaner, reducing the problem of oil-fouling of the spark-plugs and coke formation in the cylinder and the exhaust. Almost the only motors still using pre-mix are hand-held two-stroke devices such as chainsaws (which must operate in any attitude) and some of the smallest model engines.

All two-stroke engines running on a petroil mix will suffer oil-starvation if forced to rotate at speed with the throttle closed, e.g. motorcycles descending long hills and perhaps when decelerating gradually from high-speed by changing down through the gears. Two-stroke cars (such as those that were popular in Eastern Europe in mid-20th century) were in particular danger and were usually fitted with freewheel mechanisms in the powertrain, allowing the engine to idle when the throttle was closed, requiring the use of the brakes in all slowing down situations.

Large two-stroke engines, including diesels, normally use a sump lubrication system similar to four-stroke engines. The cylinder must still be pressurized but this is not done from the crankcase but by a pump or supercharger. A turbo-charger is not suitable for this purpose as it does not provide any starting pressure.

Two-stroke reversibility

For the purpose of this discussion, it is convenient to think in motorcycle terms, where the exhaust pipe faces into the cooling air stream, and the crankshaft commonly spins in the same axis and direction as do the wheels i.e. "forwards". Some of the considerations discussed here apply to four-stroke engines (which cannot reverse their direction of rotation without considerable modification) almost all of which spin forwards too.

Regular gasoline two-stroke engines will run backwards for short periods and under light load with little problem, and this has been used to provide a reversing facility in microcars such as the Messerschmitt KR200 that lacked reverse gearing. Where the vehicle has electric starting, the motor will be turned off and re-started backwards by turning the key in the opposite direction. Two-stroke golf carts have used a similar kind of system. Traditional flywheel magnetos (using contact-breaker "points" but no external coil) worked equally well in reverse because the cam controlling the points is symmetrical, breaking contact before TDC equally well whether running forwards or backwards. Reed-valve engines will run backwards just as well as piston-controlled porting, though rotary valve engine have asymmetrical inlet timing and will not run very well.

There are serious disadvantages to running any engine backwards under load for any length of time, and some of these reasons are general, applying equally to both two-stroke and four-stroke engines. Some of this disadvantage is intrinsic, unavoidable even in the case of a complete re-design. The problem comes about because in "forwards" running the major thrust face of the piston is on the back face of the cylinder which, in a two-stroke particularly, is the coolest and best lubricated part. The forward face of the piston is less well-suited to be the major thrust face since it covers and uncovers the exhaust port in the cylinder, the hottest part of the engine, where piston lubrication is at its most marginal. The front face of the piston is also more vulnerable since the exhaust port, the largest in the engine, is in the front wall of the cylinder. Piston skirts and rings risk being extruded into this port, so it is always better to have them pressing hardest on the back wall (where there are only the transfer ports) and there is good support. In some engines, the small end is offset to reduce thrust in the intended rotational direction and the forward face of the piston has been made thinner and lighter to compensate - but when running backwards, this weaker forward face suffers increased mechanical stress it was not designed to resist.

Large two-stroke ship diesels are sometimes made to be reversible. Like four-stroke ship engines (some of which are also reversible) they use mechanically operated valves and so require additional camshaft mechanisms.

On top of other considerations, the oil-pump of a modern two-stroke may not work in reverse, in which case the engine will suffer oil starvation within a short time. Running a motorcycle engine backwards is relatively easy to initiate and in rare cases can be triggered by a back-fire. It is not advisable.

Model airplane engines with reed-valves can be mounted in either tractor or pusher configuration without needing to change the propeller. These motors are compression ignition, so there are no ignition timing issues and little difference between running forwards and running backwards.

Chapter 9

Flathead Engine

Harley-Davidson flathead engine

A **flathead engine** or **sidevalve engine** (sometimes called a **flatty**) is an internal combustion engine with valves placed in the engine block beside the piston, instead of in the cylinder head, as in an overhead valve engine. The design was common on early engine designs, but has since fallen from favor.

Advantages

Generally the flathead's valves are carried on one side of the cylinder. A chamber is recessed into the underside of the head to allow the poppet valves to alternately rise from their seats to admit the fuel-air mixture and for the exhaust gases to escape the combustion chamber. This has a number of advantages, primarily making the valve gear simpler, without either long push rods and rocker arms to work overhead valves from a cam shaft mounted near the crank shaft or a long chain, belt or gear train to drive one or more overhead cam shafts. The head of a flathead engine commonly consists of only a single piece of cast metal.

Each valve is operated by pushing directly up on it, as opposed to needing some sort of mechanical arrangement to transfer the motion from the crank case to the cylinder head, as in an overhead valve engine. The line of intakes along the side of the engine leads to the alternate name **L-block** (or **L-head**), due to the cylinders having the shape of an upside-down L. This configuration is also known as (Ford) sidevalve engine. A great advantage to this design was that limited damage occurred if a valve dropped, unlike the overhead design in which serious damage could occur. One could still continue to travel even with a broken valve.

Because the intake and exhaust pass through the same small passage between the block and head, and because the light valve gear allows the valves to open and close quickly, flatheads are designed with very little "overlap", part of the cycle when both intake and exhaust valves are open. This gives better low rotation speed performance than is typical of push rod overhead valve engines or overhead cam engines tuned for high speed power. On the other hand, the light valve gear allows the engine to function at high speed, though with little power. The torque and power curves are therefore broad, making it easier for the manual transmission and driver or for the automatic transmission. This flexibility is returning to cars in the form of electric motors.

Disadvantages

The flathead configuration requires the intake and exhaust gases to make at least a 90-degree turn and to pass between the block and head to enter and leave the cylinder, which makes it less efficient, colloquially called poorer "breathing". Breathing was not greatly important for early production cars because engines could not run long and reliably at high speed, and few roads allowed sustained high speeds, so this was a minor concern given the benefits in simplicity. The maximum compression ratio is also low at only about 7:1, further reducing efficiency (although it means the engine can run well on low-octane fuel.) This is mainly because the combustion chamber must include the space for the valve movement and the space for the gas flow.

A compromise used by Willys (Jeep),Rover and Rolls-Royce in the mid 20th century was the F-head or intake over exhaust configuration, in which there is one side valve and one overhead valve per cylinder.

The greatest advancements to flathead engine technology were developed in the 1920s through experimentation by Sir Harry Ricardo of Great Britain, who improved the performance and efficiency by intently studying their flow characteristics. He published his findings, and obtained patents, in 1927. Primarily, his **Ricardo head** can be recognized on sight, because he moved the exhaust valve farther from the center of the cylinder than the intake valve (they had previously been symmetrical). He also paid careful attention to the form of the intake and exhaust tracts cast into the cylinder block as regarded turbulence in the intake stream and within the combustion chamber.

Another concern is that because the exhaust follows a more complicated path to leave the engine, there is increased tendency for the engine to overheat under sustained heavy use. This is especially true if the exhaust is routed between the cylinders, as in the Ford flathead. It is possible to arrange the sidevalve engine layout so exhaust will be taken away through a valve and an exhaust tract located on the opposite side of the cylinder from the intake valve, in which case the layout is referred to as a **T-block** or **T-head**. American LaFrance famously powered their production fire engines with T-head engines from the 1920s to the 1950s. The Cleveland Motorcycle Company produced a four-cylinder in-line motorcycle engine using the T-head configuration in the 1920s. Very early Stutz engines were T heads. This requires two passages between the block and head, within the combustion chamber, and it loses some of the simplicity.

The flathead design also greatly reduced the ability to overbore the engine for performance purposes. Since the piston, exhaust valve, and intake valve were all next to each other, the piston cylinder bore could only be slightly increased, if at all, or it would encroach upon the radii of the intake and exhaust valves, and also cause thin and weak cylinder walls.

History and applications

Although flathead in-line 4 and 6 cylinder engines were frequently used for automobiles, tractors, and other products, the best known flathead automotive engine is the early 20th century Ford V-8, which has both sets of valves (intake and exhaust) located on the inside of the "Vee," and which are all operated by a single camshaft located above the crankshaft. Other common configurations included in-line ("straight") eights and a V 12 Lincoln version of the Ford V 8.

Due to cooling and efficiency problems, flathead engines fell out of favor in "high power" applications, such as aircraft engines, prior to World War I. However they lived on for some time in the automotive world and were used on the Jeep for instance. Flatheads are no longer in common use for automobiles (except in some rodding and customizing circles), although they are still used for some small-engine applications like lawnmowers. Because of their design, the size of valves and the compression ratio are limited, which in turn reduces available power and economy.

Harley-Davidson motorcycle flathead engines

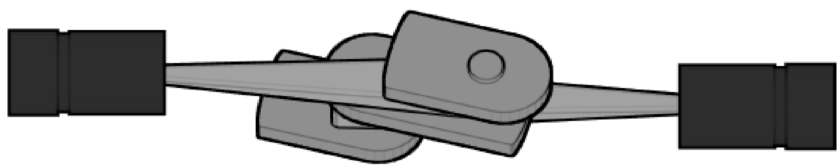
The flathead engine saw service in Harley-Davidson motorcycles beginning with the "Sport Model" opposed twin produced from 1919 to 1923, and continuing in 1924 with single cylinder export-model 21 cubic inches (340 cc) and 30.5 cubic inches (500 cc) singles and continued in the Servi-Cars until 1973. In the domestic U.S. market, the 45 cubic inches (740 cc) DL model (1929 to 1931) and its technical descendant, the RL model (1932 to 1936), started Harley's side valve tradition in the 45 cubic inch displacement class. The DL and RL models featured a total loss oiling system and were succeeded in 1937 by the WL 45, which had recirculating oil lubrication. The WL went on to serve in WWII as the U.S. and Canadian Army's primary two-wheeled mount and subsequently as a civilian middleweight through 1952. The engine continued virtually unchanged with various G-based designations in the three wheeled "Servi-Car" until production ceased in 1973.

In 1952, the K series flatheads was introduced, selling in parallel with the W series (which was discontinued after 1952), designed to compete with British sporting motorcycles of the time, as the American motorcycle Association allowed the 750 cc sidevalves to compete against 500 cc overhead-valve bikes. The K models featured a unit construction engine and transmission case, right side foot shift and left side foot brake, and evolved from 45 cubic inch (1952 to 1953) to 55 cubic inches by a 0.75 inches (19 mm) increase in stroke length (1954 to 1956) over its five year retail market run. The K series was replaced by the overhead valve Sportster series in the retail market in 1957. However, racing versions of the 750 cc K model, designated KR, continued to be produced in very limited numbers for some time after, winning both roadraces and dirt track events against overhead valve bikes limited to 500 cc through 1969, when the American Motorcycle Association finally decided to change the rules and make the venerable flatheads uncompetitive. The K racers were replaced first by the iron-head XR 750cc overhead valve engine, and two years later by the alloy-head XR, which continues in service in flat track racing to this day.

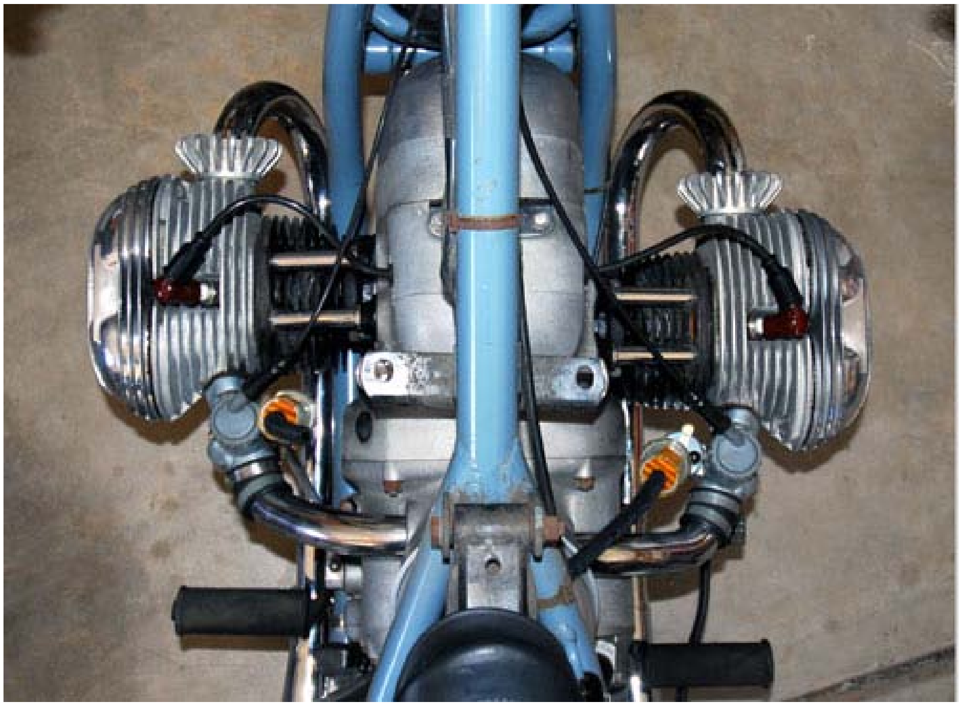
In 1930, the 74 cubic inches (1,210 cc) VL flathead replaced the JD Big Twin, which had featured intake-over-exhaust (IoE) valve configuration. The VL had a single downtube frame and total loss oiling, culminating in an 80 cubic inches (1,300 cc) version (VLH) in 1935. In 1937, that engine was redesigned to include a recirculating lubrication system, and designated the model U, and it went into the same frame and running gear configuration as the model E Knucklehead, which had originated in 1936. The U continued to be produced in varying configurations as a 74& cubic inch U & UL (1937 to 1948), and 80 cubic inch UH & ULH engine (1937 to 1941). By that time, the first year of the aluminum-head Panhead, it had been thoroughly superseded and outsold in the marketplace by the superior performance of the overhead valve model Big Twins.

Chapter 10

Flat-Twin Engine



Movement of flat-twin rotating assembly



A 1967 BMW R50/2 longitudinally mounted flat-twin engine, with tank removed. Note that the cylinders are not truly in line but displaced by the width of one crank pin and one crank-shaft web.

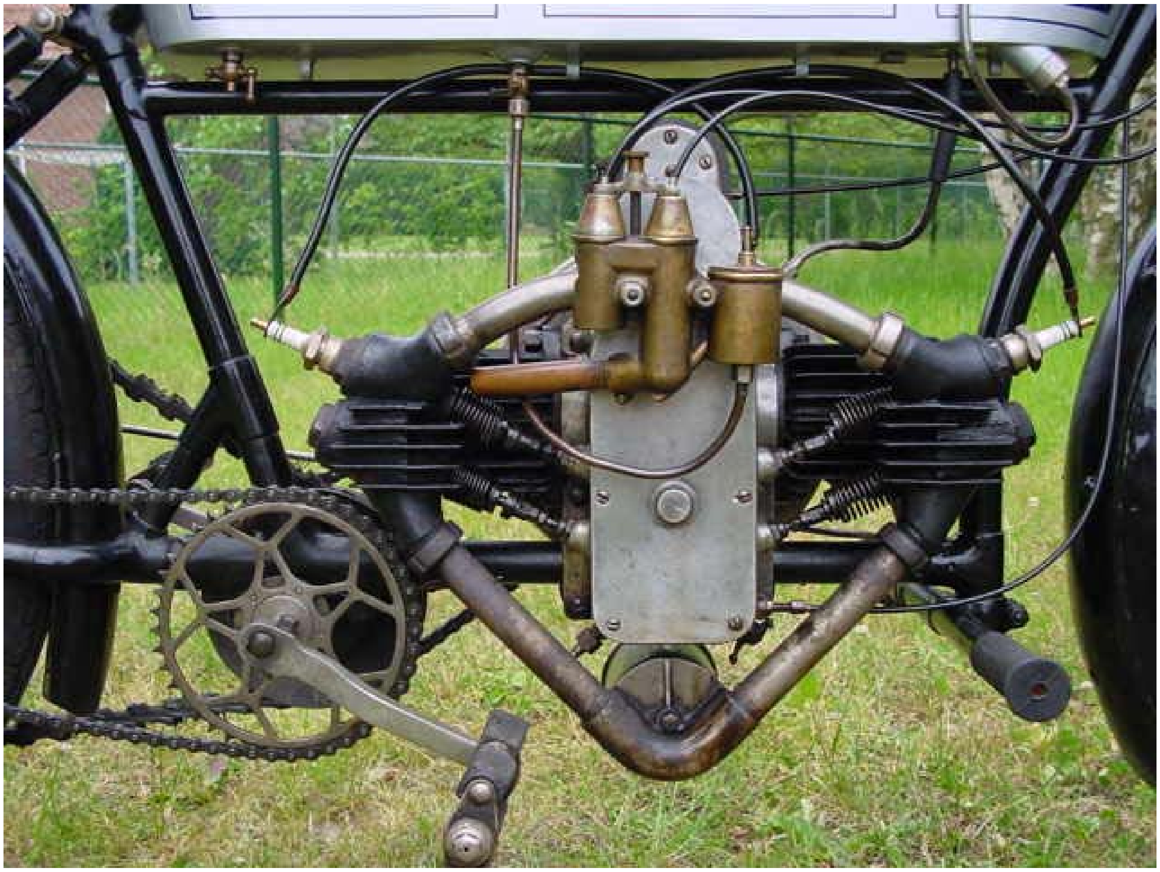
A **flat-twin** is a two cylinder internal combustion engine with the cylinders arranged on opposite sides of the crankshaft. It is part of the class of flat engines, sub-type "boxer", and shares most characteristics of those engines.

Motorcycle use

BMW Motorrad manufactures a number of flat-twin engine motorcycles, as do Ural and Dnepr. The geometry gives good primary balance, but there is an unbalanced moment on the crankshaft caused by the pistons being offset from each other.

Engine alignment

Cylinders along frame



Flat-twin engine in a 1912 Douglas N3, with its cylinders mounted along the frame

The earliest flat-twin motorcycles, including Douglas in the United Kingdom, Helios of Germany, and Harley-Davidson of the United States, had their cylinders aligned along the frame, and therefore with the crankshaft running transverse to the frame. This position allowed the use of a conventional motorcycle drivetrain by belt or chain to the rear wheel. Another advantage of this layout is that it has a low centre of gravity. However, in this layout, the front cylinder is more heavily cooled than the rear cylinder, and the wheelbase tends to be excessive due to the length of the engine. The wheelbase can be reduced by placing the transmission above the rear cylinder, as done on some Douglas motorcycles.

Cylinders across frame

1942 Harley-Davidson XA flat-twin engine

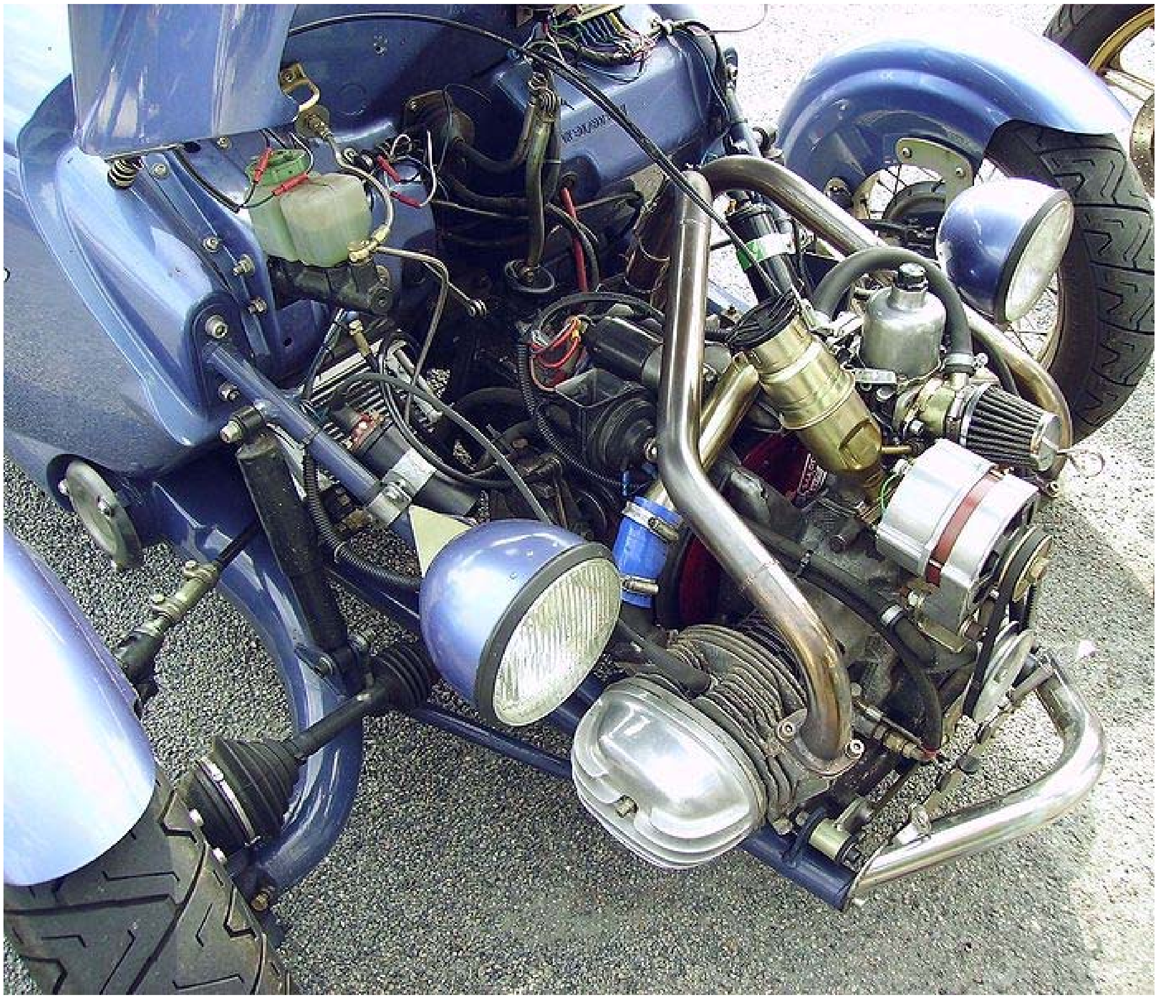
In 1919, ABC introduced a motorcycle with a flat-twin engine with the cylinders across the frame, and therefore with the crankshaft running longitudinally when referenced to the frame. To accommodate chain drive, the ABC used a bevel drive at the gearbox to change the direction of the drive through ninety degrees. The 1923 BMW R32 used a similar engine position with a drive shaft using bevel gears to power the rear axle.

This position allowed both cylinders to protrude into the airflow, providing excellent air cooling for each cylinder. The Harley-Davidson XA, which used a flat-twin engine with the cylinders across the frame, maintained an oil temperature 100 °F (56 °C) cooler than a Harley-Davidson WLA with a V-twin with the cylinders in line with the frame.

Many motorcyclists appreciate the way the cylinders in this layout provide protection to the rider in the event of a collision or fall, and keeps their feet warm in cold weather.

A disadvantage of this layout is that it exposes the cylinders and valve covers to the danger of collision damage. Longitudinal crankshaft mounting is also associated with a torque reaction that tends to twist the motorcycle to one side on sharp acceleration or when opening the throttle in neutral and in the opposite direction on sharp deceleration. Many modern motorcycle manufacturers correct for this effect by rotating flywheels or alternators in the opposite direction to that of the crankshaft.

Automotive use



Blackjack Avion displaying the cylinders of its Citroën 2CV engine

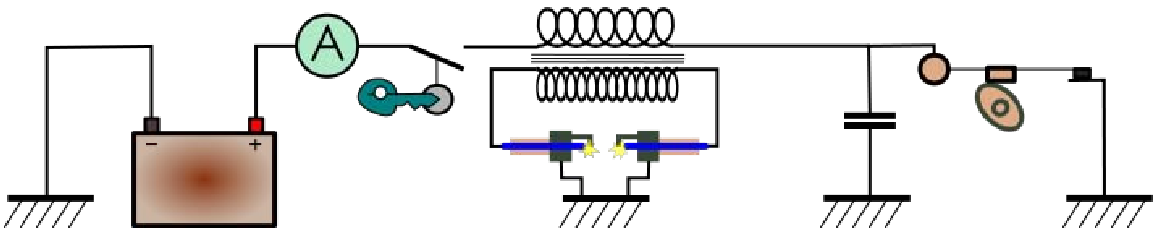
Flat-twin engines were used in several economy cars, including the Citroën 2CV, the Panhard Dyna X and Dyna Z, Steyr-Puch 500, DAF Daffodil, BMW 600, several Jowett cars between World Wars I and II, and the Toyota Publica and Toyota Sport 800. Flat-twin engines were also used in several early cars, including the Ford 1903-04 Model A, Model C and Model F.

Other uses

Maytag used its Model 72 flat-twin engines to power washing machines, although they were used as proprietary engines for other purposes as well. Maytag began manufacturing the Model 72 engine in 1937 and, after a break in production from May 1942 to June 1945 due to World War II, continued manufacturing them until the 1950s. Production ended some time between 1952 and 1960.

During World War II, motorcycle manufacturer Douglas built generators powered by their flat-twin engines, while ABC Motors used one in an Auxiliary power unit (APU).

Ignition systems



A Wasted spark ignition system used on a flat-twin engine

Flat-twin engines are well suited to the wasted spark ignition system, a distributor-less ignition system using a double-ended coil firing both spark plugs on each revolution, that is, on both the compression stroke and the exhaust stroke. This system requires only a single contact breaker and single coil to run two cylinders.