Powertrain

Kevin Hoag
Brian Dondlinger

Vehicular Engine Design

Second Edition

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I dedicated the first edition of this book to those in the engine development community who have left our company too soon. Sadly, another name has been recently added to that list. This edition is dedicated to Mark Tussing, Director of Engine Design and Development at Southwest Research, a man with soul, lost from our community in July 2014. I consider it my good fortune to have enjoyed working and laughing with Mark for over 20 years.

KLH

San Antonio, Texas

This book is dedicated to my wife Heidi, who served as my chief consultant on the book and key supporter, and to my kids Zoe Elanor and Evan Diesel. It is also dedicated to my parents, Peter and Patricia, for making me the person I am, and to Lynn whose help I couldn't have done it without.

BD

Milwaukee, Wisconsin

Preface

The mechanical engineering curriculum in most universities includes at least one elective course on the subject of reciprocating piston engines. The majority of these courses today emphasize the application of thermodynamics to engine efficiency, performance, combustion and emissions. There is at least one very good text book that supports education in these aspects of engine development.

However, in most companies engaged in engine development there are far more engineers working in the areas of design and mechanical development. University studies should include opportunities that prepare engineers desiring to work in these aspects of engine development as well. My colleagues and I have undertaken the development of a series of graduate courses in engine design and mechanical development. In doing so it becomes quickly apparent that no suitable text book exists in support of such courses.

This book was written in the hopes of beginning to address the need for an engineering-based introductory text in engine design and mechanical development. It is of necessity an overview, and focuses on the initial layout and first principles of engine operation. Its focus is limited to reciprocating piston internal combustion engines—both diesel and spark-ignition engines. Emphasis is specifically on automobile engines although much of the discussion applies to larger and smaller engines as well.

A further intent of this book is to provide a concise reference volume on engine design and mechanical development processes for engineers serving the engine industry. It is intended to provide basic information and most of the chapters include recent references to guide more in-depth study.

A few words should be said concerning the approach taken to the figures presented in this book. To aid understanding, simplified diagrams and plots are presented showing only the features being discussed at the time. Once the concept is illustrated, photos of production components and engines are shown to provide an example of how the theory can be applied in actual practice.

Acknowledgements

We are especially indebted to Dr. Josef Affenzeller who provided the guiding force and many consultations along the way. His guidance was invaluable. Also thank you to Bryce Metcalf and James Lippert who were consulted on the Gaskets and Seals chapter.

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A special thank you is reserved for Bruce Dennert at Harley-Davidson. His partnership in many engine design instruction endeavors, and his input and critique throughout the writing process are greatly valued.

Finally, we are indebted to our colleagues at the University of Wisconsin Engine Research Center. Drs. Rolf Reitz, David Foster, Jaal Ghandhi, Christopher Rutland, Scott Sanders, and David Rothammer provide a stimulating environment in which to work, and to develop the ideas contained in this book.

Contents

The Internal Combustion Engine—An Introduction

1

1.1 Heat Engines and Internal Combustion Engines

It is appropriate to begin with a simple definition of the engine as a device for converting energy into useful work. The goal of any engine is to convert energy from some other form into "mechanical force and motion." The terms "mechanical force" and "motion" are chosen to convey the idea that the interest may be both in work output—how much force can be applied to move something a given distance—and also power output—how quickly the work can be done.

Turning attention to the energy that is being converted to do the desired work, our interest is in the chemical energy contained in the molecular structure of a hydrocarbon fuel. Fundamental to any chemical reaction are the facts that it takes energy to break a chemical bond, and that energy is released when new bonds are formed. If the energy released in forming new bonds is greater than that required in breaking the old bonds the result is an ***exothermic*** reaction, and net energy available to do work.

Fundamental to any combustion engine is the reaction of a hydrocarbon fuel with oxygen to form carbon dioxide and water. This combustion reaction is highly exothermic—a large amount of energy is released. The goal of the engine will be to utilize that energy *repeatedly*, *efficiently*, and *cost-effectively*. The next question with which the engine designer is faced is that of developing a mechanical device that accomplishes these objectives.

Beginning from this general discussion of combustion engines, one can now make distinctions between various types of engines. These distinctions may be based on thermodynamic process decisions, as well as on the mechanical hardware. The first distinction to be made is that between the ***heat engine*** and the ***internal combustion engine***, as shown in Fig. 1.1—they really are two different things, although they have often been confused or incorrectly identified. By definition a heat engine is an engine in which a working fluid undergoes various state changes through an operating cycle. The working fluid experi-

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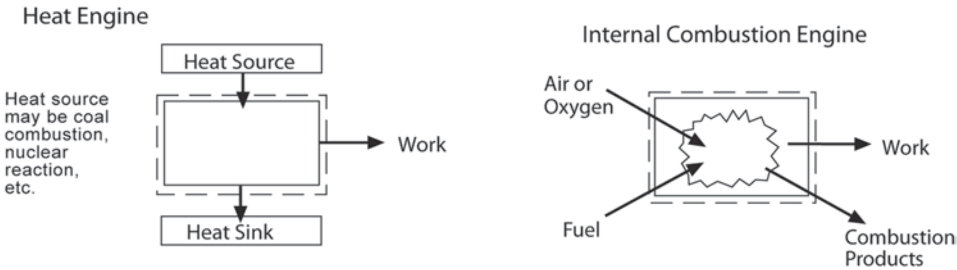

Fig. 1.1 The heat engine versus the internal combustion engine

ences a heat addition, in which its pressure and temperature increase. It then goes through a process converting a portion of its energy to work. Cycle completion requires heat rejection from the fluid to the environment. A Rankine cycle steam turbine, using either coal combustion or a nuclear reaction to provide the heat source (and steam as the working fluid) is a practical example of a heat engine.

The "air standard" Otto cycle and diesel cycle are theoretical representations of processes similar to those of a spark-ignition (SI) or diesel engine, but they assume the working fluid to be air, gaining energy from an external source. In the actual diesel or SI engine, the energy release occurs within the system, and the working fluid undergoes not only a state change but a change in chemical composition. While the mechanical device may undergo a cycle, the working fluid does not. Fuel and air enter the system, go through a series of thermodynamic processes, and are then exhausted from the system. Another example of a practical internal combustion engine is the gas turbine—not to be confused with the air standard Brayton cycle.

Earlier it was emphasized that any practical engine will be expected to produce work repeatedly (or continuously over some period of time), efficiently, and cost-effectively. These terms have been carefully chosen to convey separate expectations—all of which must be met for an engine to be practical. The discussion begins with an emphasis on efficiency and cost-effectiveness; the need for continuous production of work will be taken up shortly. Efficiency is a commonly used engineering term, and the classic definition will suffice here. With this measure one can assess how well the energy available can be converted into useful work. Cost-effectiveness is a more difficult measure to accurately obtain, and is less well understood by engineers. Nevertheless, it is every bit as important, and in many cases far more important, to a successful design. Listed below are the various elements defining the cost-effectiveness of an engine.

- Development, production, and distribution costs
- Maintenance costs
- Fuel costs
- Rebuild costs over useful life

- Disposal costs of parts and fluids
- Minus resale value at end of usage period

The elements listed together on the first line are ultimately reflected in the purchase price of the engine. As such, they provide the most direct measure of whether a given engine will be viable.

The remaining elements are tracked to a greater or lesser extent in particular markets. For example, while many automobile purchasers will consider only the purchase price (from this list) in making their buying decision, the company purchasing several hundred trucks or buses on which their company depends for its economic viability will almost certainly closely track every item on this list. The combination of these measures goes a long way in explaining why the internal combustion engine remains so difficult to replace.

Earlier the internal combustion engine was defined in general terms. Various types of practical engines fit this definition; these types are distinguished by the combination of their combustion process and mechanical configuration. The combustion process may be continuous, as with the gas turbine engine, or intermittent, as with both the diesel and the spark-ignition engine. A mechanical configuration must then be selected that meets the criteria of efficiency and cost-effectiveness, as well as allowing the work to be produced continuously. The objective is to create a mechanical arrangement that contains the combustion process, and utilizes the high pressure and temperature of the combustion products to produce useful work.

1.2 The Reciprocating Piston Engine

While many configurations have been proposed, patented, and demonstrated over the years, few have enjoyed commercial success. Such success results from the ability to address the combination of efficiency and cost-effectiveness discussed previously. In the remainder of this book the discussion will be limited to the reciprocating piston engine. This engine is characterized by a slider-crank mechanism that converts the reciprocating, cyclic motion of a piston in a cylinder into the rotating motion of a crankshaft.

The primary components of the reciprocating engine are shown in Fig. 1.2. The moving piston controls the volume of the combustion chamber between a minimum at ***top dead center*** (TDC) and a maximum at ***bottom dead center*** (BDC). The ratio between the volume at BDC and that at TDC is referred to as the ***compression ratio***. The change in volume is the ***displacement*** of the cylinder. The displacement of the cylinder, multiplied by the number of cylinders is the displacement of the engine. The cylinder is sealed opposite from the moving piston by the ***cylinder head***. In most engines the ***intake*** and ***exhaust valves*** are located in the cylinder head, as shown in the figure.

The piston is linked to the ***crankshaft*** through a ***connecting rod.*** As the crankshaft spins about its centerline (the ***main bearing bore*** in the ***cylinder block***) the offset of the

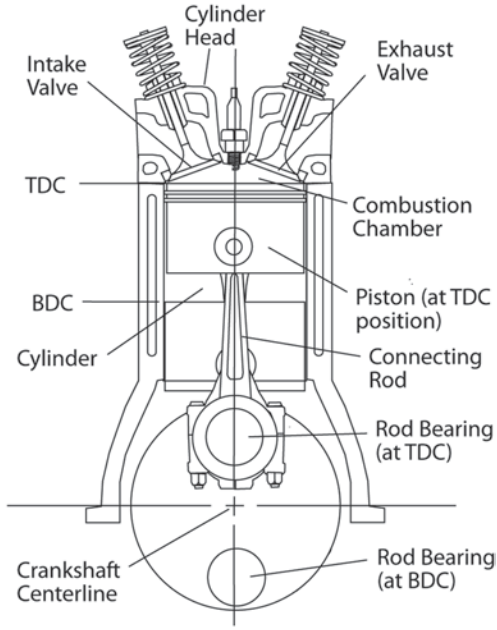

Fig. 1.2 Major operating components of the reciprocating piston internal combustion engine

rod bearing from the main bearing determines the travel of the piston. As the crankshaft rotates one half revolution from the position shown in the figure, the piston moves from its TDC to its BDC position. The distance the piston travels is referred to as the ***stroke*** of the engine. The stroke is equal to twice the offset between the main bearing and rod bearing centerlines of the crankshaft. The diameter of the cylinder is referred to as its ***bore***, and the combination of bore and stroke determine the displacement of the cylinder by the equation:

$$Displacement = \frac{\pi (Bore)^2 (Stroke)}{4}$$

The crankshaft protrudes through the rear of the engine, where a flywheel and clutch pack or flex plate and torque converter are attached through which the load will be transmitted. Typically at the front of the engine the crankshaft will drive the ***camshaft*** through a system of gears, a chain, or a cogged belt. The intake and exhaust valves are then actuated by the camshaft(s), either directly or through a ***valve train***. Various support systems for cooling and lubricating the engine and for supplying the fuel and igniting the mixture are also required.

Each of the components and sub-systems with the exception of the fuel and ignition systems will be discussed in detail in the chapters that follow. Because of the variety of fuel and ignition systems, and the availability of previously published books devoted to these systems they will not be covered in this book.

1.3 Engine Operating Cycles

Having introduced a particular mechanical mechanism designed to repeatedly extract useful work from the high temperature and pressure associated with the energy release of combustion, we are now ready to look at the specific processes required to complete this task. Shown in Fig. 1.3 is the four-stroke operating cycle, which as the name implies, requires four strokes of the piston (two complete revolutions of the crankshaft) for the completion of one cycle.

In the spark-ignition engine shown, a “charge” of pre-mixed air and fuel are drawn into the cylinder through the intake valve during the intake stroke. The valve is then closed and the mixture compressed during the compression stroke. As the piston approaches TDC, a high energy electrical spark provides the activation energy necessary to initiate the combustion process, forcing the piston down on its power stroke. As the piston nears BDC the exhaust valve opens, and the spent combustion products are forced out of the cylinder during the exhaust stroke. The work output is controlled by a throttle restricting the amount of air-fuel mixture that can pass through the intake valve.

A four-stroke ***diesel*** engine operating cycle would consist of the same processes. However, air alone would be drawn into the engine and compressed. The spark plug would be replaced with a fuel injector spraying the fuel directly into the cylinder near the end of the compression process. The activation energy would be provided by the high temperature

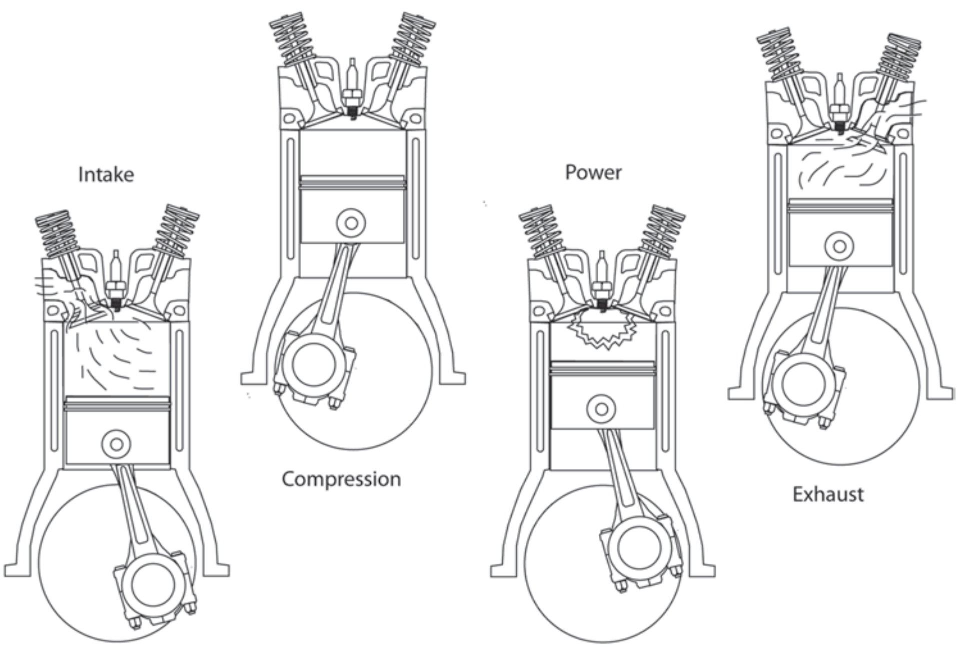

Fig. 1.3 The four-stroke operating cycle shown for a spark-ignition engine

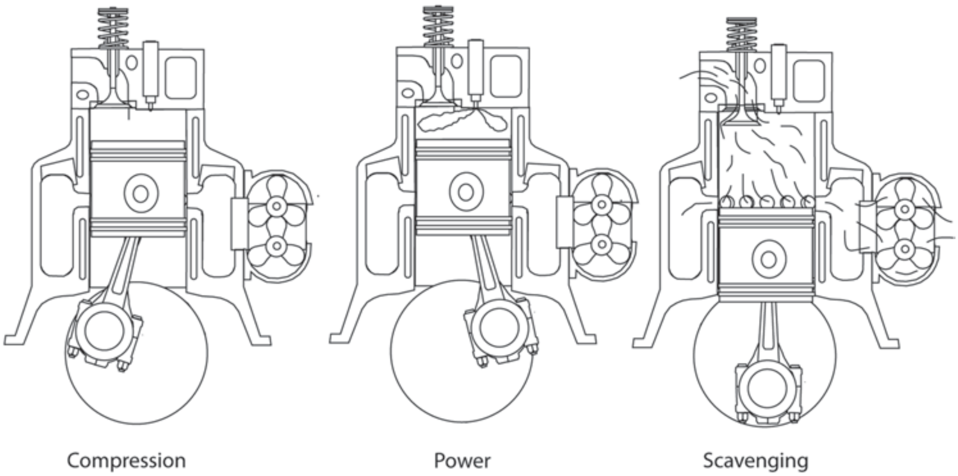

Fig. 1.4 The two-stroke operating cycle shown for a heavy-duty diesel engine

and pressure of the air into which the fuel is injected. The work output would be controlled by the amount of fuel injected.

An alternative to the four-stroke cycle is the two-stroke cycle shown in Fig. 1.4. As implied, a complete operating cycle is achieved with every two strokes of the piston (one revolution of the crankshaft). The compression and power strokes are similar to those of the four-stroke engine; however the gas exchange occurs as the piston approaches BDC, in what is termed the ***scavenging*** process. During scavenging the intake and exhaust passages are simultaneously open, and the engine relies on an intake supply pressure maintained higher than the exhaust pressure to force the spent products out and fill the cylinder with fresh air or air-fuel mixture.

The engine shown in the figure is a heavy-duty two-stroke diesel. The incoming air is pressurized with a crankshaft-driven compressor, and enters through ***ports*** near the bottom of the cylinder. In this engine exhaust valves similar to those of the four-stroke engine are mounted in the cylinder head. Light-duty two-stroke engines are often crankcase supercharged. In such engines, each time the piston moves upward in the cylinder a fresh charge (mixed with lubricating oil) is drawn into the crankcase. As the piston moves down, the crankcase is sealed and the mixture is compressed—the mixture is then transferred from the crankcase through the intake ports as the piston approaches BDC. This configuration is shown in Fig. 1.5.

In the spark-ignition configuration the engine suffers the disadvantage of sending fresh air-fuel mixture out with the exhaust during each scavenging period. Much recent attention is being given to engines that overcome this problem by injecting the fuel directly into the cylinder after the ports have been sealed.

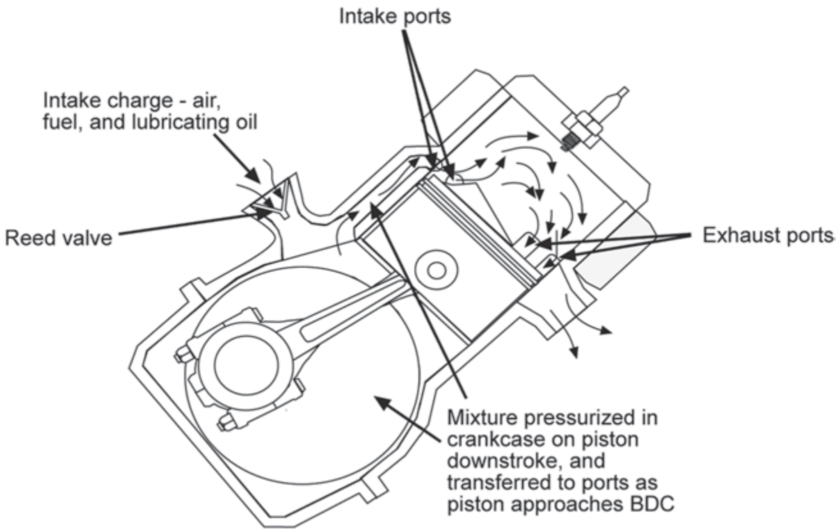

Fig. 1.5 The light-duty two-stroke engine

1.4 Supercharging and Turbocharging

In order to increase the specific power output of an engine (power output per unit of displacement) some form of pre-compression is often considered. This has become standard practice in diesel engines, and is often seen in high-performance spark-ignition engines. Downsized (reduced displacement) engines with turbocharging or supercharging are receiving increased attention as a means of achieving improved part-load fuel economy in automobile engines.

The engine that draws fresh charge into the cylinder at atmospheric pressure, and exhausts directly to the atmosphere is termed ***naturally aspirated***. As was shown in Fig. 1.4 a crankshaft-driven compressor may be added to elevate the pressure of the air (or mixture) prior to drawing it into the cylinder. This allows more mixture to be burned in a given cylinder volume. The crankshaft-driven device is generally referred to as a ***supercharger*** (although this general term is sometimes used to describe a turbocharger as well).

Recognizing that the exhaust gases leaving the engine still contain a significant quantity of energy that was not recovered as work, an alternative is to use a portion of this energy to drive the compressor. This configuration is the ***turbocharged*** engine.

Whenever the air is compressed its temperature increases. Its density can be further increased (and still more air forced into the cylinder) if it is cooled after compression. The ***charge air cooler***, variously termed ***intercooler*** (cooling between stages of compression) and ***aftercooler*** (cooling after compression) may be used with either the turbocharger or supercharger.

Most supercharged or turbocharged production applications use a single unit, in many cases followed by a charge air cooler. With some cylinder configurations, two smaller turbochargers may be used instead of one larger unit. The primary reason for such a layout is improved packaging. The smaller turbochargers also reduce acceleration lag, but result in an efficiency penalty due to higher fluid friction losses with the smaller passage sizes.

As the demand for higher specific output grows, both for increased part-load efficiency, and for reduced package volume and weight, more complex configurations are going into production. A turbocharger in series with a supercharger has long been seen on two-stroke diesel engines, formerly in heavy truck applications, and still seen today in some marine engines. The two-stroke requires pressurized intake air under all operating conditions, and this need is met with the crankshaft-driven supercharger. Placing a turbocharger in series with the supercharger allows the specific output to be increased, and improves engine efficiency through utilizing some of the exhaust energy. This arrangement is sometimes seen on four-stroke automotive engines as well.

Two turbochargers may be placed in series, with intake air drawn first through a low-pressure compressor and then a high-pressure compressor. An intercooler may be placed between stages, with an aftercooler following the high-pressure stage. The exhaust gas flows first through the high pressure turbine and then the low pressure turbine. In the series configuration the intake charge and exhaust gas flow through both units under all operating conditions. This configuration is sometimes seen in heavy truck engines, and is common in larger, off-highway diesel engines.

A more recent configuration is referred to as sequential turbocharging. This configuration also uses low- and high-pressure turbochargers, but with intake and exhaust control valves that direct the flow through either the high-pressure or low-pressure turbocharger under most conditions, and both units under only some operating conditions. This configuration allows high specific output to be maintained over a wide range of engine speeds.

At this time production applications of series and sequential turbocharging systems are more prevalent in diesel engines, where the additional boost pressure can be more readily utilized to increase specific output. With careful control and system optimization, sequential turbocharging is now being seen in a few production spark-ignition applications. The combustion system must be optimized within knock limits, but the sequential turbochargers then allow a wider speed range at high specific output.

1.5 Production Engine Examples

In automobile engines cost, weight, and package size are important design parameters in addition to the customer expectations regarding performance and fuel consumption. In most applications the duty cycle is quite light, with the full power output utilized for only a small fraction of the engine's operating time. Engines in these applications will have from three to twelve cylinders, with the majority having between four and eight. The in-line and vee configurations are most common, with horizontally-opposed and 'W' configurations sometimes seen. Spark-ignition examples are depicted in front- and side-view section drawings in Fig. 1.6a, b, and c. Those shown in Figs. 1.6a and b are both double overhead cam (DOHC) in-line four-cylinder engines. The engine shown in Fig. 1.6c is a high-performance, DOHC V-8 incorporating a variable-length intake runner system, and variable valve timing and valve event phasing. A series of photos of a DOHC V-6 engine is presented in Fig. 1.7a, b, c, and d.

Of resurgent interest in automobile applications worldwide is the diesel engine, examples of which are shown in Figs. 1.8a and b. The new diesel engines are universally turbocharged as this has allowed comparable displacements to their spark-ignition counterparts. The primary attraction of the diesel engine in automobile applications is its significantly higher inherent fuel economy. Greater reliability and durability are further attractions. These must be offset against higher initial cost, the challenges of meeting exhaust emission regulations, noise, and cold weather startability.

Heavy-duty engines, as referred to in this book are those used for trucks and buses. In many cases the same engines, or engines of very similar design, are used in agricultural and construction equipment as well as various marine, industrial, and stand-by power applications. These further applications will not be specifically addressed, but much of the engine design discussion will apply equally to these applications. Once the power and torque output requirements have been met the single most important design criterion for many of these engines is that of durability under a highly loaded duty cycle. Cost, weight, and package size are again important, but within the bounds defined by the durability requirement. In other words, these engines are significantly larger, heavier, and more expensive than automobile engines, but these design criteria remain important relative to competitive engines for similar applications. New engines for heavy-duty applications in trucks and buses are almost universally in-line six cylinder engines. They are highly turbocharged diesel or in some cases natural gas engines.

While considerably more time could be spent discussing the engines shown in these figures such discussion is deferred until later in the book. The reader will be asked to refer back to these figures many times in the upcoming chapters as various components and sub-systems are further described.

1.6 Basic Measures

A detailed discussion of engine performance measures is beyond the scope of this book, but a brief review of the most commonly used measures will be necessary to the further discussion.

Torque and Power Fundamental to engine performance is the relationship between work and power. The work, or useful energy output of the engine, is generally referred to as the torque output. Of particular interest in most engine applications is not only how much work can be done but the rate at which it can be done. The power of the engine is the time rate at which work is done. This is simply the product of engine torque and shaft speed,

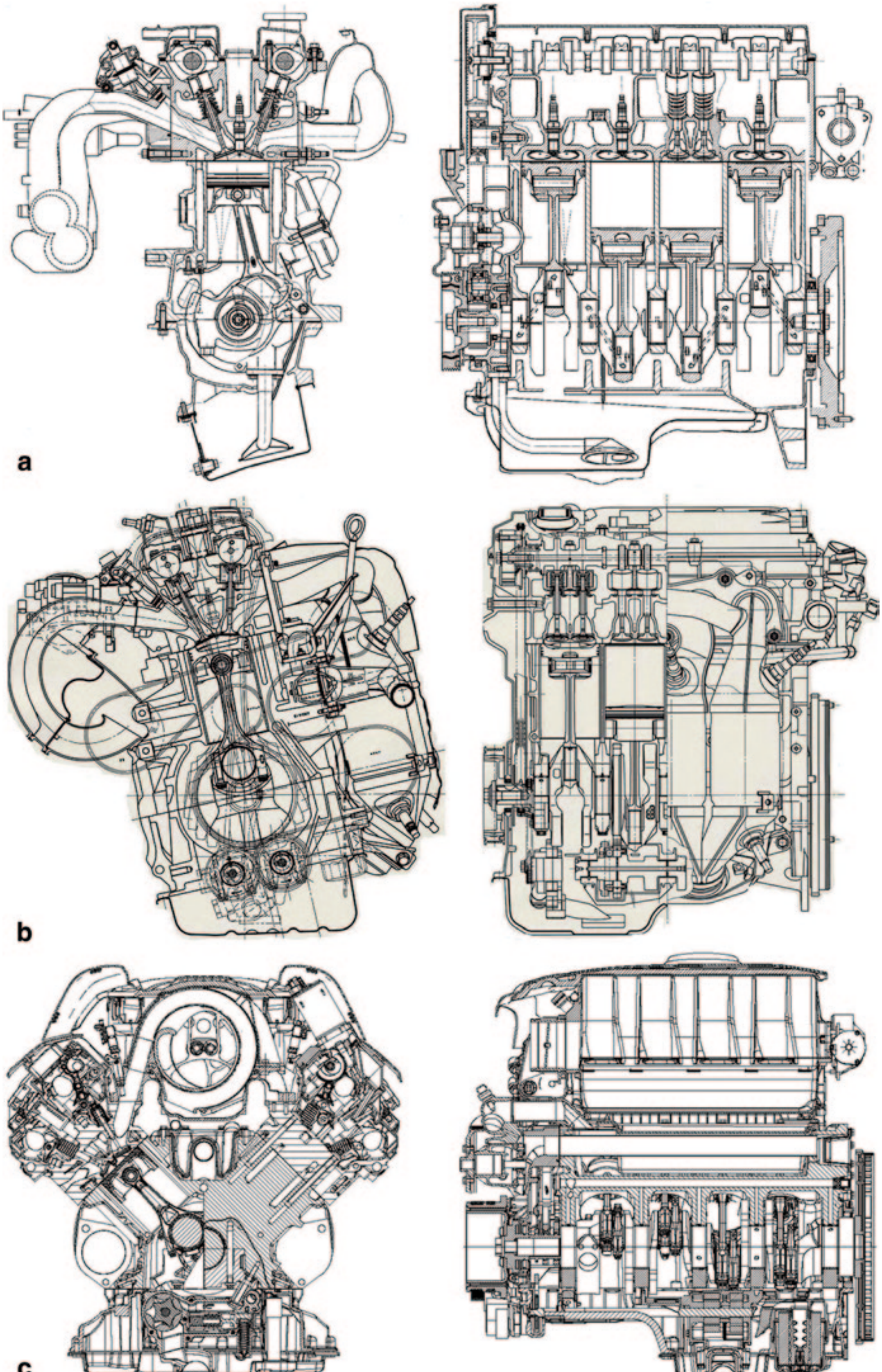

Fig. 1.6 **a** Four-cylinder, double-overhead-cam spark-ignition automobile engine (Courtesy of Toyota Motor Company). **b** Four-cylinder, double-overhead-cam spark-ignition automobile engine (Courtesy of Ford Motor Company). **c** Double-overhead-cam, high-performance V8 engine (Courtesy of BMW GmbH)

Fig. 1.7 **a** Double-overhead cam V6 engine, with cut-away showing cam drive chain (Courtesy of Nissan Motor Company). **b** Front view of engine shown in Fig. 1.7a. Serpentine belt accessory drives and cam drive cut-away are shown (Courtesy of Nissan Motor Company). **c** Details of cam drive, showing variable timing device for the intake camshaft. Engine is again that of Fig. 1.7a (Courtesy of Nissan Motor Company). **d** Cylinder head, intake and exhaust manifold cut-away for engine of Fig. 1.7a (Courtesy of Nissan Motor Company)

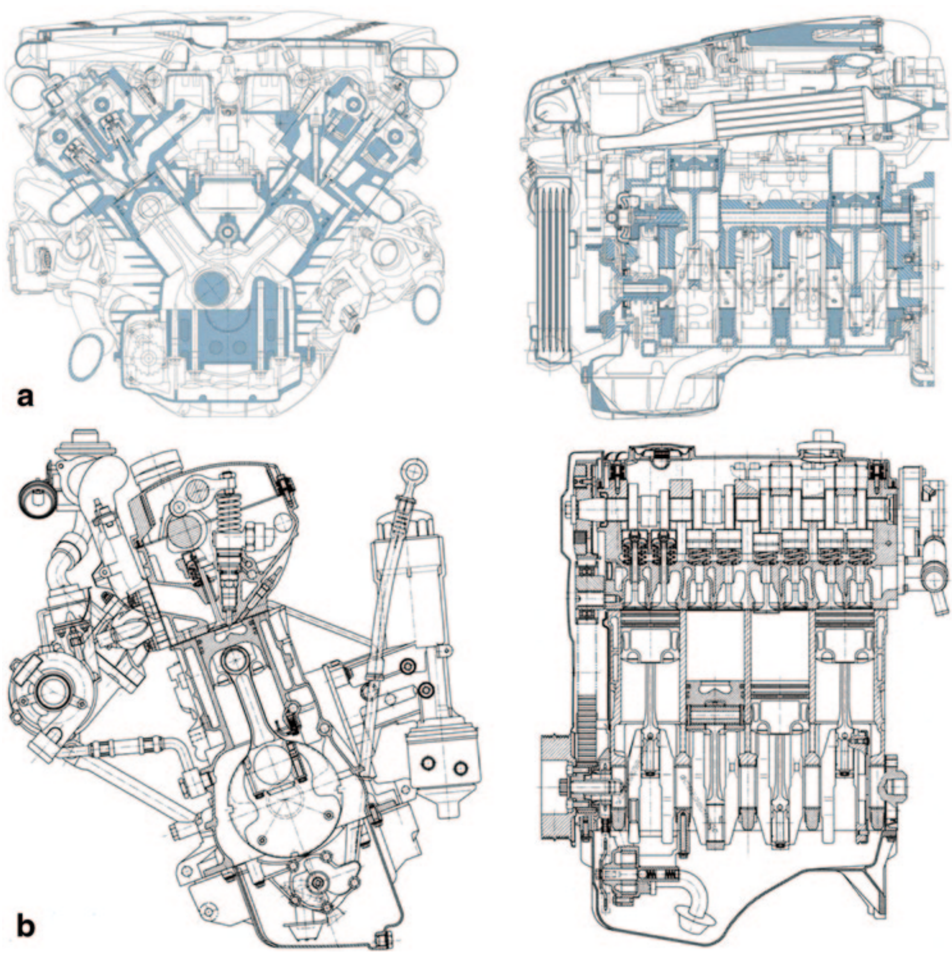

Fig. 1.8 **a** Four-cylinder, single-overhead-cam, direct-injection turbocharged diesel automobile engine (Courtesy of Volkswagen Audi GmbH). **b** Double-overhead cam V8, direct-injection turbocharged diesel automobile engine (Courtesy of Mercedes Benz GmbH)

$$P = (T) * (N)$$

English :

$$P(bhp) = (T\ ft - lbf) * (N\ rpm) * \left(\frac{1\ \text{min}}{60\ \text{sec}}\right) * \left(\frac{2\pi}{rev}\right) * \left(\frac{hp - \text{sec}}{550\ ft - lbf}\right)$$

$$= \frac{[(T\ ft - lbf) * (N\ rpm)]}{5252}$$

Metric :

$$P(kW) = (T\ N - m) * (N\ rpm) * \left(\frac{1\ \text{min}}{60\ \text{sec}}\right) * \left(\frac{2\pi}{rev}\right) * 10^{-3}$$

$$= (T\ N - m) * (N\ rpm) * \left(0.1047 * 10^{-3}\right)$$

Mean Effective Pressure There are two physical interpretations that can be used to define the mean effective pressure. First, it is the constant pressure acting over the same volume change (from TDC to BDC) that would produce the same work as the actual engine cycle. Note that since the pressure-volume analysis gives us the net indicated work this interpretation provides the ***indicated*** mean effective pressure, or ***IMEP***. The second interpretation is that mean effective pressure is the work output of the engine divided by its displacement. If indicated work is divided by engine displacement the result is the IMEP. If however the brake work is divided by displacement the result is the ***brake*** mean effective pressure, or ***BMEP***. The calculation follows:

$$BMEP = \left[\frac{(Brake\ Power) * (rev/cycle)}{(D) * (N)}\right]$$

English :

$$BMEP\ (psi) = \left[\frac{(P\ bhp) * (2\ rev/cycle\,(if\ \ four\text{-}stroke)) * 396{,}000}{\left(D\ in^3\right)(N\ rpm)}\right]$$

Metric :

$$BMEP\ (kPa) = \left[\frac{(P\ kW) * (2\,rev/cycle\,(if\ \ four\text{-}stroke)) * 10^3}{(D\ liter)(N\ rev/\text{sec})}\right]$$

Specific Fuel Consumption Another important measure of engine performance is its thermal efficiency—how efficiently the fuel energy is being converted into useful work. The measure of efficiency most commonly applied to engines is the specific fuel consumption, or ***sfc***. The specific fuel consumption is simply the mass flow rate of fuel divided by the power output. If brake power is used in the calculation the result is the brake specific fuel consumption, or ***bsfc***:

$$English:$$

$$BSFC\ (lbm\,/\,HP\text{-}hr) = \left[\frac{\dot{m}_{fuel}\ \dfrac{lbm}{hr}}{P\ bhp}\right]$$

$$Metric:$$

$$BSFC\ (gm\,/\,kW\text{-}hr) = \left[\frac{\dot{m}_{fuel}\ \dfrac{gm}{hr}}{P\ kW}\right]$$

Similarly, indicated power would be used to calculate indicated specific fuel consumption, or ***isfc***. It should be noted that if one knows the energy content per unit mass of the fuel the thermal efficiency can be directly calculated by taking the inverse of the specific fuel consumption and multiplying the mass flow rate of the fuel by the energy per unit mass. The result of these operations is the rate at which work is done (power) divided by the rate at which fuel energy is supplied. The energy of the fuel is generally taken as its Lower Heating Value (LHV) at constant pressure.

Volumetric Efficiency The ability to produce work will always be limited by the ability to supply sufficient oxygen for the combustion process. Therefore an important measure is that of how well the cylinder can be filled during each intake stroke. The measure used is volumetric efficiency. The name is a bit misleading as it is actually a mass ratio. It is the ratio of the actual mass flow rate of air into the engine divided by the ideal mass flow rate—that which would be supplied if the cylinder could be completely filled with air at the supply conditions:

$$\eta_{vol} = \left[\frac{\dot{m}_{actual}}{\dot{m}_{ideal}}\right] = \left[\frac{\dot{m}_{actual}}{\left(\rho_{ref}\right) * \left(\dfrac{(D) * (N\ rpm)}{2\ rev\,/\,cycle}\right)}\right]$$

Two important points must be noted. First, by convention, the mass flow rates used are that for the air alone. Even though the spark-ignition engine inducts a mixture of air and fuel the mass of the fuel is *not* included. This is an important point as it will have a measurable impact on the result.

Second, one must always be clear on the reference conditions being used for the density calculation. In naturally aspirated engines it is normal to use the density at ambient pressure and temperature. In supercharged or turbocharged engines one may use ambient density (in which case the resulting volumetric efficiency will be well over 100 %), or the density at the intake port pressure and temperature.

1.7 Recommendations for Further Reading

The study of thermodynamics underlying engine performance and efficiency was briefly introduced in this chapter, but the remainder of this book is devoted to the mechanical sciences as applied to engine design. For further reading on engine thermodynamics, performance, combustion and emissions the reader is referred to the following text by John Heywood. This book is an important addition to the library of anyone in the engine development field (see Heywood 1988):

Fuel injection and ignition systems have not been covered in this book. Robert Bosch, Gmbh., publishes comprehensive books on both diesel and spark-ignition fuel injection systems. These books are expected to be regularly revised, and the revisions current at the time of this writing are as follows (see Robert Bosch GmbH 2006a, b).

Engine design continues to evolve as technology and materials advance, and market and regulatory demands change. References on current practices in production engine design soon become dated, but the engine designer can maintain currency by studying the papers published each year on new engine designs. The following papers present summaries of recent engine designs at this writing:

Spark-Ignition Automobile Engines (see Matsunaga et al. 2005; Sandford et al. 2009; Kawamoto et al. 2009; Heiduk et al. 2011; Steinparzer et al. 2011; Okamoto et al. 2011; Kobayashi et al. 2012; Königstedt et al. 2012; Motohashi et al. 2013).

Rotary Spark-Ignition Engine (see Ohkubo et al. 2004).

Diesel Automobile Engines (see Abe et al. 2004; Bauder et al. 2011; Ardey et al. 2011, 2012).

Diesel Heavy-Duty Engines (see Suginuma et al. 2004; Altermatt et al. 1992; Hower et al. 1993; Kasper and Wingart 2011).

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