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Islamic University of Technology (IUT)

The Organization of the Islamic Cooperation

(OIC)

Gazipur-1704, Dhaka, Bangladesh

A STUDY OF TURBOCHARGER AND ITS APPLICATIONS

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A STUDY OF TURBOCHARGER AND ITS APPLICATIONS

A Thesis Presented to
The Academic Faculty

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ABSTRACT

Now that we're in the midst of another kind of energy crisis, the turbocharger is back. **In the 1980s,** it was difficult to escape the turbocharger. The twin energy crises of the 1970s forced automakers to produce cars that delivered better fuel economy. And that meant downsizing engines. By the 1980s, turbo technology was evolving and automakers installed them to boost the power of these smaller engines. But turbos promised more than just power—they promised fuel economy benefits too. They Increased power for an engine of the same size OR reduction in size for an engine with the same power output. Reduced specific fuel oil consumption - mechanical, thermal and scavenge efficiencies are improved due to less cylinders, greater air supply and use of exhaust gasses. Thermal loading is reduced due to shorter more efficient burning period for the fuel leading to less exacting cylinder conditions. The high-altitude performance of a turbocharged engine is significantly better. Because of the lower air pressure at high altitudes, the power loss of a naturally aspirated engine is considerable. In contrast, the performance of the turbine improves at altitude as a result of the greater pressure difference between the virtually constant pressure upstream of the turbine and the lower ambient pressure at outlet. The lower air density at the compressor inlet is largely equalized. Hence, the engine has barely any power loss. Because of reduced overall size, the sound-radiating outer surface of a turbo engine is smaller, it is therefore less noisy than a naturally aspirated engine with identical output. The turbocharger itself acts as an additional silencer.

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Praise and thanks to the Sustainer of the worlds, grace, honour and salutations on the Chief of Apostles and Seal of Prophets, Muhammad, his family and companions till the Day of Resurrection. May Allah grant him a seat of honor and nearness to Him on the Day of Resurrection. And Peace on the messengers! All Praise be to Allah with whose blessings all good affairs are accomplished. We Praise Allah, the Lord of the worlds for His favor to us in completing this Thesis/Project, praying Him to increase us in knowledge and grant us knowledge, which is beneficial.

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Chapter 1:

Turbocharger

1.1 Introduction:

Forced induction dates from the late 19th century, when Gottlieb Daimler patented the technique of using a gear-driven pump to force air into an internal combustion engine in 1885.[5] The turbocharger was invented by Swiss engineer Alfred Büchi (1879-1959), the head of diesel engine research at Gebruder Sulzer engine manufacturing company in Winterhur, who received a patent in 1905 for using a compressor driven by exhaust gasses to force air into an internal combustion engine to increase power output but it took another 20 years for the idea to come to fruition. During World War I French engineer Auguste Rateau fitted turbochargers to Renault engines powering various French fighters with some success.[9] In 1918, General Electric engineer Sanford Alexander Moss attached a turbo to a V12 *Liberty* aircraft engine. The engine was tested at Pikes Peak in Colorado at 14,000 ft (4,300 m) to demonstrate that it could eliminate the power loss usually experienced in internal combustion engines as a result of reduced air pressure and density at high altitude.[9] General Electric called the system turbosupercharging. At the time, all forced induction devices were known as superchargers, however more recently the term "supercharger" is usually applied to only mechanically-driven forced induction devices. Turbochargers were first used in production aircraft engines such as the Napier Lioness in the 1920s, although they were less common than engine-driven centrifugal superchargers. Ships and locomotives equipped with turbocharged Diesel engines began appearing in the 1920s. Turbochargers were also used in aviation, most widely used by the United States, which led the world in the technology due to General Electric's early start. During World War II, notable examples of US aircraft with turbochargers include the B-17 Flying Fortress, B-24 Liberator, P-38 Lightning, and P-47 Thunderbolt. The technology was also used in experimental fittings by a number of other manufacturers, notably a variety of Focke-Wulf Fw

190 models, but the need for advanced high-temperature metals in the turbine kept them out of widespread use.

1.1.2 Turbocharging versus supercharging

1.1.2.1 Supercharger

A **supercharger** is an air compressor used to increase the pressure, temperature, and density of air supplied to an internal combustion engine. This compressed air supplies a greater mass of oxygen per cycle of the engine to support combustion than available to a naturally aspirated engine, which makes it possible for more fuel to be burned and more work to be done per cycle, which increases the power produced by the engine.

Power for the supercharger can be provided mechanically by a belt, gear, shaft, or chain connected to the engine's crankshaft. When power is provided by a turbine powered by exhaust gas, a supercharger is known as a *turbosupercharger*– typically referred to simply as a *turbocharger* or just *turbo*. Common usage restricts the term *supercharger* to mechanically driven units.

Fig 1.1: An Eaton MP62 Roots-type supercharger is visible at the front of this Ecotec LSJ engine in a 2006 Saturn Ion Red Line.

1.1.2.2 Types of supercharger

There are two main types of superchargers defined according to the method of compression: positive displacement and dynamic compressors. The former deliver a fairly constant level of pressure increase at all engine speeds (RPM), whereas the latter deliver increasing pressure with increasing engine speed.

1.1.2.3 Positive displacement

Positive-displacement pumps deliver a nearly fixed volume of air per revolution at all speeds (minus leakage, which is almost constant at all speeds for a given pressure, thus its importance decreases at higher speeds). The device divides the air mechanically into parcels for delivery to the engine, mechanically moving the air into the engine bit by bit.

Major types of positive-displacement pumps include:

- Roots
- Lysholm twin-screw
- Sliding vane
- Scroll-type supercharger, also known as the G-Lader

1.1.2.4 Compression type

Positive-displacement pumps are further divided into internal compression and external compression types.

Roots superchargers are typically external compression only (although high-helix roots blowers attempt to emulate the internal compression of the Lysholm screw).

- External compression refers to pumps that transfer air at ambient pressure into the engine. If the engine is running under boost conditions, the pressure in the intake manifold is higher than that coming from the supercharger. That causes a backflow from the engine into the supercharger until the two reach equilibrium. It is the backflow that actually compresses the incoming gas. This is a highly inefficient process, and the main factor in the lack of efficiency of Roots superchargers when used at high boost levels. The lower the boost level the smaller is this loss, and Roots blowers are very efficient at moving air at low pressure differentials, which is what they were first invented for (hence the original term "blower").

All the other types have some degree of internal compression.

- Internal compression refers to the compression of air within the supercharger itself, which, already at or close to boost level, can be delivered smoothly to the engine with little or no back flow. This is more effective than back flow compression and allows higher efficiency to be achieved. Internal compression devices usually use a fixed internal compression ratio. When the boost pressure is equal to the compression pressure of the supercharger, the back flow is zero. If the boost pressure exceeds that compression pressure, back flow can still occur as in a roots blower. Internal compression blowers must be matched to the expected boost pressure in order to achieve the higher efficiency they are capable of, otherwise they will suffer the same problems and low efficiency of the roots blowers.

1.1.2.5 Capacity rating

Positive-displacement superchargers are usually rated by their capacity per revolution. In the case of the Roots blower, the GMC rating pattern is typical. The GMC types are rated according to how many two-stroke cylinders, and the size of those cylinders, it is designed to scavenge. GMC has made 2–71, 3–71, 4–71, and the famed 6–71 blowers. For example, a 6–71 blower is designed to scavenge six cylinders of 71 cubic inches (1,163 cc) each and would be used on a two-stroke diesel of 426 cubic inches (6,981 cc), which is designated a 6–71; the blower takes this same designation. However, because 6–71 is actually the *engine's* designation, the actual displacement is less than the simple multiplication would suggest. A 6–71 actually pumps 339 cubic inches (5,555 cc) per revolution.

Aftermarket derivatives continue the trend with 8–71 to current 16–71 blowers used in different motor sports. From this, one can see that a 6–71 is roughly twice the size of a 3–71. GMC also made 53 cubic inches (869 cc) series in 2-, 3-, 4-, 6-, and 8–53 sizes, as well as a “V71” series for use on engines using a V configuration.

1.1.2.6 Dynamic

Dynamic compressors rely on accelerating the air to high speed and then exchanging that velocity for pressure by diffusing or slowing it down.

Major types of dynamic compressor are:

- Centrifugal
- Multi-stage axial-flow
- Pressure wave supercharger

1.1.2.7 Supercharger drive types

Superchargers are further defined according to their method of drive (mechanical—or turbine)

1.1.2.8 Mechanical

- Belt (V-belt, Synchronous belt, Flat belt)
- Direct drive
- Gear drive
- Chain drive

1.1.2.9 Exhaust gas turbines

- Axial turbine
- Radial turbine

Other

- Electric motor
- Auxiliary Power Unit in some large industrial applications.

All types of compressor may be mated to and driven by either gas turbine or mechanical linkage. Dynamic compressors are most often matched with gas turbine drives due to their similar high-speed characteristics, whereas positive displacement pumps usually use one of the mechanical drives. However, all of the possible combinations have been tried with various levels of success. In principle, a positive displacement engine could be used in place of an exhaust turbine to improve low speed performance. Electric superchargers are all essentially fans (axial pumps). A form of regenerative braking has been tried where the car is slowed by compressing air for future acceleration.

1.1.3 Temperature effects and intercoolers

One disadvantage of supercharging is that compressing the air increases its temperature. When a supercharger is used on an internal combustion engine, the temperature of the fuel/air charge becomes a major limiting factor in engine performance. Extreme temperatures will cause detonation of the fuel-air mixture (spark ignition engines) and damage to the engine. In cars, this can cause a problem when it is a hot day outside, or when an excessive level of boost is reached.

It is possible to estimate the temperature rise across a supercharger by modeling it as an isentropic process.

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}$$

Where:

T_1= ambient air temperature

T_2= temperature after the compressor

p_1= ambient atmospheric pressure (absolute)

p_2= pressure after the compressor (absolute)

γ= Ratio of specific heat capacities = C_p/C_v= 1.4 for air

C_p= Specific heat at constant pressure

C_v= Specific heat at constant volume

For example, if a supercharged engine is pushing 10 psi (0.69 bar) of boost at sea level (ambient pressure of 14.7 psi (1.01 bar), ambient temperature of 75 °F (24 °C)), the temperature of the air after the supercharger will be 160.5 °F (71.4 °C). This temperature is known as the compressor discharge temperature (CDT) and highlights why a method for cooling the air after the compressor is so important.

In addition to causing possible detonation and damage, hot intake air decreases power in at least one way. At a given pressure, the hotter the air the lower its density, so the mass of intake air is decreased, reducing the efficiency and boost level of the supercharger.

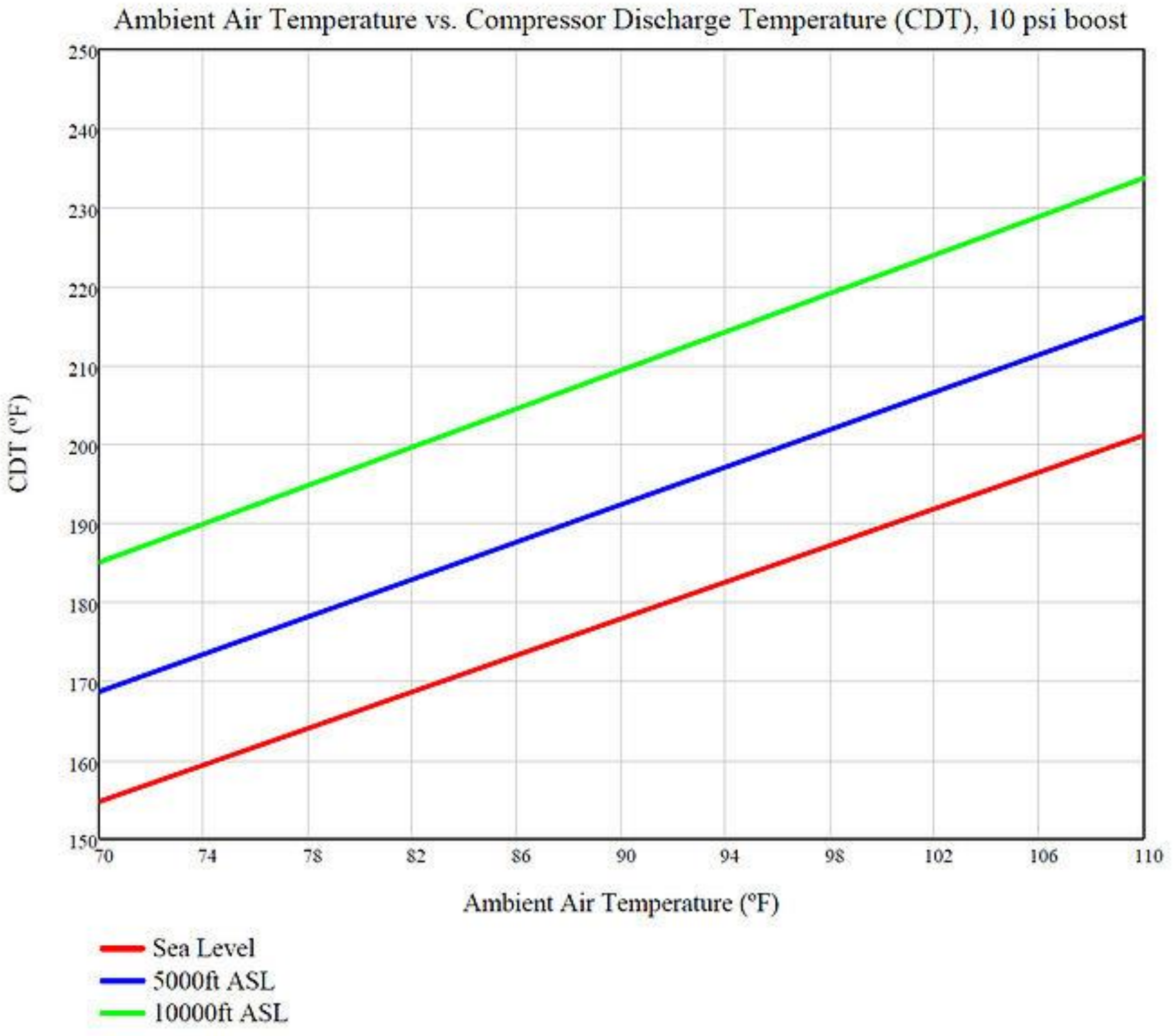


Fig 1.2 : **Supercharger CDT vs. Ambient Temperature**. Graph shows how a supercharger's CDT varies with air temperature and altitude (absolute pressure).

1.1.3.1 Supercharging versus turbocharging

Keeping the air that enters the engine cool is an important part of the design of both superchargers and turbochargers. Compressing air increases its temperature, so it is common to use a small radiator called an intercooler between the pump and the engine to reduce the temperature of the air.

There are three main categories of superchargers for automotive use:

- Centrifugal turbochargers – driven from exhaust gases.
- Centrifugal superchargers – driven directly by the engine via a belt-drive.

- Positive displacement pumps – such as the Roots, Twin Screw (Lysholm), and TVS (Eaton) blowers.

Roots blowers tend to be 40–50% efficient at high boost levels. Centrifugal superchargers are 70–85% efficient. Lysholm-style blowers can be nearly as efficient as their centrifugal counterparts over a narrow range of load/speed/boost, for which the system must be specifically designed.

Positive-displacement superchargers may absorb as much as a third of the total crankshaft power of the engine, and, in many applications, are less efficient than turbochargers. In applications for which engine response and power are more important than any other consideration, such as top-fuel dragsters and vehicles used in tractor pulling competitions, positive-displacement superchargers are very common.

The thermal efficiency, or fraction of the fuel/air energy that is converted to output power, is less with a mechanically driven supercharger than with a turbocharger, because turbochargers are using energy from the exhaust gases that would normally be wasted. For this reason, both the economy and the power of a turbocharged engine are usually better than with superchargers.

Turbochargers suffer (to a greater or lesser extent) from so-called *turbo-spool* (turbo lag; more correctly, boost lag), in which initial acceleration from low RPM is limited by the lack of sufficient exhaust gas mass flow (pressure). Once engine RPM is sufficient to start the turbine spinning, there is a rapid increase in power, as higher turbo boost causes more exhaust gas production, which spins the turbo yet faster, leading to a belated "surge" of acceleration. This makes the maintenance of smoothly increasing RPM far harder with turbochargers than with engine-driven superchargers, which apply boost in direct proportion to the engine RPM. The main advantage of an engine with a mechanically driven supercharger is better throttle response, as well as the ability to reach full-boost pressure instantaneously. With the latest turbocharging technology and direct gasoline injection, throttle response on turbocharged cars is nearly as good as with mechanically powered superchargers, but the existing lag time is still considered a major drawback, especially considering that the vast majority of mechanically driven superchargers are now driven off clutched pulleys, much like an air compressor.

Turbocharging has been more popular than superchargers among auto manufacturers owing to better power and efficiency. For instance Mercedes-Benz and Mercedes-AMG previously had supercharged "Kompressor" offerings in the early 2000s such as the C230K, C32 AMG, and S55 AMG, but they have abandoned that technology in favor of turbocharged engines released around 2010 such as the C250 and S65 AMG biturbo. However, Audi did introduce its 3.0 TFSI supercharged V6 in 2009 for its A6, S4, and Q7, while Jaguar has its supercharged V8 engine available as a performance option in the XJ, XF and XKR.

1.1.3.2 Twincharging

In the 1985 and 1986 World Rally Championships, Lancia ran the Delta S4, which incorporated both a belt-driven supercharger and exhaust-driven turbocharger. The design used a complex series of bypass valves in the induction and exhaust systems as well as an electromagnetic clutch so that, at low engine speeds, boost was derived from the supercharger. In the middle of the rev range, boost was derived from both systems, while at the highest revs the system disconnected drive from the supercharger and isolated the associated ducting.[11] This was done in an attempt to exploit the advantages of each of the charging systems while removing the disadvantages. In turn, this approach brought greater complexity and impacted on the cars reliability in WRC events, as well as increasing the weight of engine ancillaries in the finished design.

The Volkswagen TSI engine (or Twincharger) is a 1.4-litre direct-injection motor that also uses both a supercharger and turbocharger.

Fig 1.3 : A G-Lader scroll-type supercharger on a Volkswagen Golf Mk1.

1.1.3.3 Aircraft

Superchargers are a natural addition to aircraft piston engines that are intended for operation at high altitudes. As an aircraft climbs to higher altitude, air pressure and air density decreases. The output of a piston engine drops because of the reduction in the mass of air that can be drawn into the engine. For example, the air density at 30,000 ft (9,100 m) is ⅓ of that at sea level, thus only ⅓ of the amount of air can be drawn into the cylinder, with enough oxygen to provide efficient combustion for only a third as much fuel. So, at 30,000 ft (9,100 m), only ⅓ of the fuel burnt at sea level can be burnt. (An advantage of the decreased air density is that the airframe experiences only about 1/3 of the aerodynamic drag. Plus, there is decreased back pressure on the exhaust gases. On the other hand, more energy is consumed holding an airplane up with less air in which to generate lift.)

A supercharger can be thought of either as artificially increasing the density of the air by compressing it or as forcing more air than normal into the cylinder every time the piston moves down.

A supercharger compresses the air back to sea-level-equivalent pressures, or even much higher, in order to make the engine produce just as much power at cruise altitude as it does at sea level. With the reduced aerodynamic drag at high altitude and the engine still producing rated power, a supercharged airplane can fly much faster at altitude than a naturally aspirated one. The pilot controls the output of the supercharger with the throttle and indirectly via the propeller governor control. Since the size of the supercharger is chosen to produce a given amount of pressure at high altitude, the supercharger is over-sized for low altitude. The pilot must be careful with the throttle and watch the manifold pressure gauge to avoid overboosting at low altitude. As the aircraft climbs and the air density drops, the pilot must continuously open the throttle in small increments to maintain full power. The altitude at which the throttle reaches full open and the engine is still producing full rated power is known as the *critical altitude*. Above the critical altitude, engine power output will start to drop as the aircraft continues to climb.

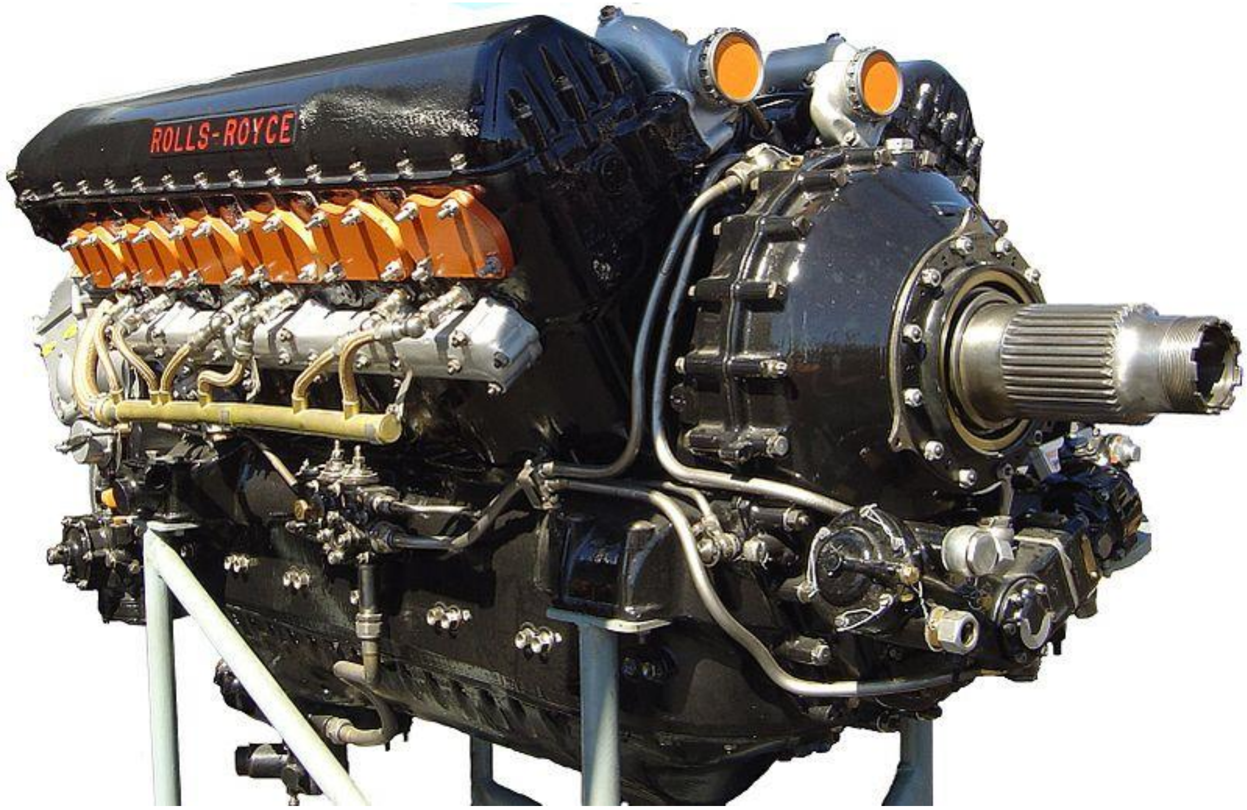


Fig 1.4 : The Rolls-Royce Merlin, a supercharged aircraft engine from World War II

1.1.3.4 Effects of temperature

As discussed above, supercharging can cause a spike in temperature, and extreme temperatures will cause detonation of the fuel-air mixture and damage to the engine. In the case of aircraft, this causes a problem at low altitudes, where the air is both denser and warmer than at high altitudes. With high ambient air temperatures, detonation could start to occur with the manifold pressure gauge reading far below the red line.

A supercharger optimized for high altitudes causes the opposite problem on the intake side of the system. With the throttle retarded to avoid overboosting, air temperature in the carburetor can drop low enough to cause ice to form at the throttle plate. In this manner, enough ice could accumulate to cause engine failure, even with the engine operating at full rated power. For this reason, many supercharged aircraft featured a carburetor air temperature gauge or warning light to alert the pilot of possible icing conditions.

Several solutions to these problems were developed: intercoolers and aftercoolers, anti-detonant injection, two-speed superchargers, and two-stage superchargers.

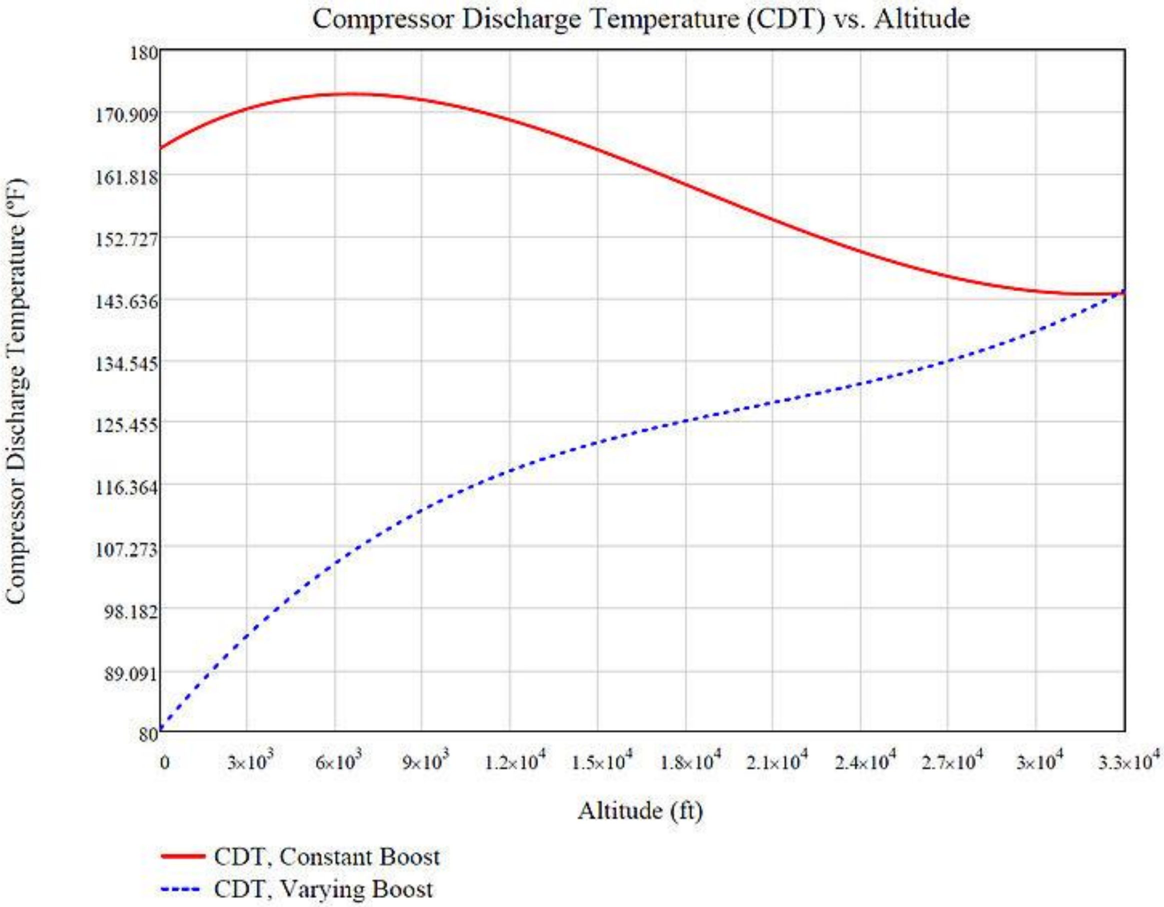


Fig 1. 5: **Supercharger CDT vs. Altitude**. Graph shows the CDT differences between a constant-boost supercharger and a variable-boost supercharger when utilized on an aircraft.

1.1.3.5 Two-stage and two-speed superchargers

In the 1930s, two-speed-drives were developed for superchargers. These provided more flexibility for the operation of the aircraft, although they also entailed more complexity of manufacturing and maintenance. The gears connected the supercharger to the engine using a system of hydraulic clutches, which were manually engaged or disengaged by the pilot with a control in the cockpit. At low altitudes, the low-speed gear would be used in order to keep the manifold temperatures low. At around 12,000 feet (3,700 m), when the throttle was full forward and the manifold pressure started to drop off, the pilot would retard the throttle and switch to the higher gear, then readjust the throttle to the desired manifold pressure.

Another way to accomplish the same level of control was the use of two compressors (also known as stages) in series. After the air was compressed in the *low-pressure stage*, the air flowed through an intercooler radiator where it was cooled before being compressed again by the *high-pressure stage* and then *aftercooled* in another heat exchanger. In these systems, damper doors could be opened or closed by the pilot in order to bypass one stage as needed. Some systems had a cockpit control for opening or closing a damper to the intercooler/aftercooler, providing another way to control temperature. The most complex systems used a two-speed, two-stage system with both an intercooler and an aftercooler, but these were found to be prohibitive in cost and complicated. In the end, it was found that, for most engines, a single-stage two-speed setup was most suitable.

1.1.3.6 Turbocharging

A mechanically-driven supercharger has to take its drive power from the engine. Taking a single-stage single-speed supercharged engine, such as the Rolls-Royce Merlin, for instance, the supercharger uses up about 150 hp (110 kW). Without a supercharger, the engine could produce about 750 horsepower (560 kilowatts), but with a supercharger, it produces about 1,000 hp (750 kW)—an increase of about 400 hp (750 - 150 + 400 = 1000 hp), or a net gain of 250 hp (190 kW). This is where the principal disadvantage of a supercharger becomes apparent. The engine has to burn extra fuel to provide power to drive the supercharger. The increased air density during the input cycle increases the specific power of the engine and its power-to-weight ratio, but at the cost of an increases in the specific fuel consumption of the engine. These factors could increases the cost of running the airplane and reducing its overall range -- **except** that with more engine power, the airplanes could carry more fuel, especially in external drop tanks, especially in the American P-38 Lightning, P-47 Thunderbolt, P-51 Mustang, and F6F Hellcat fighter planes.

For example, with their external fuel tanks and supercharged engines, the P-38 and the P-51 could fly from England to Berlin and back, the P-47 could fly from England to the Ruhr and back, and the F6F had the longest range of any fighter based on aircraft carriers of the war. Also, the P-51 could fly even further - from Iwo Jima to Tokyo and back. These ranges were much longer than those of any Nazi German, British, Japanese, Canadian, or Soviet fighter planes of World War II. These American fighters also had excellent fighting performance at high altitudes.

As opposed to a supercharger driven by the engine itself, a turbocharger is driven using the exhaust gases from the engines. The amount of power in the gas is proportional to the difference between the exhaust pressure and air pressure, and this difference increases with altitude, helping a turbocharged engine to compensate for changing altitude.

The majority of high-altitude aircraft engines used during World War II used mechanically-driven superchargers, because these had three significant manufacturing advantages over turbochargers. Turbochargers - used by large American aircraft engines such as the Allison V-1710 (used in the P-38) and the Pratt & Whitney R-2800, used extra piping, and required expensive high-temperature metal alloys in the gas turbine and preturbine section of the exhaust system, but they were very useful in high-altitude bombers and some fighter planes. The size of the piping alone was a serious problem. For example, both the F4U Corsair and the P-47 Thunderbolt used the same multicylinder radial engine, but the huge barrel-shaped fuselage of the P-47 was needed because of the amount of piping to and from the turbocharger in the back of the engine. The F - 4U used a two stage supercharger with compact intercooler layout.

Turbocharged piston engines are also subject to many of the same operating restrictions as those of gas turbine engines. Turbocharged engines also require frequent inspections of their turbochargers and exhaust systems to search for possible damage caused by the extreme heat and pressure of the turbochargers. Such damage was a prominent problem in the early models of the American B-29 Superfortress high-altitude bombers used in the Pacific Theater of Operations during 1944 - 45.

Turbocharged piston engines continued to be used in a large number of postwar airplanes, such as the F8F Bearcat, the F7F Tigercat, the B-50 Superfortress, the KC-97 Stratotanker, the Boeing Stratoliner, the Lockheed Constellation, and the C-124 Globemaster II.

In more recent times most aircraft engines for general aviation (light airplanes) are naturally aspirated, but the smaller number of modern aviation piston engines designed to run at high altitudes use turbocharger or turbo-normalizer systems, instead of a supercharger driven from the crank shafts. The change in thinking is largely due to economics. Aviation gasoline was once plentiful and cheap, favoring the simple but fuel-hungry supercharger. As the cost of fuel has increased, the ordinary supercharger has fallen out of favor. Also, depending on what monetary inflation factor one uses, fuel costs have not decreased as fast as production and maintenance costs have.

1.1.3.7 Effects of fuel octane rating

Until World War II all automobile and aviation fuel was generally rated at 87 octane or less. This is the rating that was achieved by the simple distillation of "light crude" oil. Engines from around the world were designed to work with this grade of fuel, which set a limit to the amount of boosting that could be provided by the supercharger, while maintaining a reasonable compression ratio.

Octane rating boosting through additives was a line of research being explored at the time. Using these techniques, less valuable crude could still supply large amounts of useful gasoline, which made it a valuable economic process. However, the additives were not limited to making poor-quality oil into 87-octane gasoline; the same additives could also be used to boost the gasoline to much higher octane ratings.

Higher-octane fuel resists auto ignition and detonation better than does low-octane fuel. As a result, the amount of boost supplied by the superchargers could be increased, resulting in an increase in engine output. The development of 100-octane aviation fuel, pioneered in the USA before the war, enabled the use of higher boost pressures to be used on high-performance aviation engines, and was used to develop extremely high-power outputs – for short periods – in several of the pre-war speed record airplanes. Operational use of the new fuel during World War II began in early 1940 when 100-octane fuel was delivered to the British Royal Air Force from refineries in America and the East Indies. The German *Luftwaffe* also had supplies of a similar fuel.

Increasing the knocking limits of existing aviation fuels became a major focus of aero engine development during World War II. By the end of the war, fuel was being delivered at a nominal 150-octane rating, on which late-war aero engines like the Rolls-Royce Merlin 66 or the Daimler-Benz DB 605DC developed as much as 2,000 hp (1,500 kW).

1.2 Operating principle:

In most piston engines, intake gases are "pulled" into the engine by the downward stroke of the piston (which creates a low-pressure area), similar to drawing liquid using a syringe. The amount of air which is actually inhaled, compared with the theoretical amount if the engine could maintain atmospheric pressure, is called volumetric efficiency. The objective of a turbocharger is to improve an engine's volumetric efficiency by increasing density of the intake gas (usually air).

The turbocharger's compressor draws in ambient air and compresses it before it enters into the intake manifold at increased pressure. This results in a greater mass of air entering the cylinders on each intake stroke. The power needed to spin the centrifugal compressor is derived from the kinetic energy of the engine's exhaust gases.

A turbocharger may also be used to increase fuel efficiency without increasing power. This is achieved by recovering waste energy in the exhaust and feeding it back into the engine intake. By using this otherwise wasted energy to increase the mass of air, it becomes easier to ensure that all fuel is burned before being vented at the start of the exhaust stage. The increased temperature from the higher pressure gives a higher Carnot efficiency.

The control of turbochargers is very complex and has changed dramatically over the 100-plus years of its use. Modern turbochargers can use wastegates, blow-off valves and variable geometry, as discussed in later sections.

The reduced density of intake air is often compounded by the loss of atmospheric density seen with elevated altitudes. Thus, a natural use of the turbocharger is with aircraft engines. As an aircraft climbs to higher altitudes, the pressure of the surrounding air quickly falls off. At 5,486 metres (17,999 ft), the air is at half the pressure of sea level, which means that the engine will produce less than half-power at this altitude.

1.2 Pressure increase / boost:

In automotive applications, "boost" refers to the amount by which intake manifold pressure exceeds atmospheric pressure. This is representative of the extra air pressure that is achieved over what would be achieved without the forced induction. The level of boost may be shown on a pressure gauge, usually in bar, psi or possibly kPa.

In aircraft engines, turbocharging is commonly used to maintain manifold pressure as altitude increases (i.e. to compensate for lower-density air at higher altitudes). Since atmospheric pressure reduces as the aircraft climbs, power drops as a function of altitude in normally aspirated engines. Systems that use a turbocharger to maintain an engine's sea-level power output are called turbo-normalized systems. Generally, a turbo-normalized system will attempt to maintain a manifold pressure of 29.5 inches of mercury (100 kPa).

In all turbocharger applications, boost pressure is limited to keep the entire engine system, including the turbo, inside its thermal and mechanical design operating range. Over-boosting an engine frequently causes damage to the engine in a variety of ways including pre-ignition, overheating, and over-stressing the engine's internal hardware.

For example, to avoid engine knocking (aka detonation) and the related physical damage to the engine, the intake manifold pressure must not get too high, thus the pressure at the intake manifold of the engine must be controlled by some means. Opening the wastegate allows the excess energy destined for the turbine to bypass it and pass directly to the exhaust pipe, thus reducing boost pressure. The wastegate can be either controlled manually (frequently seen in aircraft) or by an actuator (in automotive applications, it is often controlled by the Engine Control Unit).

1.3 Turbo lag:

Turbocharger applications can be categorized according to those which require changes in output power (such as automotive) and those which do not (such as marine, aircraft, commercial automotive, industrial, locomotives). While important to varying degrees, turbo lag is most problematic when rapid changes in power output are required.

Turbo lag is the time required to change power output in response to a throttle change, noticed as a hesitation or slowed throttle response when accelerating from idle as compared to a naturally aspirated engine. This is due to the time needed for the exhaust system and turbocharger to generate the required boost. Inertia, friction, and compressor load are the primary contributors to turbo lag. Superchargers do not suffer this problem, because the turbine is eliminated due to the compressor being directly powered by the engine.

Lag can be reduced in a number of ways:

- lowering the rotational inertia of the turbocharger; for example by using lighter, lower radius parts to allow the spool-up to happen more quickly. Ceramic turbines are of benefit in this regard and or billet compressor wheel.
- changing the aspect ratio of the turbine.
- increasing the upper-deck air pressure (compressor discharge) and improving the wastegate response
- reducing bearing frictional losses (such as by using a foil bearing rather than a conventional oil bearing)
- using variable-nozzle or twin-scroll turbochargers (discussed below).
- decreasing the volume of the upper-deck piping.
- using multiple turbos sequentially or in parallel.
- using an Antilag system.

1.4 Boost threshold:

Lag is not to be confused with the boost threshold. The boost threshold of a turbo system describes the lower bound of the region within which the compressor will operate. Below a certain rate of flow, a compressor will not produce significant boost. This has the effect of limiting boost at particular rpm regardless of exhaust gas pressure. Newer turbocharger and engine developments have caused boost thresholds to steadily decline.

Electrical boosting ("E-boosting") is a new technology under development; it uses an electric motor to bring the turbo up to operating speed quicker than is possible using available exhaust gases. An alternative to e-boosting is to completely separate the turbine and compressor into a turbine-generator and electric-compressor as in the hybrid turbocharger. This allows the compressor speed to become independent to that of the turbine. A similar system utilising a hydraulic drive system and overspeed clutch arrangement was fitted in 1981 to accelerate the turbocharger of the MV *Canadian Pioneer* (Doxford 76J4CR engine).

Turbochargers start producing boost only when a certain amount of kinetic energy is present in the exhaust gasses. Without adequate exhaust gas flow to spin the turbine blades, the turbo cannot produce the necessary force needed to compress the air going into the engine. The boost threshold is determined by the engine displacement, engine rpm, throttle opening, and the size of the turbo. The operating speed (rpm) at which there is enough exhaust gas momentum to compress the air going into the engine is called the "boost threshold rpm". Reducing the "boost threshold rpm" can improve throttle response.

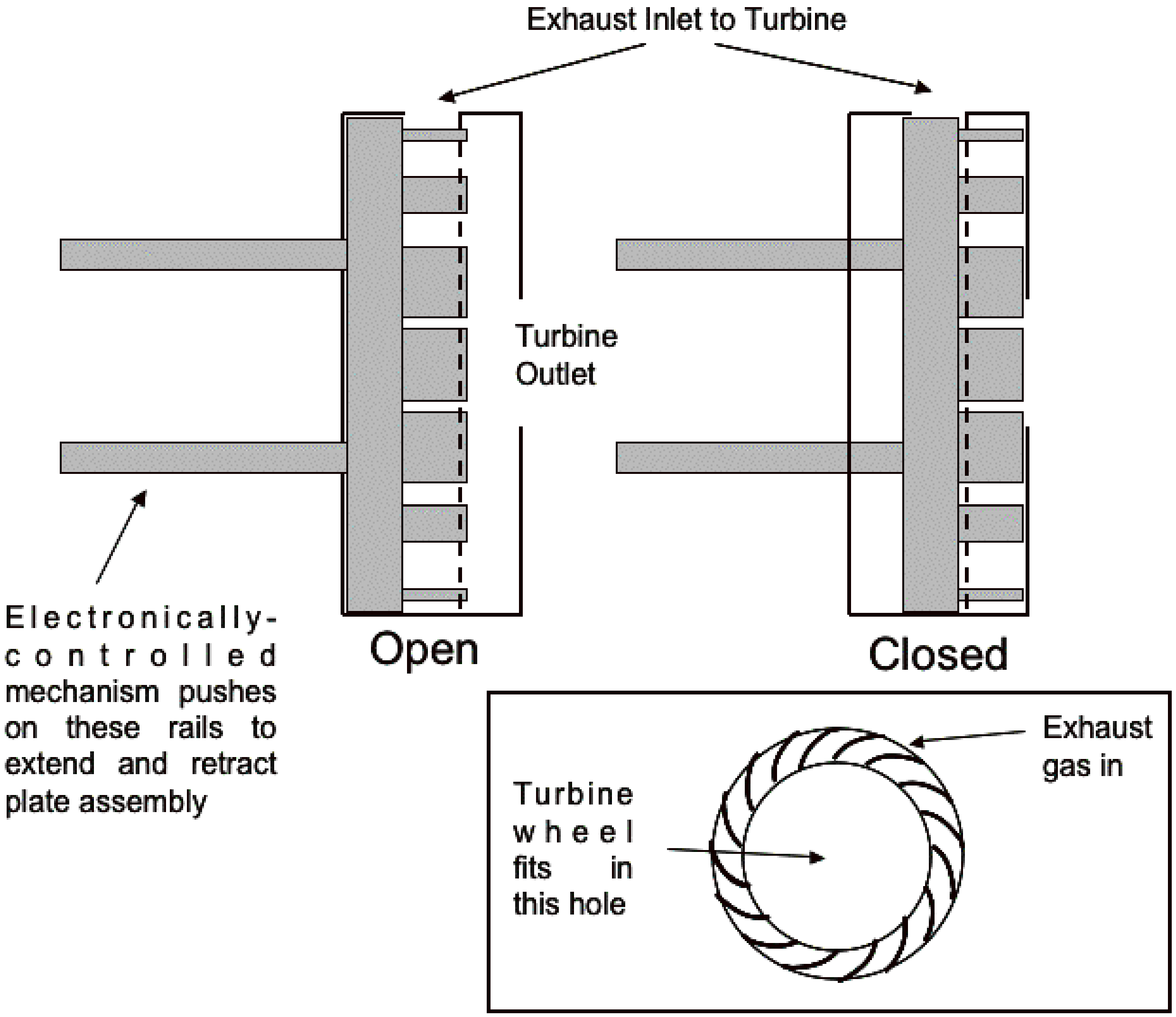


Fig 1.6: Operating principle

Chapter 2:

Key Components of a Turbocharger

2.1 Introduction:

The turbocharger has three main components:

1. the turbine, which is almost always a radial inflow turbine
2. the compressor, which is almost always a centrifugal compressor
3. the center housing/hub rotating assembly

Many turbocharger installations use additional technologies, such as wastegates, intercooling and blow-off valves.

2.1.1 Turbine:

Energy provided for the turbine work is converted from the enthalpy and kinetic energy of the gas. The turbine housings direct the gas flow through the turbine as it spins at up to 250,000 rpm. The size and shape can dictate some performance characteristics of the overall turbocharger. Often the same basic turbocharger assembly will be available from the manufacturer with multiple housing choices for the turbine and sometimes the compressor cover as well. This allows the balance between performance, response, and efficiency to be tailored to the application.

The turbine and impeller wheel sizes also dictate the amount of air or exhaust that can be flowed through the system, and the relative efficiency at which they operate. In general, the larger the turbine wheel and compressor wheel the larger the flow capacity. Measurements and shapes can vary, as well as curvature and number of blades on the wheels.

A turbocharger's performance is closely tied to its size. Large turbochargers take more heat and pressure to spin the turbine, creating turbo lag at low RPMs. Small turbochargers spin quickly, but may not have the same performance at high acceleration. To efficiently combine the benefits of large and small wheels, advanced schemes are used such as twin-turbochargers, twin-scroll turbochargers, or variable-geometry turbochargers.

2.1.1.2 Design and Function of a Turbocharger Turbine:

✓ Design and function

The turbocharger turbine, which consists of a turbine wheel and a turbine housing, converts the engine exhaust gas into mechanical energy to drive the compressor.
The gas, which is restricted by the turbine's flow cross-sectional area, results in a pressure and temperature drop between the inlet and outlet. This pressure drop is converted by the turbine into kinetic energy to drive the turbine wheel.

There are two main turbine types: axial and radial flow. In the axial-flow type, flow through the wheel is only in the axial direction. In radial-flow turbines, gas inflow is centripetal, i.e. in a radial direction from the outside in, and gas outflow in an axial direction.

Up to a wheel diameter of about 160 mm, only radial-flow turbines are used. This corresponds to an engine power of approximately 1000 kW per turbocharger. From 300 mm onwards, only axial-flow turbines are used. Between these two values, both variants are possible.

As the radial-flow turbine is the most popular type for automotive applications, the following description is limited to the design and function of this turbine type.
In the volute of such radial or centripetal turbines, exhaust gas pressure is converted into kinetic energy and the exhaust gas at the wheel circumference is directed at constant velocity to the turbine wheel. Energy transfer from kinetic energy into shaft power takes place in the turbine wheel, which is designed so that nearly all the kinetic energy is converted by the time the gas reaches the wheel outlet.

✓ Operating characteristics

- ✓ The turbine performance increases as the pressure drop between the inlet and outlet increases, i.e. when more exhaust gas is dammed upstream of the turbine as a result of a higher engine speed, or in the case of an exhaust gas temperature rise due to higher exhaust gas energy.
- ✓ The turbine's characteristic behaviour is determined by the specific flow cross-section, the throat cross-section, in the transition area of the inlet channel to the volute. By reducing this throat cross-section, more exhaust gas is dammed upstream of the turbine

and the turbine performance increases as a result of the higher pressure ratio. A smaller flow cross-section therefore results in higher boost pressures. The turbine's flow cross-sectional area can be easily varied by changing the turbine housing.

- ✓ Besides the turbine housing flow cross-sectional area, the exit area at the wheel inlet also influences the turbine's mass flow capacity. The machining of a turbine wheel cast contour allows the cross-sectional area and, therefore, the boost pressure, to be adjusted. A contour enlargement results in a larger flow cross-sectional area of the turbine.
- ✓ Turbines with variable turbine geometry change the flow cross-section between volute channel and wheel inlet. The exit area to the turbine wheel is changed by variable guide vanes or a variable sliding ring covering a part of the cross-section.
- ✓ In practice, the operating characteristics of exhaust gas turbocharger turbines are described by maps showing the flow parameters plotted against the turbine pressure ratio. The turbine map shows the mass flow curves and the turbine efficiency for various speeds. To simplify the map, the mass flow curves, as well as the efficiency, can be shown by a mean curve
- ✓ For a high overall turbocharger efficiency, the co-ordination of compressor and turbine wheel diameters is of vital importance. The position of the operating point on the compressor map determines the turbocharger speed. The turbine wheel diameter has to be such that the turbine efficiency is maximised in this operating range.

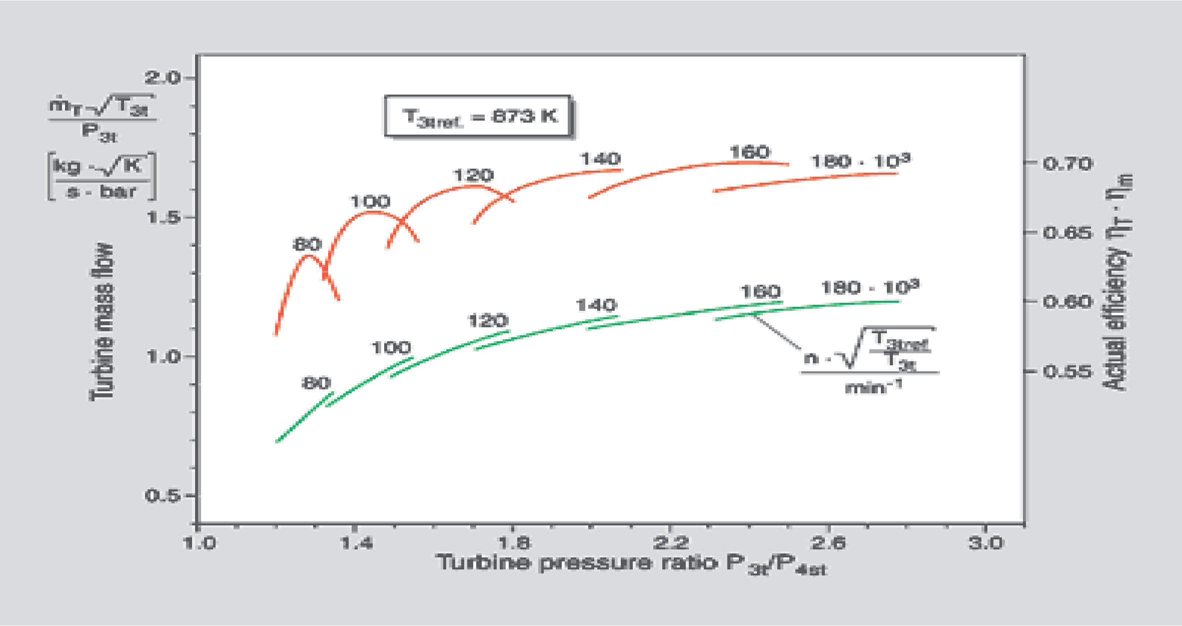


Fig 2.a Turbocharger turbine map

The turbine is rarely subjected to constant exhaust pressure. In pulse turbocharged commercial diesel engines, twin-entry turbines allow exhaust gas pulsations to be optimised, because a higher turbine pressure ratio is reached in a shorter time. Thus, through the increasing pressure ratio, the efficiency rises, improving the all-important time interval when a high, more efficient mass flow is passing through the turbine. As a result of this improved exhaust gas energy utilisation, the engine's boost pressure characteristics and, hence, torque behaviour is improved, particularly at low engine speeds.

To prevent the various cylinders from interfering with each other during the charge exchange cycles, three cylinders are connected into one exhaust gas manifold. Twin-entry turbines then allow the exhaust gas flow to be fed

Fig 2.b: Turbocharger with twin-entry turbine

✓ Water-cooled turbine housings

Safety aspects also have to be taken into account in turbocharger design. In ship engine rooms, for instance, hot surfaces have to be avoided because of fire risks. Therefore, water-cooled turbocharger turbine housings or housings coated with insulating material are used for marine applications.

Fig 2 .C: Turbocharger with water-cooled turbine housing for marine applications

2.1.2 Twin-turbo:

Twin-turbo or **bi-turbo** designs have two separate turbochargers operating in either a sequence or in parallel. In a parallel configuration, both turbochargers are fed one-half of the engine’s exhaust. In a sequential setup one turbocharger runs at low speeds and the second turns on at a predetermined engine speed or load. Sequential turbochargers further reduce turbo lag, but require an intricate set of pipes to properly feed both turbochargers.

Two-stage variable twin-turbos employ a small turbocharger at low speeds and a large one at higher speeds. They are connected in a series so that boost pressure from one turbo is multiplied by another, hence the name "2-stage." The distribution of exhaust gas is continuously variable, so the transition from using the small turbo to the large one can be done incrementally. Twin turbochargers are primarily used in diesel engines. For example, in Opel bi-turbo diesel, only the smaller turbocharger is active at low rpm, providing high torque at 1500-1700 rpm; both turbochargers operate together in mid range, with the larger one pre-compressing the air which is further compressed by the smaller, with bypass valve regulating the exhaust flow to each turbocharger; and at high 2500-3000 rpm, only the larger turbocharges is active, providing maximum performance.

Smaller turbochargers have less turbo lag than larger ones, so often two small turbochargers are used instead of one large one. This configuration is popular in engines over 2,500 CCs and in V-shape or boxer engines.

2.1.3 Twin-scroll:

Twin-scroll or **divided** turbochargers have two exhaust gas inlets and two nozzles, a smaller sharper angled one for quick response and a larger less angled one for peak performance.

With high-performance camshaft timing, the exhaust valves in different cylinders can be opened at the same time, overlapping at the end of the power stroke in one cylinder and the end of exhaust stroke in another. In twin-scroll designs, the exhaust manifold physically separates the channels for cylinders which can interfere with each other, so that the pulsating exhaust gasses flow through separate spirals (scrolls). This allows the engine to efficiently utilise exhaust scavenging techniques, which decreases exhaust gas temperatures and NOx emissions and improves turbine efficiency, reducing turbo lag

Fig 2.1 Cut-out of a twin-scroll turbocharger, with two differently angled nozzles.

Fig 2.2 Cut-out of a twin-scroll exhaust and turbine; the dual "scrolls" pairing cylinders 1-4 and 2-3 are clearly visible.

2.1.4 Variable-geometry:

Variable-geometry or **variable-nozzle** turbochargers use nine moveable vanes to adjust the air-flow to the turbine, imitating a turbocharger of the optimal size throughout the power curve. The vanes are placed just in front of the turbine like a set of slightly overlapping walls. Their angle is adjusted by an actuator to block or increase air flow to the turbine. This variability maintains a comparable exhaust velocity and back pressure throughout the engine's RPMs. The result is that the turbocharger improves fuel efficiency without a noticeable level of turbo lag.

Fig 2.3 Garrett variable-geometry turbocharger on DV6TED4 engine.

2.1.5 Center housing/hub rotating assembly:

The center hub rotating assembly (CHRA) houses the shaft that connects the compressor impeller and turbine. It also must contain a bearing system to suspend the shaft, allowing it to rotate at very high speed with minimal friction. For instance, in automotive applications the CHRA typically uses a thrust bearing or ball bearing lubricated by a constant supply of pressurized engine oil. The CHRA may also be considered "water-cooled" by having an entry and exit point for engine coolant to be cycled. Water-cooled models allow engine coolant to be used to keep the lubricating oil cooler, avoiding possible oil coking (the destructive distillation of the engine oil) from the extreme heat found in the turbine. The development of air-foil bearings has removed this risk.

Ball bearings designed to support high speeds and temperatures are sometimes used instead of fluid bearings to support the turbine shaft. This helps the turbocharger accelerate more quickly and reduces turbo lag.[34] Some variable nozzle turbochargers use a rotary electric actuator, which uses a direct stepper motor to open and close the vanes, rather than pneumatic controllers that operate based on air pressure.

2.2.1 Compressor:

The compressor increases the mass of intake air entering the combustion chamber. The compressor is made up of an impeller, a diffuser and a volute housing.The operating range of a compressor is described by the "compressor map".

Ported shroud The flow range of a turbocharger compressor can be increased by allowing air to bleed from a ring of holes or a circular groove around the compressor at a point slightly downstream of the compressor inlet (but far nearer to the inlet than to the outlet).

The ported shroud is a performance enhancement that allows the compressor to operate at significantly lower flows. It achieves this by forcing a simulation of impeller stall to occur continuously. Allowing some air to escape at this location inhibits the onset of surge and widens the operating range. While peak efficiencies may decrease, high efficiency may be achieved over a greater range of engine speeds. Increases in compressor efficiency result in slightly cooler (more dense) intake air, which improves power. This is a passive structure that is constantly open (in contrast to compressor exhaust blow off valves, which are mechanically or electronically controlled). The ability of the compressor to provide high boost at low rpm may also be increased marginally (because near choke conditions the compressor draws air inward through the bleed path). Ported shrouds are used by many turbocharger manufacturers

2.2.1.1 Centrifugal compressors:

Centrifugal compressors, sometimes termed **radial compressors**, are a sub-class of dynamic axisymmetric work-absorbing turbomachinery.

The idealized compressive dynamic turbo-machine achieves a pressure rise by adding kinetic energy/velocity to a continuous flow of fluid through the rotor or impeller. This kinetic energy is then converted to an increase in potential energy/static pressure by slowing the flow through a diffuser. The pressure rise in impeller is in most cases almost equal to the rise in the diffuser section.

Fig 2.4 **Centrifugal** Compressor.

Centrifugal compressors are similar to axial compressors in that they are rotating airfoil based compressors as shown in the adjacent figure. It should not be surprising that the first part of the centrifugal impeller looks very similar to an axial compressor. This first part of the centrifugal impeller is also termed an *inducer*. Centrifugal compressors differ from axials as they use a greater change in radius from inlet to exit of the rotor/impeller.

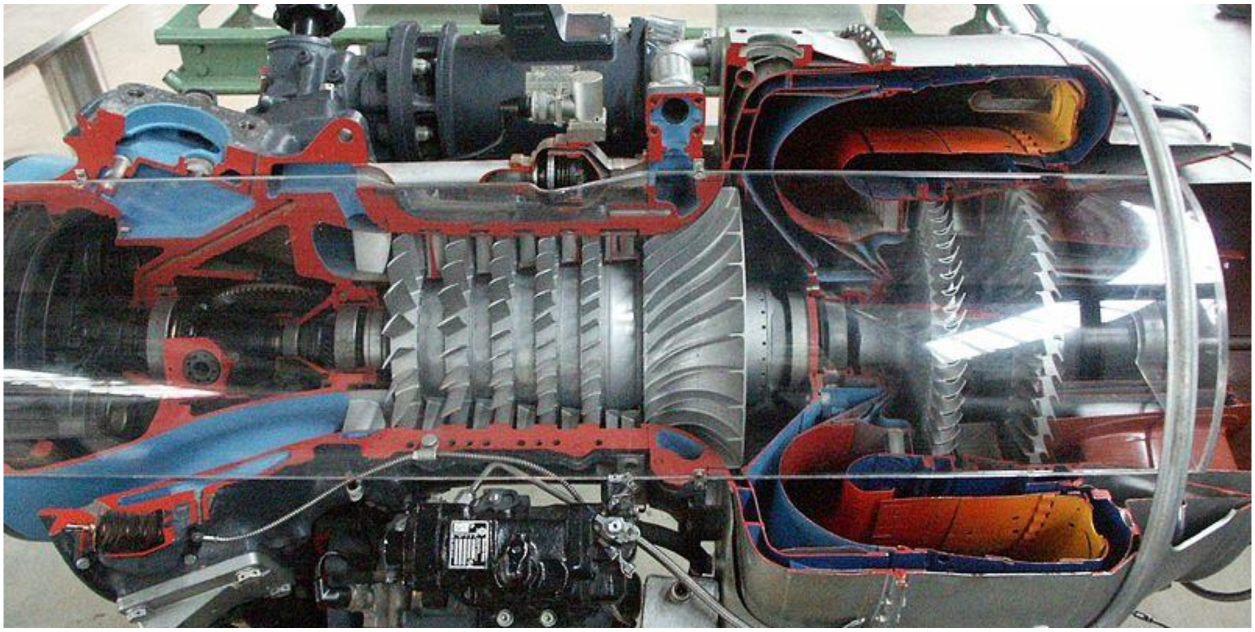


Fig 2.5 Cutaway showing an axi-centrifugal compressor gas turbine.

Centrifugal compressors are also similar to centrifugal fans of the style shown in neighboring figure as they both increase the flows energy through increasing radius. In contrast to centrifugal fans, compressors operate at higher speeds to generate greater pressure rises. In many cases the engineering methods used to design a centrifugal fan is the same as those to design a centrifugal compressor. As a result they can at times look very similar.This relationship is less true in comparison to a squirrel-cage fans as shown in figure farthest right.

For purposes of generalization and definition, it can be said that centrifugal compressors often have density increases greater than 5 percent. Also, they often experience relative fluid velocities above Mach number 0.3when the working fluid is air or nitrogen. In contrast, fans or blowers are often considered to have density increases of less than five percent and peak relative fluid velocities below Mach 0.3.

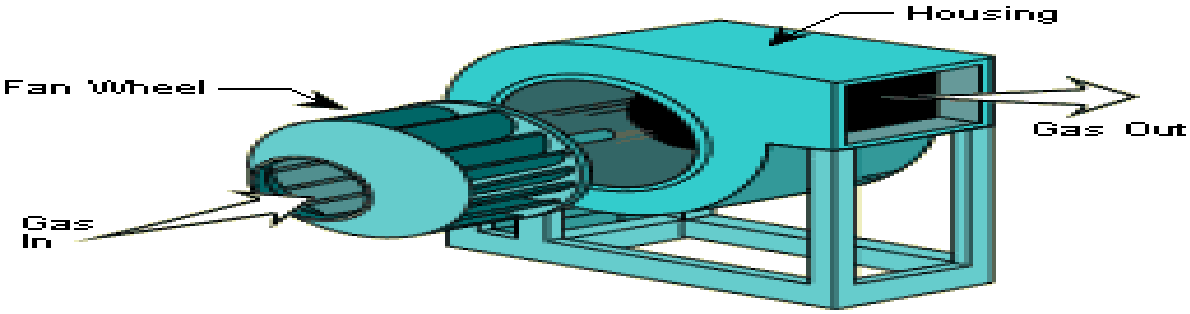


Fig 2.6 A squirrel-cage fan, without a discharge diffuser

Centrifugal compressors are also similar to centrifugal pumps[1] of the style shown in the adjacent figures. The key difference between such compressors and pumps is that the compressor working fluid is a gas (compressible) and the pump working fluid is liquid (incompressible). Again, the engineering methods used to design a centrifugal pump are the same as those to design a centrifugal compressor. Yet, there is one important difference: the need to deal with cavitation in pumps.

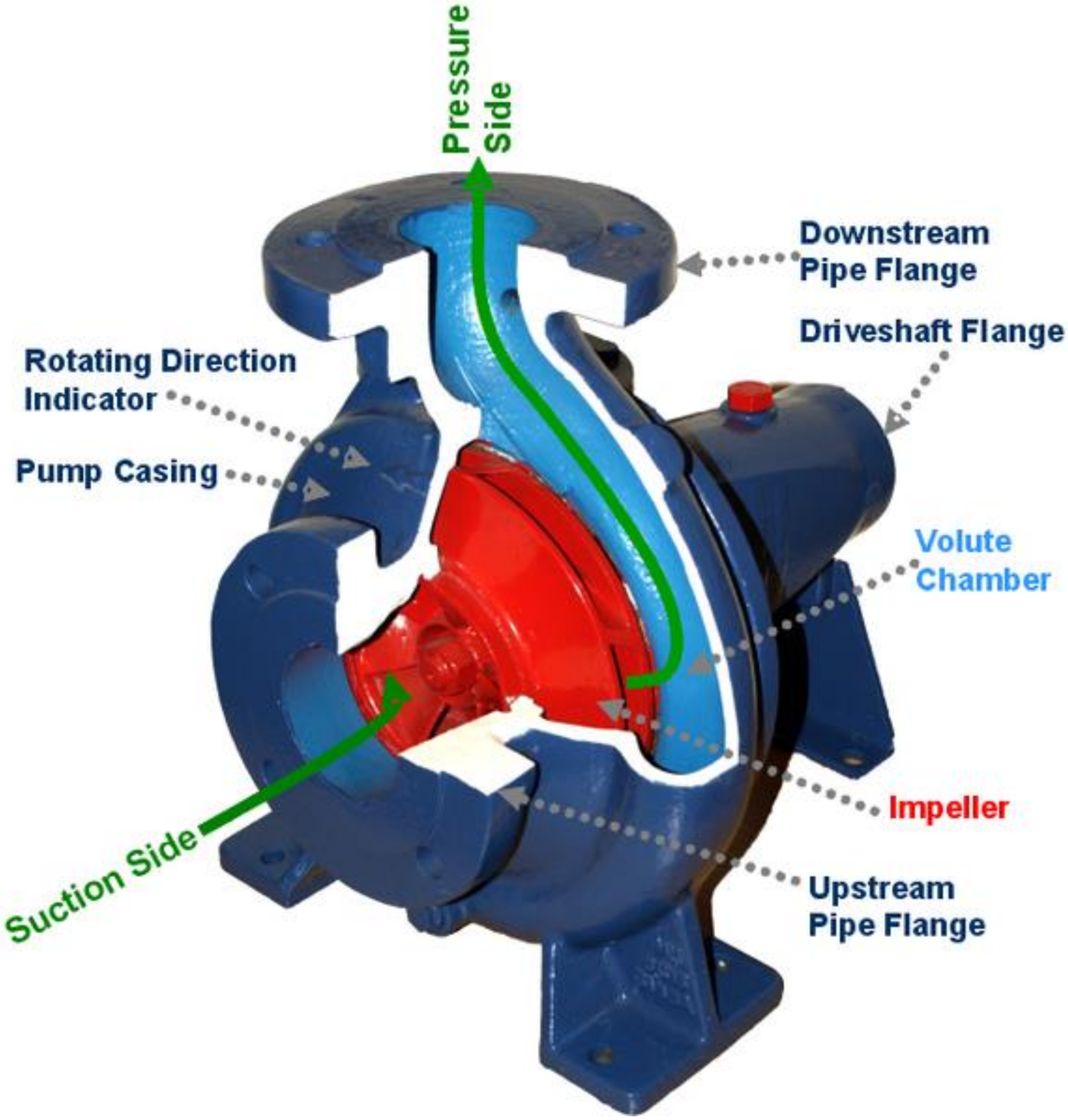


Fig 2.7 Cut-away of a centrifugal pump

2.2.2 Components of a simple centrifugal compressor:

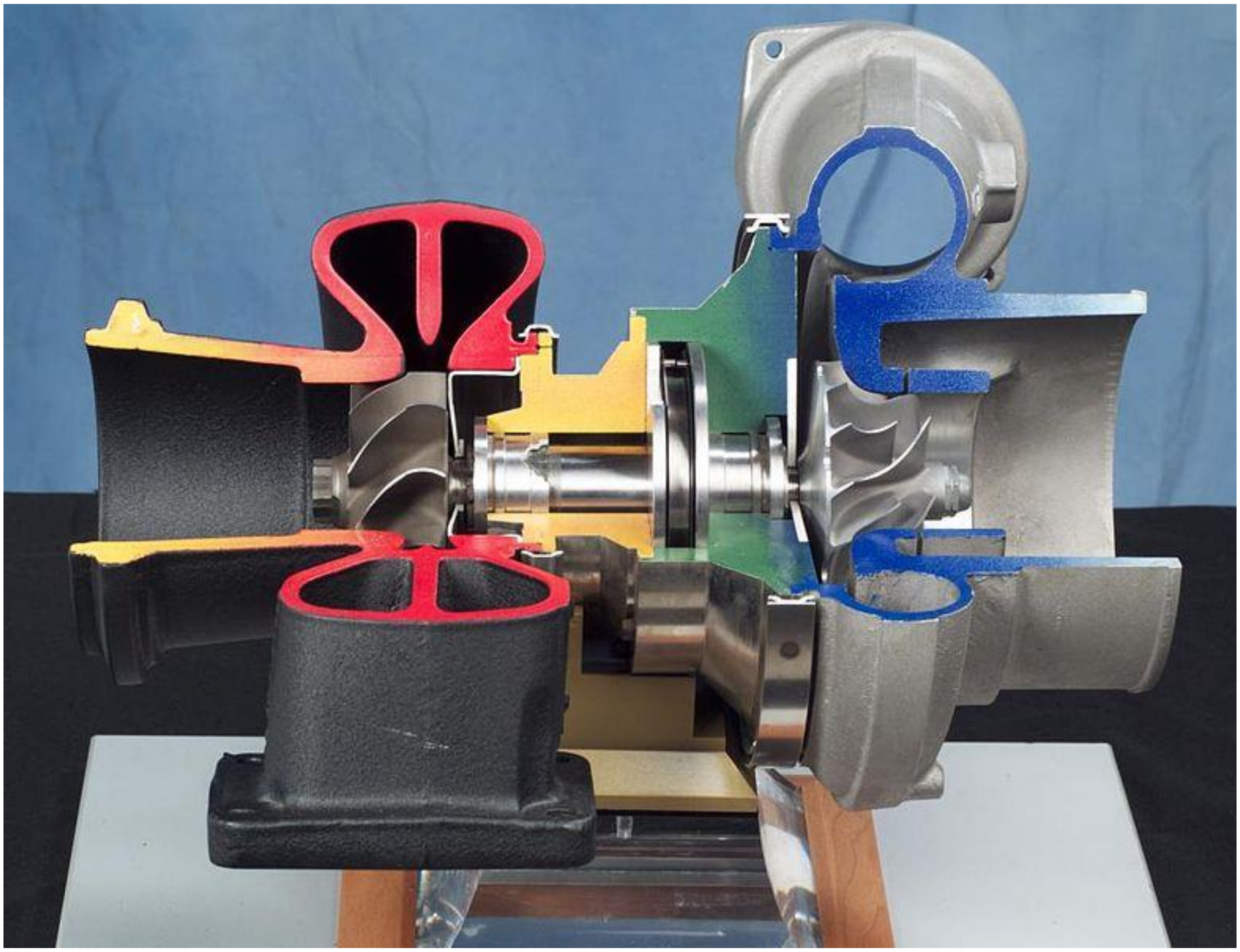


Fig 2.8 Cut-away view of a turbo-charger showing the centrifugal compressor (blue) on the right end of the rotor.

2.2.2.1 Inlet:

The inlet to a centrifugal compressor is typically a simple pipe. It may include features such as a valve, stationary vanes/airfoils (used to help swirl the flow) and both pressure and temperature instrumentation. All of these additional devices have important uses in the control of the centrifugal compressor.

2.2.2.2 Centrifugal impeller:

The key component that makes a compressor centrifugal is the centrifugal impeller, Figure 01. It is the impeller's rotating set of vanes (or blades) that gradually raises the energy of the working gas. This is identical to an axial compressor with the exception that the gases can reach higher velocities and energy levels through the impeller's increasing radius. In many modern high-efficiency centrifugal compressors the gas exiting the impeller is traveling near the speed of sound.

Impellers are designed in many configurations including "open" (visible blades), "covered or shrouded", "with splitters" (every other inducer removed) and "w/o splitters" (all full blades). Both Figures 0.1 and 3.1 show open impellers with splitters. Most modern high efficiency impellers use "backsweep" in the blade shape.

Euler’s pump and turbine equation plays an important role in understanding impeller performance.

2.2.2.3 Diffuser:

The next key component to the simple centrifugal compressor is the diffuser. Downstream of the impeller in the flow path, it is the diffuser's responsibility to convert the kinetic energy (high velocity) of the gas into pressure by gradually slowing (diffusing) the gas velocity. Diffusers can be vaneless, vaned or an alternating combination. High efficiency vaned diffusers are also designed over a wide range of solidities from less than 1 to over 4. Hybrid versions of vaned diffusers include: wedge, channel, and pipe diffusers. There are turbocharger applications that benefit by incorporating no diffuser. Bernoulli's fluid dynamic principle plays an important role in understanding diffuser performance.

2.2.2.4 Collector:

The collector of a centrifugal compressor can take many shapes and forms. When the diffuser discharges into a large empty chamber, the collector may be termed a *Plenum*. When the diffuser discharges into a device that looks somewhat like a snail shell, bull's horn or a French horn, the collector is likely to be termed a *volute* or *scroll*. As the name implies, a collector’s purpose is to gather the flow from the diffuser discharge annulus and deliver this flow to a downstream pipe. Either the collector or the pipe may also contain valves and instrumentation to control the compressor.

2.2.3 Applications:

Below, is a partial list of centrifugal compressor applications each with a brief description of some of the general characteristics possessed by those compressors. To start this list two of the most well-known centrifugal compressor applications are listed; gas turbines and turbochargers

- In gas turbines and auxiliary power units.

In their simple form, modern gas turbines operate on the Brayton cycle. (ref Figure 5.1) Either or both axial and centrifugal compressors are used to provide compression. The types of gas turbines that most often include centrifugal compressors include turboshaft, turboprop, auxiliary power units, and micro-turbines. The industry standards applied to all of the centrifugal compressors used in aircraft applications are set by the FAA and the military to maximize both safety and durability under severe conditions. Centrifugal impellers used in gas turbines are commonly made from titanium alloy forgings. Their flow-path blades are commonly flank milled or point milled on 5-axis milling machines. When tolerances and clearances are the tightest, these designs are completed as hot operational geometry and deflected back into the cold geometry as required for manufacturing. This need arises from the impeller's deflections experienced from start-up to full speed/full temperature which can be 100 times larger than the expected hot running clearance of the impeller.

- In automotive engine and diesel engine turbochargers and superchargers.[20] Ref. Figure 1.1

  Centrifugal compressors used in conjunction with reciprocating internal combustion engines are known as turbochargers if driven by the engine’s exhaust gas and turbo-superchargers if mechanically driven by the engine. Standards set by the industry for turbochargers may have been established by SAE.[21] Ideal gas properties often work well for the design, test and analysis of turbocharger centrifugal compressor performance.

- In pipeline compressors of natural gas to move the gas from the production site to the consumer.[22]

  Centrifugal compressors for such uses may be one- or multi-stage and driven by large gas turbines. Standards set by the industry (ANSI/API, ASME) result in large thick casings to maximize safety. The impellers are often if not always of the covered style which makes them look much like pump impellers. This type of compressor is also often termed an *API-style*. The power needed to drive these compressors is most often in the thousands of horsepower (HP). Use of real gas properties is needed to properly design, test and analyze the performance of natural gas pipeline centrifugal compressors.

- In oil refineries, natural gas processing, petrochemical and chemical plants.[22]

  Centrifugal compressors for such uses are often one-shaft multi-stage and driven by large steam or gas turbines. Their casings are often termed *horizontally split* or *barrel*. Standards set by the industry (ANSI/API, ASME) for these compressors result in large thick casings to maximize safety. The impellers are often if not always of the covered style which makes them look much like pump impellers. This type of compressor is also often termed *API-style*. The power needed to drive these compressors is most often in the thousands of HP. Use of real gas properties is needed to properly design, test and analyze their performance.

- Air-conditioning and refrigeration and HVAC: Centrifugal compressors quite often supply the compression in water chillers cycles.[23]

  Because of the wide variety of vapor compression cycles (thermodynamic cycle, thermodynamics) and the wide variety of workings gases (refrigerants), centrifugal compressors are used in a wide range of sizes and configurations. Use of real gas properties is needed to properly design, test and analyze the performance of these machines. Standards set by the industry for these compressors include ASHRAE, ASME & API.

- In industry and manufacturing to supply compressed air for all types of pneumatic tools.[24]

  Centrifugal compressors for such uses are often multistage and driven by electric motors. Inter-cooling is often needed between stages to control air temperature. Note that the road repair crew and the local automobile repair garage find screw compressors better adapt to their needs. Standards set by the industry for these compressors include ASME and government regulations that emphasize safety. Ideal gas relationships are often used to properly design, test and analyze the performance of these machines. Carrier's equation is often used to deal with humidity.

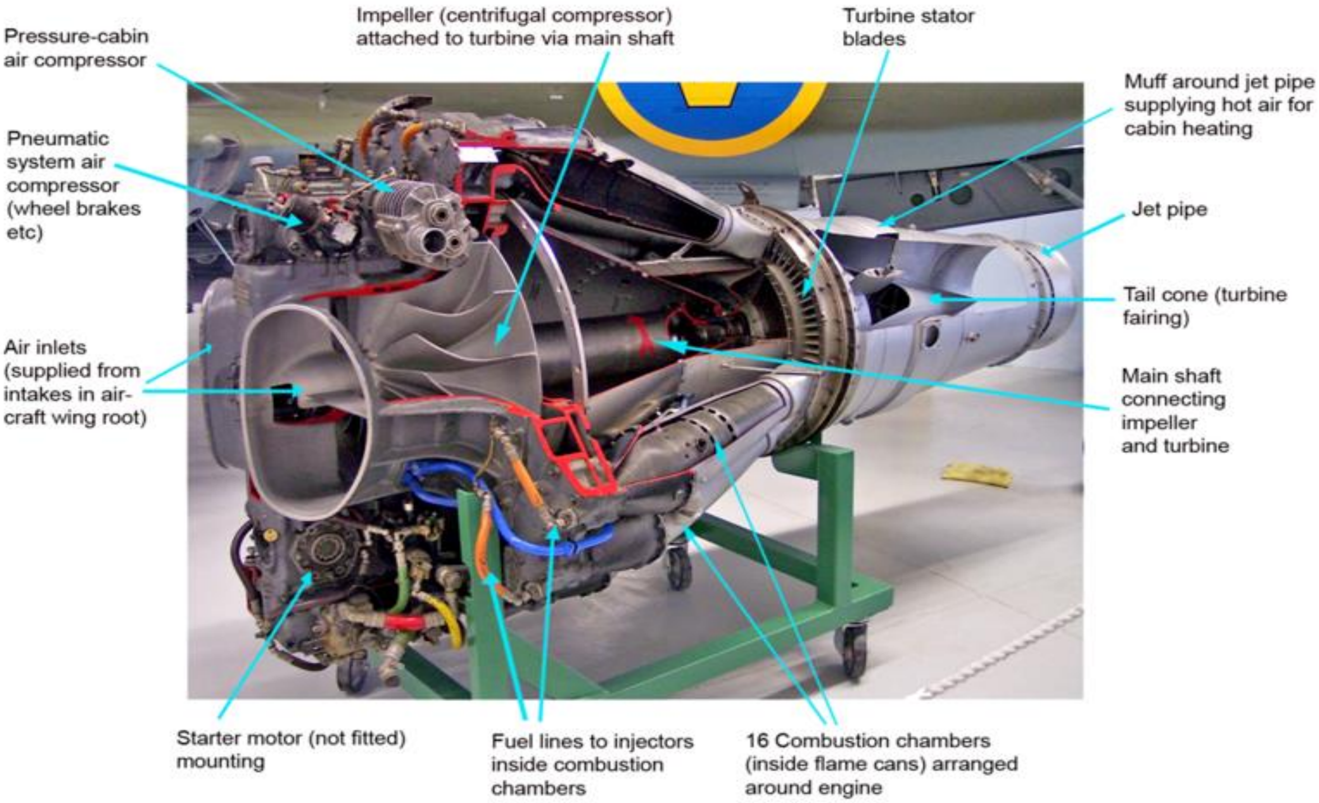


Fig 2.9 Jet engine cutaway showing the centrifugal compressor and other parts.

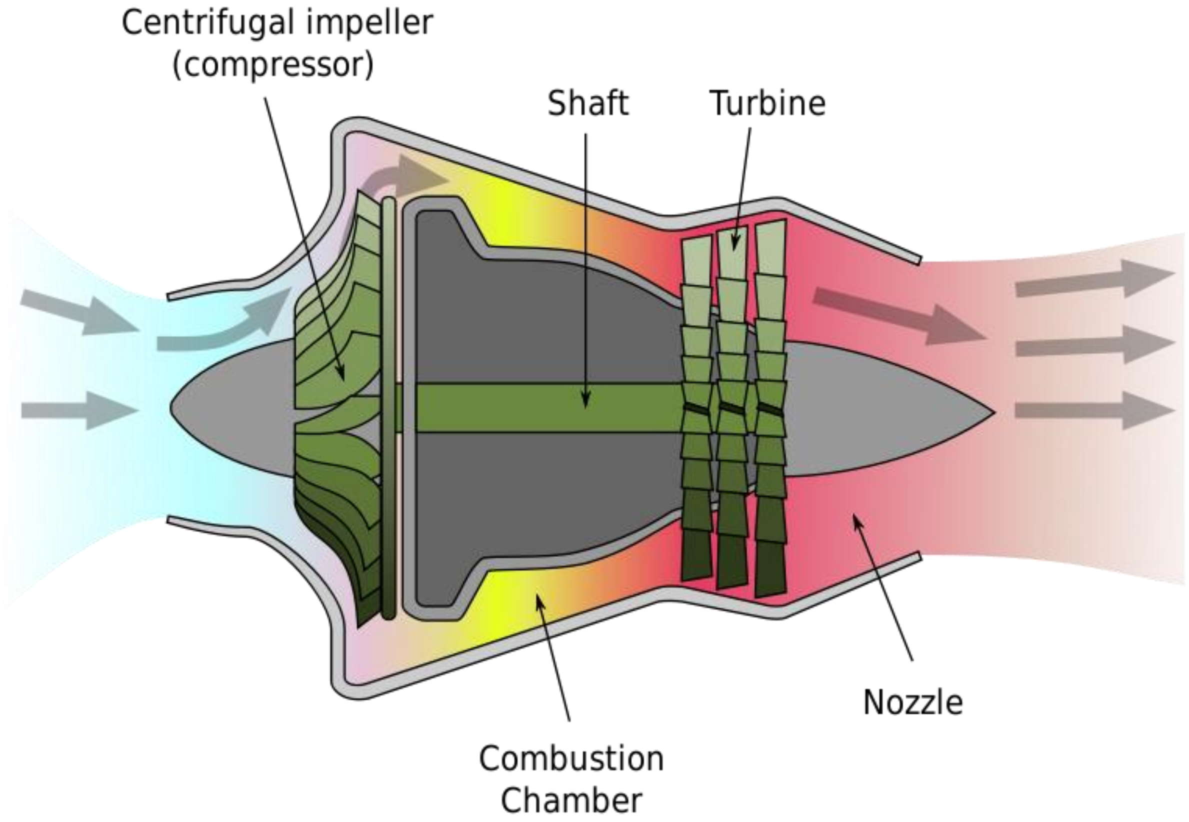


Fig 2.10 Jet engine cross section showing the centrifugal compressor and other parts.

Chapter 3:

Additional Technologies Commonly used in Turbocharger Installations.

3.1 Intercooling:

When the pressure of the engine's intake air is increased, its temperature will also increase. In addition, heat soak from the hot exhaust gases spinning the turbine may also heat the intake air. The warmer the intake air the less dense, and the less oxygen available for the combustion event, which reduces volumetric efficiency. Not only does excessive intake-air temperature reduce efficiency, it also leads to engine knock, or detonation, which is destructive to engines.

Turbocharger units often make use of an intercooler (also known as a charge air cooler), to cool down the intake air. Intercoolers are often tested for leaks during routine servicing, particularly in trucks where a leaking intercooler can result in a 20% reduction in fuel economy.

(Note that "intercooler" is the proper term for the air cooler between successive stages of boost, whereas "charge air cooler" is the proper term for the air cooler between the boost stage(s) and the appliance that will consume the boosted air.)

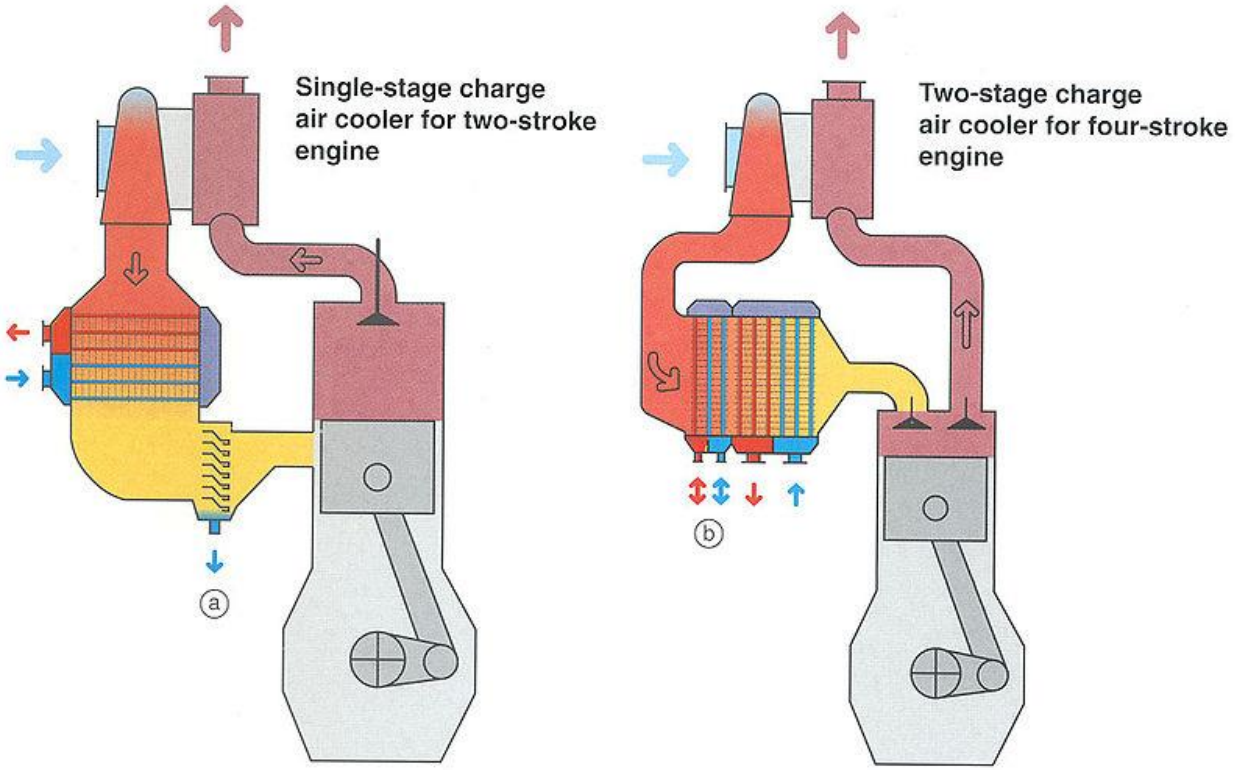


Fig 3.1 Illustration of inter-cooler location.

3.2 Water injection:

An alternative to intercooling is injecting water into the intake air to reduce the temperature. This method has been used in automotive and aircraft applications

Water injection (engines)

In internal combustion engines, **water injection**, also known as **anti-detonant injection**, is spraying water into the cylinder or incoming fuel-air mixture to cool the combustion chambers of the engine, allowing for greater compression ratios and largely eliminating the problem of engine knocking (detonation). This effectively reduces the air intake temperature in the combustion chamber, meaning that performance gains can be obtained when used in conjunction with a supercharger, turbocharger, altered spark ignition timing, and other modifications. The reduction of the air intake temperature allows for a more aggressive ignition timing to be employed, which increases the power output of the engine. Depending on the engine, improvements in power and fuel efficiency can also be obtained solely by injecting water. Water injection may also be used to reduce NOx or carbon monoxide emissions.

Water injection is also used in some jet turbine engines and in some shaft turbine engines, when a momentary high-thrust setting is needed to increase power and fuel efficiency.

3.2.1 Composition of fluid:

Many water injection systems use a mixture of water and alcohol (approximately 50/50), with trace amounts of water-soluble oil. The water provides the primary cooling effect due to its great density and high heat absorption properties. The alcohol is combustible, and also serves as an antifreeze for the water. The purpose of the oil is to prevent corrosion of water injection and fuel system components. [2] Because the alcohol mixed into the injection solution is often methanol (CH_3OH), the system is known as methanol-water injection, or MW50. In the United States, the system is commonly referred to as anti-detonant injection, or ADI.

3.2.2 Effects:

In a piston engine, the initial injection of water cools the fuel-air mixture significantly which increases its density and hence the amount of mixture that enters the cylinder. The water (if in small liquid droplets) may absorb heat (and lower the pressure) as the charge is compressed, thus reducing compression work.[1] An additional effect comes later during combustion when the water absorbs large amounts of heat as it vaporizes, reducing peak temperature and resultant NO_x formation, and reducing the amount of heat energy absorbed into the cylinder walls. This also converts part of combustion energy from the form of heat to the form of pressure. As the water droplets vaporize by absorbing heat, it turns to high pressure steam (water vapor or steam mainly resulted from combustion chemical reaction). The alcohol in the mixture burns, but is also much more resistant to detonation than gasoline. The net result is a higher octane charge that will support very high compression ratios or significant forced induction pressures before onset of detonation.

Fuel economy can be improved with water injection. Depending on the engine, the effect of water injection, with no other modification, like leaning out the mixture, may be quite significant[1] or rather limited and in some cases negligible[*original research?*].

Most modern consumer vehicle engines are pre-programmed with specific fuel-to-air ratios and that introducing water without re-programming the car's computer will not have any benefit and in most cases will reduce performance and possibly damage the engine. Most modern fuel systems cannot determine that water in any form has been added and cannot determine a new compression ratio or take advantage of lower cylinder temperatures. In most cases in cars that are pre-programmed, introducing water vapor will cause them to lose power because the water vapor will then take the place of air and fuel that is required to produce power. Only in vehicles in which the owner can take the car to a tuner will any benefit be seen. However, as soon as the water source is depleted the engine will be running rich and power and fuel economy will be lost again.

Damage can occur to the engine if too much water is injected or if there is a malfunction of the injector itself. Water is not compressible and if too much water makes it into the cylinder prior to detonation (during the compression cycle), the volume of liquid may exceed the engine block's head bolts threshold, causing blown heads, hydrolock, or shattering of the piston connecting rods. This damage is fatal to the engine and typically requires a full rebuild.

Water injection is typically used in aviation and is not intended for use in consumer grade vehicles. When used in consumer grade vehicles it is for the extremely high performance arena (1000 HP+) where vehicles are super- or turbocharged and produce excessive heat. These vehicles are typically driven only in an event or controlled race and require extremely high levels of knowledge to maintain and are only driven for very short distances. In most forms of water injection, water is mixed with a combustible fuel and not injected directly from the tap.

Many product scams exist touting that inserting a tube of misting spray into an intake manifold will increase your mileage gains or horsepower. However, unless the user reprograms the car's ECU, power loss and damage will eventually occur.

In some cases water may also reduce CO emissions. This may be attributable to the water gas shift reaction, in which CO and H_2O shift to form CO_2 and H_2.[1] However, water may also increase hydrocarbon emissions, possibly due to an increased quenching layer thickness.

Some degree of control over the water injection is important. It needs to be injected only when the engine is heavily loaded and the throttle is wide open. Otherwise injecting water cools the combustion process unnecessarily and reduces efficiency.

Direct injection of water is possible and is likely advantageous. In a piston engine, this can be done late in the power stroke or during the exhaust stroke.

3.2.3 Use in aircraft:

Water injection has been used in both reciprocating and turbine aircraft engines. When used in a turbine engine, the effects are similar, except that preventing detonation is not the primary goal. Water is normally injected either at the compressor inlet or in the diffuser just before the combustion chambers. Adding water increases the mass being accelerated out of the engine, increasing thrust, but it also serves to cool the turbines. Since temperature is normally the limiting factor in turbine engine performance at low altitudes, the cooling effect allows the engines to be run at a higher RPM with more fuel injected and more thrust created without overheating. The drawback of the system is that injecting water quenches the flame in the combustion chambers somewhat, as there is no way to cool the engine parts without cooling the flame accidentally. This leads to unburned fuel out the exhaust and a characteristic trail of black smoke.

Piston engined petrol military aircraft utilized water injection technology prior to World War II in order to increase takeoff power. This was used so that heavily-laden fighters could take off from shorter runways, climb faster, and quickly reach high altitudes to intercept enemy bomber formations. Some fighter aircraft also used water injection to allow higher boost in short bursts during dogfights.

As a general rule, the fuel mixture is set at full rich on an aircraft engine when running it at a high power settings (such as during takeoff). The extra fuel does not burn; its only purpose is to evaporate to absorb heat. This uses up more fuel, and it also decreases the efficiency of the combustion process. By using water injection, the cooling effect of the water allows the fuel mixture to be run leaner at its best-power setting. Many military aircraft engines of the 1940s utilized a pressure carburetor, a type of fuel metering system similar to a throttle body injection system. In a water-injected engine, the pressure carburetor features a mechanical *derichment valve* which makes the system nearly automatic. When the pilot turns on the water injection pump, water pressure moves the derichment valve to restrict fuel flow to lean the mixture while at the same time mixing the water/methanol fluid in to the system. When the system runs out of fluid the derichment valve shuts and cuts off the water injection system, while enriching the fuel mixture to provide a cooling quench to prevent sudden detonation.

Due to the cooling effect of the water, aircraft engines can run at much higher manifold pressures without detonating, creating more power. This is the primary advantage of a water injection system when used on an aircraft engine.

The extra weight and complexity added by a water injection system was considered worthwhile for military purposes, while it is usually not considered worthwhile for civilian use. The one exception is racing aircraft, which are focused on making a tremendous amount of power for a short time; in this case the disadvantages of a water injection system are less important.

The use of water injection in turbine engines has been limited, again, mostly to military aircraft. Many pictures are available of Boeing B-52 takeoffs which clearly show the black smoke emitted by turbine engines running with water injection. For early B-52s, water injection was seen as a vital part of take-off procedures. For later versions of the B-52 as well as later turbine-powered bombers, the problem of taking off heavily loaded from short runways was solved by the availability of more powerful engines that had not been available previously.

The BAC One-Eleven airliner also used water injection for its Rolls-Royce Spey turbofan engines. Filling the tanks with jet fuel instead of water led to the Paninternational Flight 112 crash.

3.2.4 Use in automobiles:

A limited number of road vehicles with large-displacement engines from manufacturers such as Chrysler have included water injection. The 1962 Oldsmobile F85 was delivered with the Fluid-Injection Jetfire engine, which, incidentally, shares the title of "the world's first turbocharged road car" with the Corvair Spyder. Oldsmobile referred to the water/alcohol mixture as 'Turbo-Rocket Fluid'. Saab offered water injection for the Saab 99 Turbo. With the introduction of the intercooler the interest in water injection disappeared, but today, water injection is also of interest because it can potentially decrease nitrogen oxide (NO_x) emissions in exhaust. The most common use of water injection today is in vehicles with aftermarket forced induction systems, such as turbochargers or superchargers. Such engines are commonly tuned with a narrower margin of safety from detonation and hence benefit greatly from the cooling effects of vaporized water.

3.3 Fuel-air mixture ratio:

In addition to the use of intercoolers, it is common practice to add extra fuel to the intake air (known as "running an engine rich") for the sole purpose of cooling. The amount of extra fuel varies, but typically reduces the air-fuel ratio to between 11 and 13, instead of the stoichiometric 14.7 (in petrol engines). The extra fuel is not burned (as there is insufficient oxygen to complete the chemical reaction), instead it undergoes a phase change from vapor (liquid) to gas. This phase change absorbs heat, and the added mass of the extra fuel reduces the average kinetic energy of the charge and exhaust gas. Even when a catalytic converter is used, the practice of running an engine rich increases exhaust emissions.

3.4 Wastegate :

Many turbochargers use a basic wastegate, which allows smaller turbochargers to reduce turbo lag. A wastegate regulates the exhaust gas flow that enters the exhaust-side driving turbine and therefore the air intake into the manifold and the degree of boosting. It can be controlled by a solenoid operated by the engine’s electronic control unit or a boost controller but most production vehicles use a spring loaded diaphragm.

3.5 Anti-surge/dump/blow off valves:

Turbocharged engines operating at wide open throttle and high rpm require a large volume of air to flow between the turbo and the inlet of the engine. When the throttle is closed, compressed air will flow to the throttle valve without an exit (i.e., the air has nowhere to go).

In this situation, the surge can raise the pressure of the air to a level that can cause damage. This is because if the pressure rises high enough, a compressor stall will occur, where the stored pressurized air decompresses backward across the impeller and out the inlet. The reverse flow back across the turbocharger causes the turbine shaft to reduce in speed more quickly than it would naturally, possibly damaging the turbocharger.

In order to prevent this from happening, a valve is fitted between the turbo and inlet, which vents off the excess air pressure. These are known as an anti-surge, diverter, bypass, blow-off valve (BOV), or dump valve. It is a pressure relief valve, and is normally operated by the vacuum in the intake manifold.

The primary use of this valve is to maintain the spinning of the turbocharger at a high speed. The air is usually recycled back into the turbo inlet (diverter or bypass valves) but can also be vented to the atmosphere (blow off valve). Recycling back into the turbocharger inlet is required on an engine that uses a mass-airflow fuel injection system, because dumping the excessive air overboard downstream of the mass airflow sensor will cause an excessively rich fuel mixture (this is because the mass-airflow sensor has already accounted for the extra air that is no longer being used). Valves that recycle the air will also shorten the time needed to re-spool the turbo after sudden engine deceleration, since the load on the turbo when the valve is active is much lower than it is if the air charge is vented to atmosphere.

Fig 3.2 A recirculating type anti-surge valve.

3.6 Free Floating :

A free floating turbocharger is the simplest type of turbocharger. This configuration has no wastegate and can’t control its own boost levels. They are typically designed to attain maximum boost at full throttle. Free floating turbochargers produce more horsepower because they have less backpressure but are not driveable in performance applications without an external wastegate.

Fig 3.3 A free floating turbocharger is used in the 100 liter engine of the caterpillar mining vehicle.

Chapter 4:

Applications of Turbochargers

4.1 Gasoline-powered cars:

The first turbocharged passenger car was the Oldsmobile Jetfire option on the 1962-1963 F85/Cutlass which utilized a turbocharger mounted to a 215 cu in (3.52 L) all aluminum V8. Also in 1962 Chevrolet introduced a special run of turbocharged Corvairs called the Monza Spyder (1962-1964) and later renamed the Corsa (1965-1966) which mounted a turbocharger to its air cooled flat 6 cylinder engine. This model really popularized the turbocharger in North America and set the stage for later turbocharged models from Porsche on the 1975-up 911/930 and Saab on the 1978-1984 Saab 99 Turbo and the very popular 1978-1987 Buick Regal/T Type/Grand National. Today, turbocharging is commonly used by many manufacturers of both diesel and gasoline-powered cars. Turbocharging can be used to increase power output for a given capacity or to increase fuel efficiency by allowing a smaller displacement engine to be used. Low pressure turbocharging is the optimum when driving in the city, whereas high pressure turbocharging is more for racing and driving on highways/motorways/freeways.

4.2 Diesel-powered cars:

The first production turbo diesel passenger car was the Garrett-turbocharged Mercedes introduced in 1978. Today, many automotive diesels are turbocharged, since the use of turbocharging improved efficiency, driveability and performance of diesel engines, greatly increasing their popularity.

4.3 Motorcycles:

The first example of a turbocharged bike is the 1978 Kawasaki Z1R TC. Several Japanese companies produced turbocharged high performance motorcycles in the early 1980s. Since then, few turbocharged motorcycles have been produced.

The Dutch manufacturer EVA motorcycles builds a small series of turbocharged diesel motorcycle with an 800cc smart CDI engine.

.Trucks

The first turbocharged diesel truck was produced by *Schweizer Maschinenfabrik Saurer* (Swiss Machine Works Saurer) in 1938

4.4 Aircraft:

A natural use of the turbocharger - and its earliest known use for any internal combustion engine, starting with experimental installations in the 1920s - is with aircraft engines. As an aircraft climbs to higher altitudes the pressure of the surrounding air quickly falls off. At 5,486 m (18,000 ft), the air is at half the pressure of sea level and the airframe experiences only half the aerodynamic drag. However, since the charge in the cylinders is being pushed in by this air pressure, it means that the engine will normally produce only half-power at full throttle at this altitude. Pilots would like to take advantage of the low drag at high altitudes in order to go faster, but a naturally aspirated engine will not produce enough power at the same altitude to do so.

The table below is used to demonstrate the wide range of conditions experienced. As seen in the table below, there is significant scope for forced induction to compensate for lower density environments.

A turbocharger remedies this problem by compressing the air back to sea-level pressures, or even much higher, in order to produce rated power at high altitude. Since the size of the turbocharger is chosen to produce a given amount of pressure at high altitude, the turbocharger is over-sized for low altitude. The speed of the turbocharger is controlled by a wastegate. Early systems used a fixed wastegate, resulting in a turbocharger that functioned much like a supercharger. Later systems utilized an adjustable wastegate, controlled either manually by the pilot or by an automatic hydraulic or electric system. When the aircraft is at low altitude the wastegate is usually fully open, venting all the exhaust gases overboard. As the aircraft climbs and the air density drops, the wastegate must continuously close in small increments to maintain full power. The altitude at which the wastegate is fully closed and the engine is still producing full rated power is known as the *critical altitude.* When the aircraft climbs above the critical altitude, engine power output will decrease as altitude increases just as it would in a naturally aspirated engine.

With older supercharged aircraft, the pilot must continually adjust the throttle to maintain the required manifold pressure during ascent or descent. The pilot must also take great care to avoid overboosting the engine and causing damage, especially during emergencies such as go-arounds. In contrast, modern turbocharger systems use an automatic wastegate, which controls the manifold pressure within parameters preset by the manufacturer. For these systems, as long as the control system is working properly and the pilot's control commands are smooth and deliberate, a turbocharger will not overboost the engine and damage it.

Yet the majority of World War II engines used superchargers, because they maintained three significant manufacturing advantages over turbochargers, which were larger, involved extra piping, and required exotic high-temperature materials in the turbine and pre-turbine section of the exhaust system. The size of the piping alone is a serious issue; American fighters Vought F4U and Republic P-47 used the same engine but the huge barrel-like fuselage of the latter was, in part, needed to hold the piping to and from the turbocharger in the rear of the plane. Turbocharged piston engines are also subject to many of the same operating restrictions as gas turbine engines. Pilots must make smooth, slow throttle adjustments to avoid overshooting their target manifold pressure. The fuel/air mixture must often be adjusted far on the rich side of stoichiometric combustion needs to avoid pre-ignition or detonation in the engine when running at high power settings. In systems using a manually operated wastegate, the pilot must be careful not to exceed the turbocharger's maximum rpm. Turbocharged engines require a cooldown period after landing to prevent cracking of the turbo or exhaust system from thermal shock. Turbocharged engines require frequent inspections of the turbocharger and exhaust systems for damage due to the increased heat, increasing maintenance costs. The great majority of World War II American heavy bombers used by the USAAF - particularly the Wright R-1820 *Cyclone-9* powered B-17 Flying Fortress, and Pratt & Whitney R-1830 Twin Wasp powered Consolidated B-24 Liberator four-engined bombers both used similar models of General Electric-designed turbochargers in service, as did the twin Allison V-1710-engined Lockheed P-38 Lightning American heavy fighter during the war years.

Today, most general aviation aircraft are naturally aspirated. The small number of modern aviation piston engines designed to run at high altitudes in general use a turbocharger or turbo-normalizer system rather than a supercharger. The change in thinking is largely due to economics. Aviation gasoline was once plentiful and cheap, favoring the simple but fuel-hungry supercharger. As the cost of fuel has increased, the supercharger has fallen out of favor.

Turbocharged aircraft often occupy a performance range between that of normally aspirated piston-powered aircraft and turbine-powered aircraft. The increased maintenance costs of a turbocharged engine are considered worthwhile for this purpose, as a turbocharged piston engine is still far cheaper than any turbine engine.

As the turbocharged aircraft climbs, however, the pilot (or automated system) can close the wastegate, forcing more exhaust gas through the turbocharger turbine, thereby maintaining manifold pressure during the climb, at least until the critical pressure altitude is reached (when the wastegate is fully closed), after which manifold pressure will fall. With such systems, modern high-performance piston engine aircraft can cruise at altitudes above 20,000 feet, where low air density results in lower drag and higher true airspeeds. This allows flying "above the weather". In manually controlled wastegate systems, the pilot must take care not to overboost the engine, which will cause pre-ignition, leading to engine damage. Further, since most aircraft turbocharger systems do not include an intercooler, the engine is typically operated on the rich side of peak exhaust temperature in order to avoid overheating the turbocharger.

In non-high-performance turbocharged aircraft, the turbocharger is solely used to maintain sea-level manifold pressure during the climb (this is called turbo-normalizing).

Modern turbocharged aircraft usually forgo any kind of temperature compensation, because the turbochargers are in general small and the manifold pressures created by the turbocharger are not very high. Thus, the added weight, cost, and complexity of a charge cooling system are considered to be unnecessary penalties. In those cases, the turbocharger is limited by the temperature at the compressor outlet, and the turbocharger and its controls are designed to prevent a large enough temperature rise to cause detonation. Even so, in many cases the engines are designed to run rich in order to use the evaporating fuel for charge cooling.

4.5 Marine and land-based diesel turbochargers:

Turbocharging, which is common on diesel engines in automobiles, trucks, tractors, and boats is also common in heavy machinery such as locomotives, ships, and auxiliary power generation.

- Turbocharging can dramatically improve an engine's specific power and power-to-weight ratio, performance characteristics which are normally poor in non-turbocharged diesel engines.
- Diesel engines have no detonation because diesel fuel is injected at or towards the end of the compression stroke and is ignited solely by the heat of compression of the charge air. Because of this, diesel engines can use a much higher boost pressure than spark ignition engines, limited only by the engine's ability to withstand the additional heat and pressure.

Turbochargers are also employed in certain two-stroke cycle diesel engines, which would normally require a Roots blower for aspiration. In this specific application, mainly Electro-Motive Diesel (EMD) 567, 645, and 710 Series engines, the turbocharger is initially driven by the engine's crankshaft through a gear train and an overrunning clutch, thereby providing aspiration for combustion. After combustion has been achieved, and after the exhaust gases have reached sufficient heat energy, the overrunning clutch is disengaged, and the turbo-compressor is thereafter driven exclusively by the exhaust gases. In the EMD application, the turbocharger is used for normal aspiration during starting and low power output settings and is used for true turbocharging during medium and high power output settings. This is particularly beneficial at high altitudes, as are often encountered on western U.S. railroads.

Fig 4.1 A medium-sized six-cylinder marine Diesel-engine, with turbocharger and exhaust in the foreground.

4.6 Similarities between Turbocharger and supercharger

Turbochargers can fit on any engine type, given the use of the appropriate exhaust manifold and a decompressed engine block. However, the turbo must be sized properly according to the application. Small turbos mean faster boost responses, but limited amounts of boost. Larger sized turbos take up more time to build up boost, but they give a lot of boost. Turbochargers are propelled by the exhaust gas velocity of the vehicle and are directly proportional to the temperature of the engine. Turbos feed on fresh oil constantly, so oils with high ratings must be used in the vehicle.

Superchargers use the same concept as turbochargers in the effect that it also compresses air. Superchargers can also be made to fit on any type of engine, and only comes in two types of kits. Both are fanbelt pulley driven units. When it comes to horsepower and torque, superchargers can gain as much as 40 percent in horsepower and 50 percent in torque with the use of just a base kit.

Turbochargers and Superchargers are two of the best ways to accomplish your goals by producing more power and faster times. Both have great sounds, the superchargers with their aggressive whistling sound, and the turbos with their jet engine type sound.

In a nutshell, Turbochargers are efficient and flexible, allowing a wide range of swaps and upgrades to achieve the desired power output. They are not noisy and do not rob any power from the engine, however they do require a little more attention than superchargers. This setup is ideal for front wheel drive and lightweight cars, due to the lack of traction when you launch from a dead stop; the lag in boost is actually an advantage. You don't want your boost to kick in before you get traction.

Superchargers give you instant boost on demand and require very low maintenance. With boost available at 2000rpm, you don't have to watch the other guy start jump pass you for long. This setup is ideal if you have a rear wheel drive car with lots of horse power to spare, then the petty power it steals from the engine is well compensated for.

Chapter 5:

Types of Turbochargers

5.1 Hybrid turbocharger:

A **hybrid turbocharger** is an electric turbocharger consisting of an ultra high speed turbine-generator and an ultra high speed electric air compressor. The turbine and compressor are high-speed aeromachines, as in a conventional turbocharger. The electrical motors run at speeds in excess of 120,000 rpm and when used as generators, generate electricity at up to 98.5% electrical efficiency. High electrical efficiency is paramount, because there is no mechanical link between the turbine and compressor. In other words, hybrid turbocharger refers to a series hybrid setup, in which compressor speed and power are independent from turbine speed and power. This design flexibility leads to further improvements in turbine and compressor efficiency, beyond a conventional turbocharger.

The designers claim that hybrid turbocharger technology (HTT) virtually eliminates turbo lag and enables engine downsizing without compromising engine performance. This means that a HTT equipped engine can save up to 30% on CO_2 emissions and fuel economy compared to an equivalent naturally aspirated engine.

HTT has currently been developed and tested to proof of concept stage by UK based company, Aeristech Ltd who also hold the patents for the design.

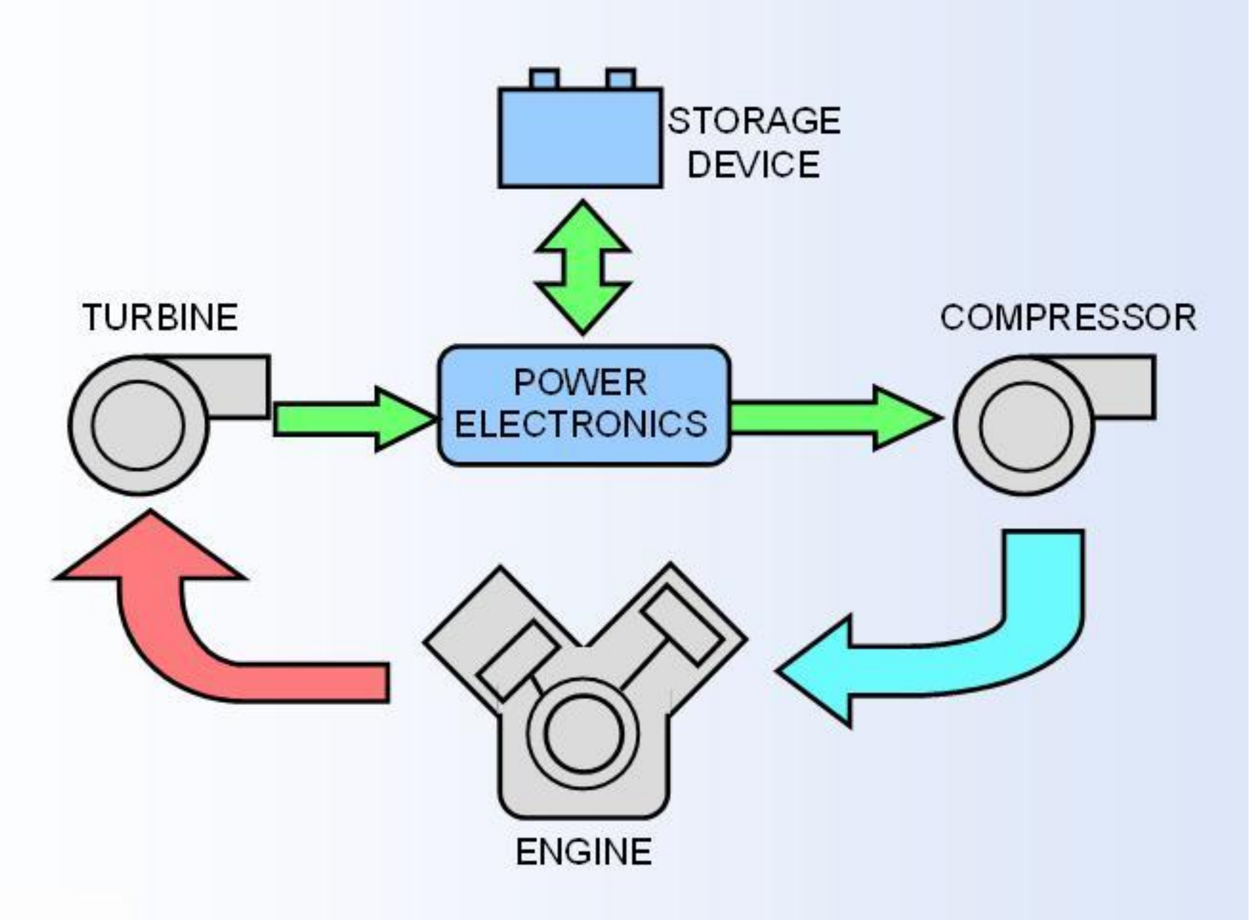


Fig 5.1 Basic schematic of an Aeristech Hybrid Turbocharger.

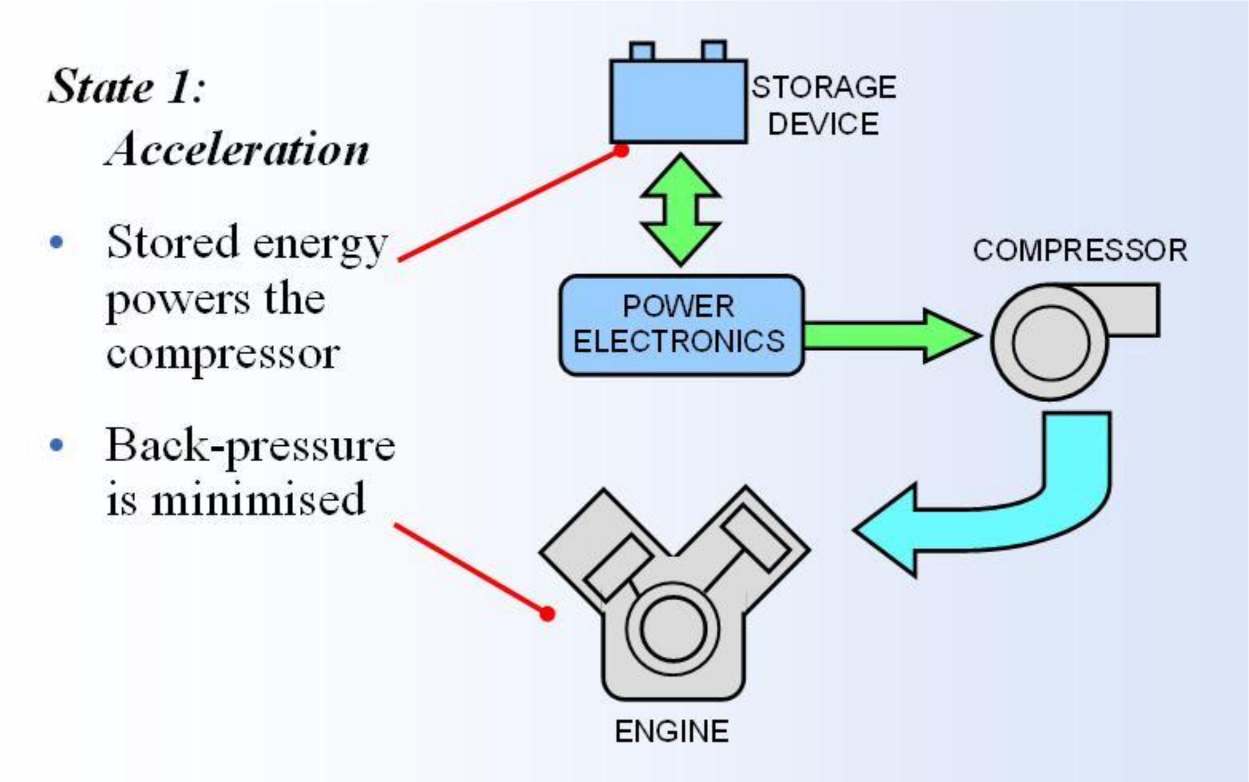
Operating modes.

5.1.1 Acceleration:

When the driver depresses the throttle, the HTT initially acts like an electric supercharger. The compressor motor is powered from the energy storage medium allowing it to accelerate to full operating speed in <500 ms. This rate of acceleration eliminates the turbo lag which is a major limiting factor on the performance of standard turbocharged engines.

During this transient stage, the engine control unit (ECU) on a standard turbocharged engine uses a combination of sensors such as lambda sensors and air mass flow sensors to regulate the fuel flow rate. In an HTT equipped engine the ECU can deliver the precise fuel flow rate for complete combustion more accurately. This is achieved by directly controlling the air flow rate and boost pressure via control of the compressor speed.

Aeristech's prototype motor delivers 26 kW (35 PS; 35 hp) at 120,000 rpm, weighs under 3.5 kg (8 lb) and is approximately 10 centimetres (4 in) in length.


State 1: Acceleration

- Stored energy powers the compressor
- Back-pressure is minimised

Fig 5.2 Acceleration mode for an HTT Turbocharger.

5.1.2 Charging:

At high engine speeds there is more energy generated by the turbine than is required by the compressor. Under these conditions, the excess energy can be used to recharge the energy storage for the next acceleration phase or used to power some of the auxiliary loads such as an electric air conditioning system.

When combined with a variable geometry turbine, the back pressure on the engine can be varied according to the electrical demands of the vehicle and charge state of the energy storage medium.

Development is underway for replacing battery energy storage with a super capacitor which can be charged and discharged very quickly.

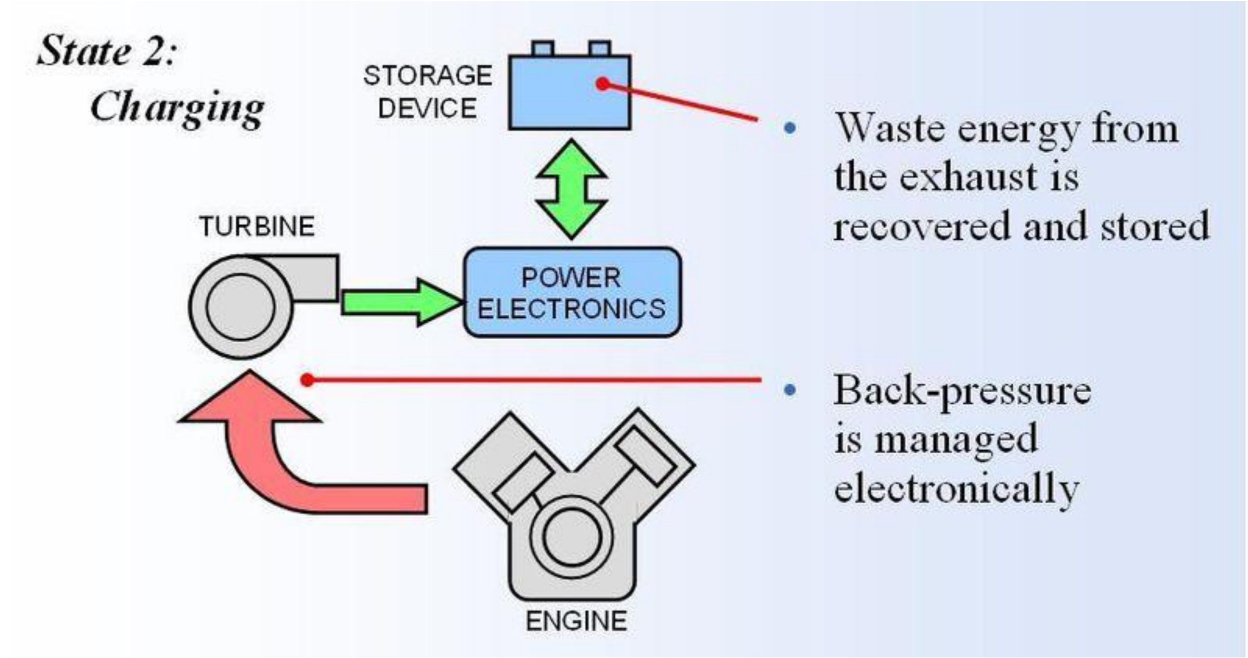


Fig 5.3 Charging mode for an HTT Turbocharger.

5.1.3 Steady state:

For the majority of the time the hybrid turbocharger is operating, the compressor and turbine power (not necessarily speed) will be matched. This gives an extra degree of freedom to the designer of a turbocharger impeller.

Here the hybrid turbocharger efficiently transfers the electricity between the turbine and compressor. Aeristech's latest test program has proven the efficiency of the hybrid turbocharger to be equivalent to (if not better than) that of an ordinary mechanical turbocharger.

5.1.3.1 System benefits

Aeristech claim many other benefits to running a hybrid turbocharged engine:

- Improved packaging by enabling the turbine and compressor to be placed in separate parts of the engine bay.
- Higher density charge air by reducing the length of intake ducts and increasing the size of the compressor wheel.
- ECU controlled boost levels will enable tighter predictive control of in-cylinder combustion.
- Similar engine downsizing benefits to a hybrid vehicle, but with far less (approx 1/7th) energy storage capacity to achieve the same level of downsizing.

Other types of electric turbochargers and electric superchargers are under development with varying degrees of success:

- eBooster by BorgWarner - a small auxiliary electric compressor powered by the vehicle's electric system.
- TurboPac by TurboDyne - Electric supercharger
- Garrett electrically-assisted turbo
- Valeo - Electric supercharger using a low-inertia switched-reluctance motor

5.2 Twin-turbo:

Twin-turbo **or** biturbo **refers to a turbocharged engine, in which two turbochargers compress the intake charge. More specifically called "parallel twin-turbos". Other kinds of turbocharging, include sequential turbocharging and, staged turbocharging. The latter is used in diesel automobile racing applications.**

Fig 5.4 Ford EcoBoost engine (Twin Turbo)

5.2.1 Advantages in Diesel emissions:

While spark ignition engines have fallen out of favor of the sequential turbo design,[*citation needed*] many diesel companies now make engines with sequential turbos in order to reduce emissions. Caterpillar Inc. ACERT engines utilize sequential turbos as well as International on some of their newest engines.

5.3 Variable-geometry turbocharger:

Variable-geometry turbocharger**s (**VGT**s) are a family of turbochargers, usually designed to allow the effective aspect ratio (A:R) of the turbo to be altered as conditions change. This is done because optimum aspect ratio at low engine speeds is very different from that at high engine speeds. If the aspect ratio is too large, the turbo will fail to create boost at low speeds; if the aspect ratio is too small, the turbo will choke the engine at high speeds, leading to high exhaust manifold pressures, high pumping losses, and ultimately lower power output. By altering the geometry of the turbine housing as the engine accelerates, the turbo's aspect ratio can be maintained at its optimum. Because of this, VGTs have a minimal amount of lag, have a low boost threshold, and are very efficient at higher engine speeds. VGTs do not require a wastegate. VGTs tend to be much more common on diesel engines as the lower exhaust temperatures mean they are less prone to failure. The few early gasoline-engine VGTs required significant pre-charge cooling to extend the turbocharger life to reasonable levels, but advances in material technology has improved their resistance to the high temperatures of gasoline engine exhaust and they have started to appear increasingly in, e.g., gasoline-engined sports cars.**

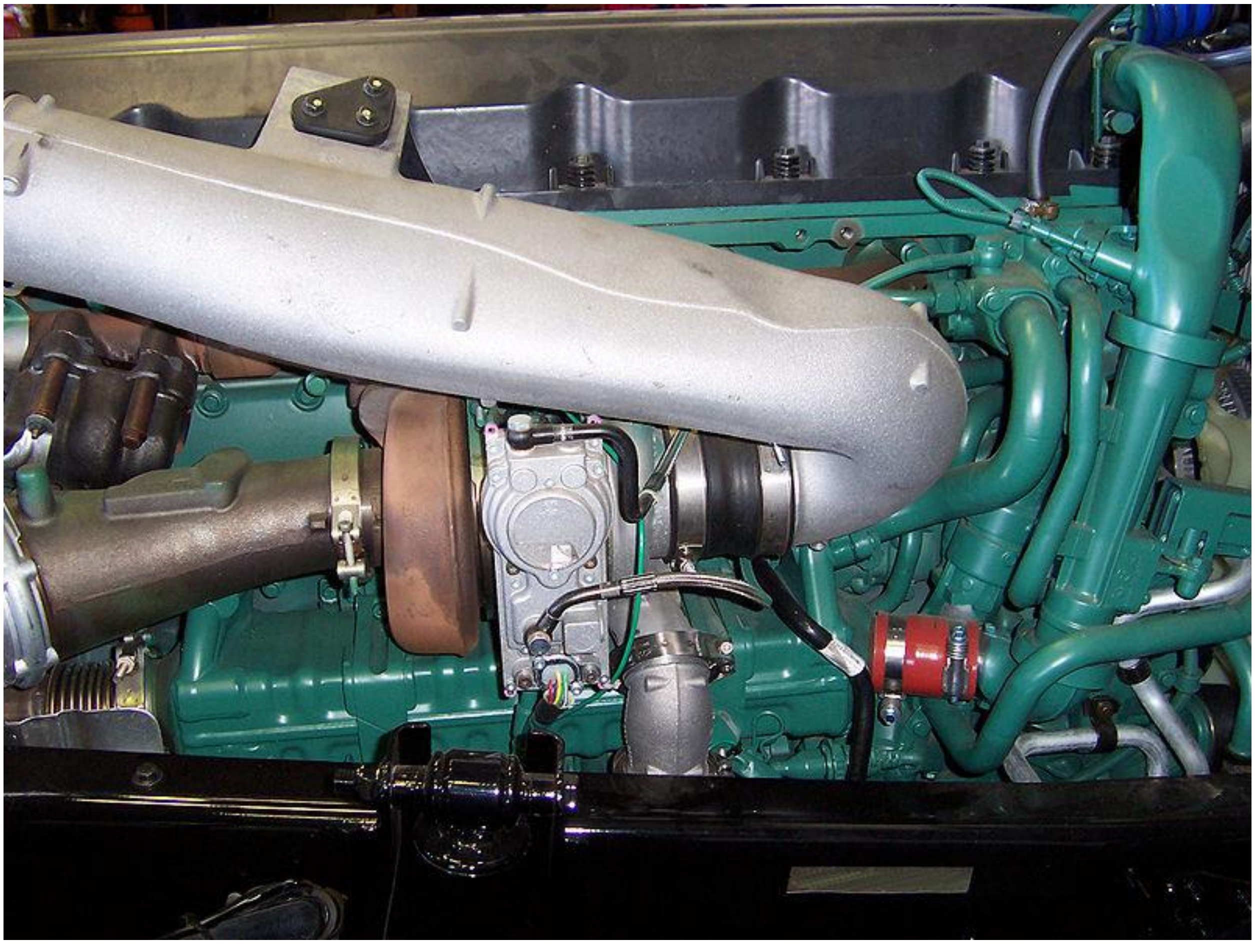


Fig 5.5 Volvo FM VGT diesel engine with EGR emission technology

5.3.1 Most common designs:

The two most common implementations include a ring of aerodynamically-shaped vanes in the turbine housing at the turbine inlet. In general, for light-duty engines (passenger cars, race cars, and light commercial vehicles), the vanes rotate in unison to vary the gas swirl angle and the cross sectional area. In general, for heavy-duty engines, the vanes do not rotate, but instead the axial width of the inlet is selectively blocked by an axially sliding wall (either the vanes are selectively covered by a moving slotted shroud or the vanes selectively move vs a stationary slotted shroud). Either way, the area between the tips of the vanes changes, leading to a variable aspect ratio.

5.3.2 Other common uses:

In trucks, VG turbochargers are also used to control the ratio of exhaust recirculated back to the engine inlet (they can be controlled to selectively increase the exhaust manifold pressure exceeds the inlet manifold pressure, which promotes exhaust gas recirculation (EGR). Although excessive engine backpressure is detrimental to overall fuel efficiency, ensuring a sufficient EGR rate even during transient events (e.g., gear changes) can be sufficient to reduce nitrogen oxide emissions down to that required by emissions legislation (e.g., Euro 5 for Europe and EPA 10 for the USA).

Another use for the sliding vane type of turbocharger is as downstream engine exhaust brake (non-decompression-type), so that an extra exhaust throttle valve is not needed (turbo brake). Also, the mechanism can be deliberately modified to reduce the turbine efficiency in a predefined position. This mode can be selected to sustain a raised exhaust temperature to promote "light-off" and "regeneration" of a diesel particulate filter (this involves heating the carbon particles stuck in the filter until they oxidize away in a semi-self-sustaining reaction - rather like the self-cleaning process some ovens offer). Actuation of a VG turbocharger for EGR flow control or to implement braking or regeneration modes in general requires hydraulic or electric servo actuation.

Chapter 6

Conclusion and Summary.

6.1 Conclusion:

Compared with a naturally aspirated engine of identical power output, the fuel consumption of a turbo engine is lower, as some of the normally wasted exhaust energy contributes to the engine's efficiency. Due to the lower volumetric displacement of the turbo engine, frictional and thermal losses are less.

6.2 Advantages of turbocharging

6.2.1 Fuel Consumption

Comparing an engine with a turbo charger and one without which produces the same amount of power, the engine with the turbo will use less fuel. This is because the actual engine size will be smaller. For example, if both engines produce 200 horsepower, the turbocharged version may be able to do this with only four cylinders, while the one without would require six cylinders. A turbocharged engine can get up to 20 percent better fuel economy.

6.2.2 Noise Pollution

With a smaller overall engine size to produce the same amount of power, the turbocharged engine is less noisy than a naturally aspirated engine. Also, the turbocharger acts as an additional silencer, muffling any noise generated.

6.2.3 High-Altitude Performance

Engines require air pressure to burn fuel and generate power. At higher altitudes there is lower air pressure, so regular engines will produce much less power. On the other hand, the performance and power generation of a turbocharged engine actually improves. This is because there is a greater pressure difference between the air pressure ahead of the turbo and the lower pressure at the exhaust. The turbocharger increases the density of air entering the engine to generate more power.

6.2.4 Size and Weight

With fewer cylinders to produce the same amount of power, the overall engine size and weight will be less than a normal engine. A lighter car is more efficient. To generate the same amount of power with a regular engine, you need to make it bigger and heavier.

6.2.5 Reduced Emissions

Governments are requiring that car manufacturers improve the average gas mileage and reduce the emissions produced in cars they manufacture. A turbocharged engine is smaller than a regular engine, burns less fuel and generates less environmentally unfriendly carbon dioxide.

6.3 Disadvantages of turbocharging

6. 3.1 Installation

Installation is a key component in the effectiveness of a turbocharger, and not all mechanics are capable of installing one properly. If the mechanic even makes a minor mistake, it will not only make the turbocharger ineffective, but may cause damage within the engine.

6.3.2 System

The system in some vehicles may not be able to handle a turbocharger and can cause the system to malfunction and break down. This is often caused by the inadequate fuel-to-oxygen ratio. A professional mechanic needs to make the modifications to the engine and increase the fuel ratio to ensure the maximum benefit of the turbocharger. Turbochargers also can cause wear and tear on an engine and may also require an engine to be replaced sooner then expected.

6.3.3 Cost

Turbochargers are quite expensive, and it's important to determine whether the advantages are worth the cost. When calculating the cost of a turbocharger, it's also important to include the service charge and installation. Turbochargers often cost between $2,000 and $5,000 as of 2010.

6.3.4 Driving

Because turbocharged vehicles travel at high speeds, any malfunctions could lead to dangerous situations. While a turbocharger may be beneficial for those living in the mountains and having to climb steep hills, traveling at high speeds could cause a driver to veer off the road or crash into another vehicle. Driving at fast speeds can be dangerous on commercial roads and lead to accidents or suspension of license.

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