TROUBLESHOOTING AND REPAIRING

DIESEL ENGINES

4TH EDITION

PAUL DEMPSEY

1
CHAPTER

Rudolf Diesel

Rudolf Diesel was born of German parentage in Paris in 1858. His father was a self-employed leather worker who, by all accounts, managed to provide only a meager income for his wife and three children. Their stay in the City of Light was punctuated by frequent moves from one shabby flat to another. Upon the outbreak of the Franco-Prussian War in 1870, the family became political undesirables and was forced to emigrate to England. Work was almost impossible to find, and in desperation, Rudolf's parents sent the boy to Augsburg to live with an uncle. There he was enrolled in school.

Diesel's natural bent was for mathematics and mechanics. He graduated as the head of his class, and on the basis of his teachers' recommendations and a personal interview by the Bavarian director of education, he received a scholarship to the prestigious Polytechnikum in Munich.

His professor of theoretical engineering was the renowned Carl von Linde, who invented the ammonia refrigeration machine and devised the first practical method of liquefying air. Linde was an authority on thermodynamics and high-compression phenomena. During one of his lectures he remarked that the steam engine had a thermal efficiency of 6–10%; that is, one-tenth or less of the heat energy of its fuel was used to turn the crankshaft, and the rest was wasted. Diesel made special note of this fact. In 1879 he asked himself whether heat could not be directly converted into mechanical energy instead of first passing through a working fluid such as steam.

On the final examination at the Polytechnikum, Diesel achieved the highest honors yet attained at the school. Professor Linde arranged a position for the young diploma engineer in Paris, where, in few months, he was promoted to general manager of the city's first ice-making plant. Soon he took charge of distribution of Linde machines over southern Europe.

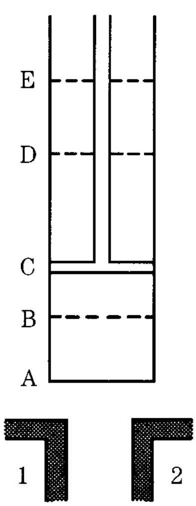
By the time he was thirty, Diesel had married, fathered three children, and was recognized throughout the European scientific community as one of the most gifted engineers of the period. He presented a paper at the Universal Exposition held in Paris in 1889—the only German so honored. When he received the first of several citations of merit from a German university, he announced wryly in his acceptance speech: "I am an iceman. . ."

The basis of this acclaim was his preeminence in the new technology of refrigeration, his several patents, and a certain indefinable air about the young man that marked him as extraordinary. He had a shy, self-deprecating humor and an absolute passion for factuality. Diesel could be abrupt when faced with incompetence and was described by relatives as "proud." At the same time he was sympathetic to his workers and made friends among them. It was not unusual for Diesel to wear the blue cotton twill that was the symbol of manual labor in the machine trades.

He had been granted several patents for a method of producing clear ice, which, because it looked like natural ice, was much in demand by the upper classes. Professor Linde did not approve of such frivolity, and Diesel turned to more serious concerns. He spent several years in Paris, working on an ammonia engine, but in the end was defeated by the corrosive nature of this gas at pressure and high temperatures.

The theoretical basis of this research was a paper published by N.L.S. Carnot in 1824. Carnot set himself to the problem of determining how much work could be accomplished by a heat engine employing repeatable cycles. He conceived the engine drawn in Fig. 1-1. Body 1 supplies the heat; it can be a boiler or other heat exchanger. The piston is at position C in the drawing. As the air is heated, it expands in correspondence to Boyle's law. If we assume a frictionless engine, its temperature will not rise. Instead, expansion will take place, driving the piston to D. Then A is removed, and the piston continues to lift to E. At this point the temperature of the air falls until it exactly matches cold surface 2 (which can be a radiator or cooling tank). The air column is now placed in contact with 2, and the piston falls because the air is compressed. Note, however, that the temperature of the air does not change. At B cold body 2 is removed, and the piston falls to A. During this phase the air gains temperature, until it is equal to 2. The piston climbs back into the cylinder.

The temperature of the air, and consequently the pressure, is higher during expansion than during compression. Because the pressure is greater during expansion, the



1-1 Carnot cycle.

power produced by the expansion is greater than that consumed by the compression. The net result is a power output that is available for driving other machinery.

Of course this is an "ideal" cycle. It does not take into account mechanical friction nor transfer of heat from the air to the piston and cylinder walls. The infinitesimal difference of heat between 1 and 2 is sufficient to establish a gradient and drive the engine. It would be completely efficient.

In 1892 and 1893 Diesel obtained patent specifications from the German government covering his concept for a new type of *Verbrennungskraftmaschinen*, or heat engine. The next step was to build one. At the insistence of his wife, he published his ideas in a pamphlet and was able to interest the leading Augsburg engine builder in the idea. A few weeks later the giant Krupp concern opened negotiations. With typical internationalism he signed another contract with the Sulzer Brothers of Switzerland.

The engine envisioned in the pamphlet and protected by the patent specifications had these characteristics:

- *Compression of air prior to fuel delivery.* The compression was to be adiabatic; that is, no heat would be lost to the piston crown or cylinder head during this process.
- *Metered delivery of fuel so compression pressures would not be raised by combustion temperatures.* The engine would operate on a *constant-pressure* cycle; expanding gases would keep precisely in step with the falling piston. This is a salient characteristic of Carnot's ideal gas cycle, and stands in contrast to the Otto cycle, in which combustion pressures rise so quickly upon spark ignition that we describe it as a *constant-volume* engine.
- *Adiabatic expansion.*
- *Instantaneous exhaust at constant volume.*

It is obvious that Diesel did not expect a working engine to attain these specifications. Adiabatic compression and exhaust phases are, by definition, impossible unless the engine metal is at combustion temperature. Likewise, fuel metering cannot be so precise as to limit combustion pressures to compression levels. Nor can a cylinder be vented instantaneously. But these specifications are significant in that they demonstrate an approach to invention. The rationale of the diesel engine was to save fuel by as close an approximation to the Carnot cycle as materials would allow. The steam, or *Rankine cycle*, engine was abysmal in this regard; and the *Otto* four-stroke-cycle spark or hot-tube e-ignition engine was only marginally better.

This approach, from the mathematically ideal to materially practical, is exactly the reverse of the one favored by inventors of the Edison, Westinghouse, and Kettering school. When Diesel visited America in 1912, Thomas A. Edison explained to the young inventor that these men worked *inductively*, from the existing technology, and not *deductively*, from some ideal or model. Diesel felt that such procedure was at best haphazard, even though the results of Edison and other inventors of the inductive school were obviously among the most important. Diesel believed that productivity should be measured by some absolute scientific standard.

The first Diesel engine was a single-cylinder four-cycle design, operated by gasoline vapor. The vapor was sprayed into the cylinder near top dead center by means of an air compressor. The engine was in operation in July of 1893. However, it was discovered that a misreading of the blueprints had caused an increase in the size of the chamber. This was corrected with a new piston, and the engine was connected to a pressure gauge. The gauge showed approximately 80 atmospheres before it shattered, spraying the room with brass and glass fragments. The best output of what Diesel called his “black mistress” was slightly more than 2 hp—not enough power to overcome friction and compression losses. Consequently, the engine was redesigned.

The second model was tested at the end of 1894. It featured a variable-displacement fuel pump to match engine speed with load. In February of the next year, the mechanic Linder noted a remarkable development. The engine had been sputtering along, driven by a belt from the shop power plant, but Linder noticed that the driving side of the belt was slack, indicating that the engine was putting power into the system. For the first time the Diesel engine ran on its own.

Careful tests—and Diesel was nothing if not careful and methodical—showed that combustion was irregular. The next few months were devoted to redesigning the nozzle and delivery system. This did not help, and in what might have been a fit of desperation, Diesel called upon Robert Bosch for an ignition magneto. Bosch personally fitted one of his low-tension devices to the engine, but it had little effect on the combustion problem. Progress came about by varying the amount of air injected with the fuel, which, at this time, was limited to kerosene or gasoline.

A third engine was built with a smaller stroke/bore ratio and fitted with two injectors. One delivered liquid fuel, the other a mixture of fuel and air. This was quite successful, producing 25 hp at 200 rpm. It was several times as efficient as the first model. Further modifications of the injector, piston, and lubrication system ensued, and the engine was deemed ready for series production at the end of 1896.

Diesel turned his attention to his family, music, and photography. Money began to pour in from the patent licensees and newly organized consortiums wanting to build engines in France, England, and Russia. The American brewer Adolphus Busch purchased the first commercial engine, similar to the one on display at the Budweiser plant in St. Louis today. He acquired the American patent rights for one million marks, which at the current exchange rate amounted to a quarter of a million dollars—more than Diesel had hoped for.

The next stage of development centered around various fuels. Diesel was already an expert on petroleum, having researched the subject thoroughly in Paris in an attempt to refine it by extreme cold. It soon became apparent that the engine could be adapted to run on almost any hydrocarbon from gasoline to peanut oil. Scottish and French engines routinely ran on shale oil, while those sold to the Nobel combine in Russia operated well on refinery tailings. In a search for the ultimate fuel, Diesel attempted to utilize coal dust. As dangerous as this fuel is in storage, he was able to use it in a test engine.

These experiments were cut short by production problems. Not all the licensees had the same success with the engine. In at least one instance, a whole production run had to be recalled. The difficulty was further complicated by a shortage of trained technicians. A small malfunction could keep the engine idle for weeks, until the customer lost patience and sent it back to the factory. With these embarrassments came the question of whether the engine had been oversold. Some believed that it needed much more development before being put on the market. Diesel was confident that his creation was practical—if built and serviced to specifications. But he encouraged future development by inserting a clause in the contracts that called for pooled research: the licensees were to share the results of their research on Diesel engines.

Diesel's success was marred in two ways. For one, he suffered exhausting patent suits. The Diesel engine was not the first to employ the principle of compression ignition; Akroyd Stuart had patented a superficially similar design in 1890. Also, Diesel had a weakness for speculative investments. This weakness, along with a tendency to maintain a high level of personal consumption, cost Rudolf Diesel millions. His American biographers, W. Robert Nitske and Charles Morrow Wilson, estimate that the mansion in Munich cost a million marks to construct at the turn of the century.

The inventor eventually found himself in the uncomfortable position of living on his capital. His problem was analogous to that of an author who is praised by the critics but who cannot seem to sell his books. Diesel engines were making headway in stationary and marine applications, but they were expensive to build and required special service techniques. True mass production was out of the question. At the same time, the inventor had become an international celebrity, acclaimed on three continents.

Diesel returned to work. After mulling a series of projects, some of them decidedly futuristic, he settled on an automobile engine. Two such engines were built. The smaller, 5-hp model was put into production, but sales were disappointing. The engine is, by nature of its compression ratio, heavy and, in the smaller sizes, difficult to start. (The latter phenomenon is due to the unfavorable surface/volume ratio of the chamber as piston size is reduced. Heat generated by compression tends to bleed off into the surrounding metal.) A further complication was the need for compressed air to deliver the fuel into the chamber. Add to these problems precision machine work, and the diesel auto engine seemed impractical. Mercedes-Benz offered a diesel-powered passenger car in 1936. It was followed by the Austin taxi (remembered with mixed feelings by travelers to postwar London), by the Land Rover, and more recently, by the Peugeot. However desirable diesel cars are from the point of view of fuel economy and longevity, they have just recently become competitive with gasoline-powered cars.

Diesel worked for several months on a locomotive engine built by the Suizer Brothers in Switzerland. First tests were disappointing, but by 1914 the Prussian and Saxon State Railways had a diesel in everyday service. Of course, most of the world's locomotives are diesel-powered today.

Maritime applications came as early as 1902. Nobel converted some of his tanker fleet to diesel power, and by 1905 the French navy was relying on these engines for their submarines. Seven years later, almost 400 boats and ships were propelled solely or in part by compression engines. The chief attraction was the space saved, which increased the cargo capacity or range.

In his frequent lectures Diesel summed up the advantages of his invention. The first was efficiency, which was beneficial to the owner and, by extension, to all of society. In immediate terms, efficiency meant cost savings. In the long run, it meant conserving world resources. Another advantage was that compression engines could be built on any scale from the fractional horsepower to the 2400-hp Italian Tosi of 1912. Compared to steam engines, the diesel was compact and clean. Rudolf Diesel was very much concerned with the question of air pollution, and mentioned it often.

But the quintessential characteristic, and the one that might explain his devotion to his "black mistress," was her quality. Diesel admitted that the engines were expensive, but his goal was to build the best, not the cheapest.

During this period Diesel turned his attention to what his contemporaries called "the social question." He had been poor and had seen the effects of industrialization firsthand in France, England, and Germany. Obviously machines were not freeing men, or at least not the masses of men and women who had to regulate their lives by the factory system. This paradox of greater output of goods and intensified physical and spiritual poverty had been seized on by Karl Marx as the key "contradiction" of the capitalistic system. Diesel instinctively distrusted Marx because he distrusted the violence that was implicit in "scientific socialism." Nor could he take seriously a theory of history whose exponent claimed it was based on absolute principles of mathematical integrity.

He published his thoughts on the matter under the title *Solidarismus* in 1903. The book was not taken seriously by either the public or politicians. The basic concept was that nations were more alike than different. The divisions that characterize modern society are artificial to the extent that they do not have an economic rationale. To find solidarity, the mass of humanity must become part owners in the sources of production. His formula was for every worker to save a penny a day. Eventually these pennies would add up to shares or part shares in business enterprises: Redistributed, wealth and, more important, the sense of controlling one's destiny would be achieved without violence or rancor through the effects of the accumulated capital of the workers.

Diesel wrote another book that was better received. Entitled *Die Enstehung des Dieselmotors*, it recounted the history of his invention and was published in the last year of his life.

For years Diesel had suffered migraine headaches, and in his last decade, he developed gout, which at the end forced him to wear a special oversized slipper. Combined with this was a feeling of fatigue, a sense that his work was both done and undone, and that there was no one to continue. Neither of his two sons showed any interest in the engine, and he himself seemed to have lost the iron concentration of earlier years when he had thought nothing of a 20-hour workday. It is probable that technicians in the various plants knew more about the current state of diesel development than he did.

And the bills mounted. A consultant's position, one that he would have coveted in his youth, could only postpone the inevitable; a certain level of indebtedness makes a salary superfluous. Whether he was serious in his acceptance of the English-offered consultant position is unknown. He left his wife in Frankfort in apparent good spirits and gave her a present. It was an overnight valise, and she was instructed not to open it for a week. When she did, she found it contained 20,000 marks. This was, it is believed, the last of his liquid reserves. At Antwerp he boarded the ferry to Warwick in the company of three friends. They had a convivial supper on board and retired to their staterooms. The next morning Rudolf Diesel could not be found. One of the crew discovered his coat, neatly folded under a deck rail. The captain stopped the ship's progress, but there was no sign of the body. A few days later a pilot boat sighted a body floating in the channel, removed a corn purse and spectacle case from the pockets, and set the-corpse adrift. The action was not unusual or callous; seamen had, and still do have, a horror of retrieving bodies from the sea. These items were considered by the family to be positive identification. They accepted the death as suicide, although the English newspapers suggested foul play at the hands of foreign agents who did not want Diesel's engines in British submarines.

2
CHAPTER
Diesel basics

At first glance, a diesel engine looks like a heavy-duty gasoline engine, minus spark plugs and ignition wiring (Fig. 2-1). Some manufacturers build compression ignition (CI) and spark ignition (SI) versions of the same engine. Caterpillar G3500 and G3600 SI natural-gas fueled engines are built on diesel frames and use the same blocks, crankshafts, heads, liners, and connecting rods.

But there are important differences between CI and SI engines that cut deeper than the mode of igniting the fuel.

Compression ratio

When air is compressed, collisions between molecules produce heat that ignites the diesel fuel. The compression ratio (c/r) is the measure of how much the air is compressed (Fig. 2-2).

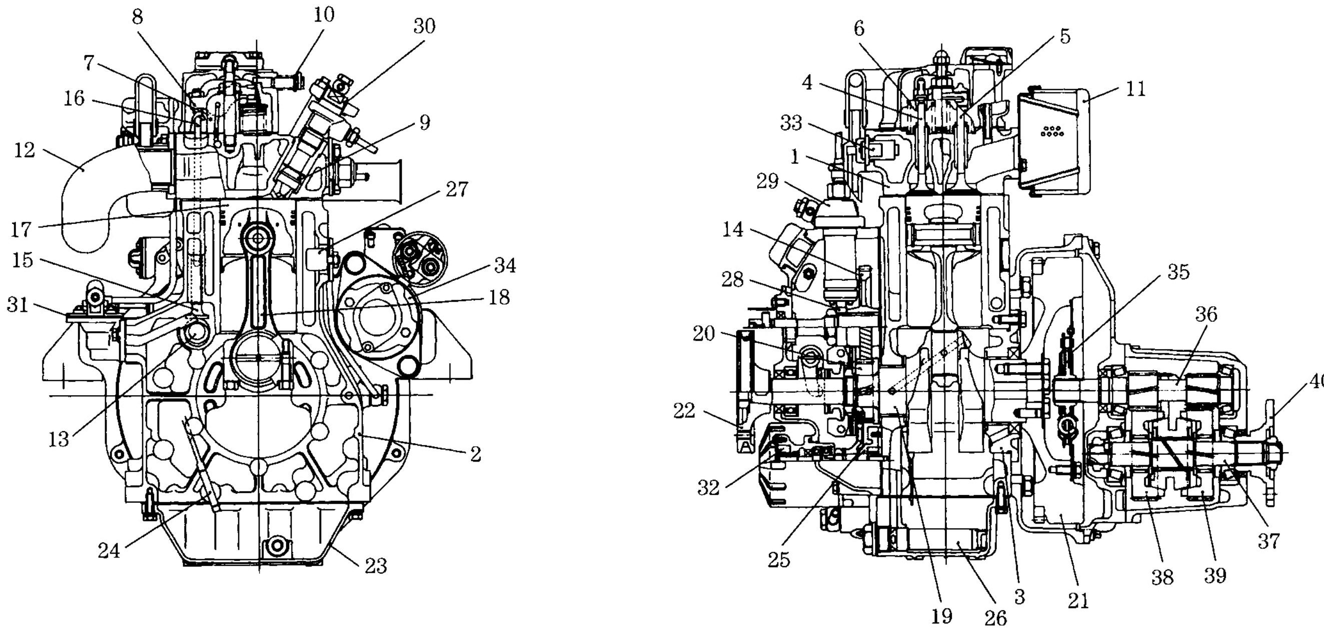
Compression ratio = swept volume + clearance volume ÷ swept volume

Swept volume = the volume of the cylinder traversed by the piston in its travel from top dead center (tdc) to bottom dead center (bdc)

Clearance volume = combustion chamber volume

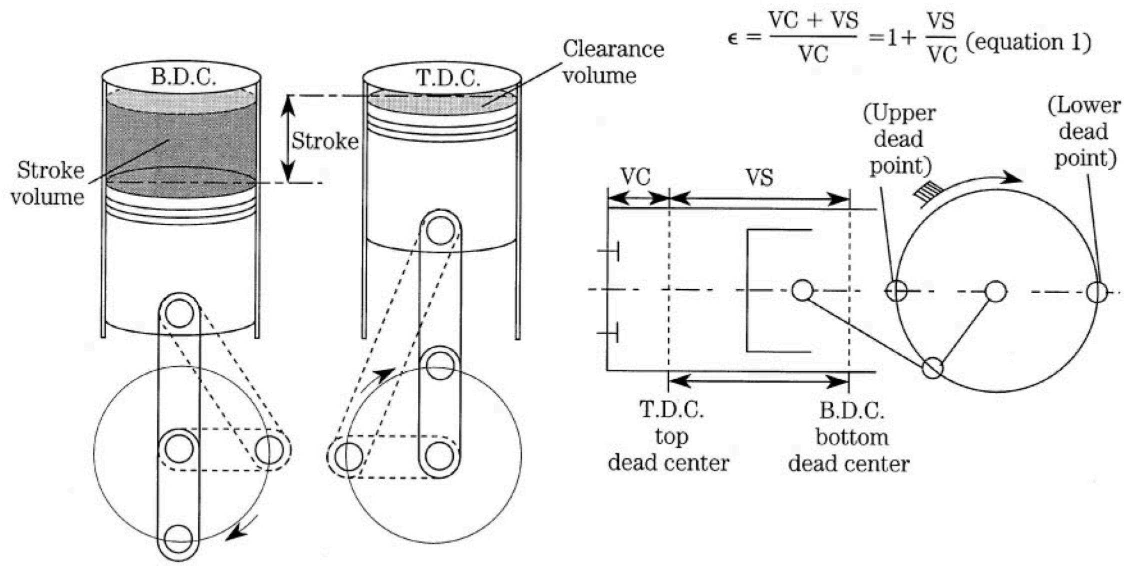
Figure 2-3 graphs the relationship between c/r's and thermal efficiency, which reaffirms what every mechanic knows: high c/r's are a precondition for power and fuel economy.

At the very minimum, a diesel engine needs a c/r of about 16:1 for cold starting. Friction, which increases more rapidly than the power liberated by increases in compression, sets the upper limit at about 24:1. Other inhibiting factors are the energy required for cranking and the stresses produced by high power outputs. Diesels with c/r's of 16 or 17:1 sometimes benefit from a point or two of higher compression. Starting becomes easier and less exhaust smoke is produced. An example is the

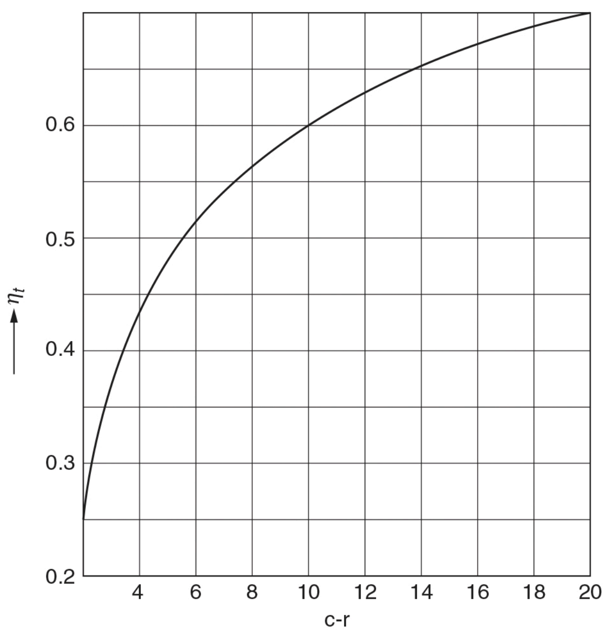


1. Cylinder head	11. Intake silencer	21. Flywheel	31. Fuel feed pump
2. Cylinder body	12. Mixing elbow	22. Crankshaft V-pulley	32. Cooling water pump
3. Main bearing housing	13. Camshaft	23. Oil pan	33. Thermostat
4. Exhaust valve	14. Camshaft gear	24. Dipstick	34. Starter motor
5. Intake valve	15. Tappet	25. Lubricating oil pump	35. Damper disc
6. Valve spring	16. Push rod	26. Lubricating oil inlet pipe	36. Input shaft
7. Valve rocker arm support	17. Piston	27. Anti corrosion zinc	37. Output shaft
8. Valve rocker arm	18. Connecting rod	28. Fuel injection pump cam	38. Forward large gear
9. Precombustion chamber	19. Crankshaft	29. Fuel injection pump	39. Reverse large gear
10. Decompression lever	10. Crankshaft gear	30. Fuel injection nozzle	40. Output shaft coupling

2-1 The Yanmar 1GM10, shown with a marine transmission, provides auxiliary power for small sailboats. The 19.4 CID unit develops 9 hp and forms the basic module for two- and three-cylinder versions.



2-2 Compression ratio is a simple concept, but one that mathematics and pictures express better than words.



2-3 The relationship between diesel compression ratios and thermal efficiency.

Caterpillar 3208 that has a tendency to smoke and "wet stack," that is, to saturate its exhaust system with unburned fuel. These problems can be alleviated with longer connecting rods that raise the compression ratio from 16.5:1 to 18.2:1.

It should be noted that a compressor, in the form of a turbocharger or supercharger, raises the effective c/r. Consequently, these engines have c/r's of 16 or 17:1, which are just adequate for starting. Once the engine is running, the compressor provides additional compression.

Gasoline engines have lower c/r's—half or less—than CI engines. This is because the fuel detonates when exposed to the heat and pressure associated with higher c/r's. Detonation is a kind of maverick combustion that occurs after normal ignition. The unburned fraction of the charge spontaneously explodes. This sudden rise in pressure can be heard as a rattle or, depending upon the natural frequency of the connecting rods, as a series of distinct pings. Uncontrolled detonation destroys crankshaft bearings and melts piston crowns.

Induction

Modern SI engines mix air and fuel in the intake manifold by way of one or more low-pressure (50-psi or so) injectors. A throttle valve regulates the amount of air admitted, which is only slightly in excess of the air needed for combustion. As the throttle opens, the injectors remain open longer to increase fuel delivery. For a gasoline engine, the optimum mixture is roughly 15 parts air to 1 part fuel. The air-fuel mixture then passes into the cylinder for compression and ignition.

In a CI engine, air undergoes compression before fuel is admitted. Injectors open late during the compression stroke as the piston approaches tdc. Compressing air, rather than a mix of air and fuel, improves the thermal efficiency of diesel engines. To understand why would require a course in thermodynamics; suffice to say that air contains more latent heat than does a mixture of air and vaporized fuel.

Forcing fuel into a column of highly compressed air requires high injection pressures. These pressures range from about 6000 psi for utility engines to as much as 30,000 psi for state-of-the-art examples.

CI engines dispense with the throttle plate—the same amount of air enters the cylinders at all engine speeds. Typically, idle-speed air consumption averages about 100 lb of air per pound of fuel; at high speed or under heavy load, the additional fuel supplied drops the ratio to about 20:1.

Without a throttle plate, diesels breathe easily at low speeds, which explains why truck drivers can idle their rigs for long periods without consuming appreciable fuel. (An SI engine requires a fuel-rich mixture at idle to generate power to overcome the throttle restriction.)

Since diesel air flow remains constant, the power output depends upon the amount of fuel delivered. As power requirements increase, the injectors deliver more fuel than can be burned with available oxygen. The exhaust turns black with partially oxidized fuel. How much smoke can be tolerated depends upon the regulatory climate, but the smoke limit always puts a ceiling on power output.

To get around this restriction, many diesels incorporate an air pump in the form of an exhaust-driven turbocharger or a mechanical supercharger. Forced induction can double power outputs without violating the smoke limit. And, as far as turbochargers are concerned, the supercharge effect is free. That is, the energy that drives the turbo would otherwise be wasted out the exhaust pipe as heat and exhaust-gas velocity.

The absence of an air restriction and an ignition system that operates as a function of engine architecture can wrest control of the engine from the operator. All that's needed is for significant amounts of crankcase oil to find its way into the combustion chambers. Oil might be drawn into the chambers past worn piston rings or from a failed turbocharger seal. Some industrial engines have an air trip on the intake manifold for this contingency, but many do not. A runaway engine generally accelerates itself to perdition because few operators have the presence of mind to engage the air trip or stuff a rag into the intake.

Ignition and combustion

SI engines are fired by an electrical spark timed to occur just before the piston reaches the top of the compression stroke. Because the full charge of fuel and air is present, combustion proceeds rapidly in the form of a controlled explosion. The rise in cylinder pressure occurs during the span of a few crankshaft degrees. Thus, the cylinder volume above the piston undergoes little change between ignition and peak pressure. Engineers, exaggerating a bit, describe SI engines as "constant volume" engines (Fig. 2-4).

Compared to SI, the onset of diesel ignition is a leisurely process (Fig. 2-4). Some time is required for the fuel spray to vaporize and more time is required for the spray to reach ignition temperature. Fuel continues to be injected during the delay period.

Once ignited, the accumulated fuel burns rapidly with correspondingly rapid increases in cylinder temperature and pressure. The injector continues to deliver fuel through the period of rapid combustion and into the period of controlled combustion that follows. When injection ceases, combustion enters what is known as the afterburn period.

The delay between the onset of fuel delivery and ignition (A–B in Fig. 2-5) should be as brief as possible to minimize the amount of unburnt fuel accumulated in the cylinder. The greater the ignition lag, the more violent the combustion and resulting noise, vibration, and harshness (NVH).

Ignition lag is always worst upon starting cold, when engine metal acts as a heat sink. Mechanics sometimes describe the clatter, white exhaust smoke, and rough combustion that accompany cold starts as "diesel detonation," a term that is misleading because diesels do not detonate in the manner of SI engines. Combustion should smooth out after the engine warms and ignition lag diminishes. Heating the incoming air makes cold starts easier and less intrusive.

In normal operation, with ignition delay under control, cylinder pressures and temperatures rise more slowly (but to higher levels) than for SI engines. In his proposal of 1893, Rudolf Diesel went one step further and visualized constant pressure expansion: fuel input and combustion pressure would remain constant during the