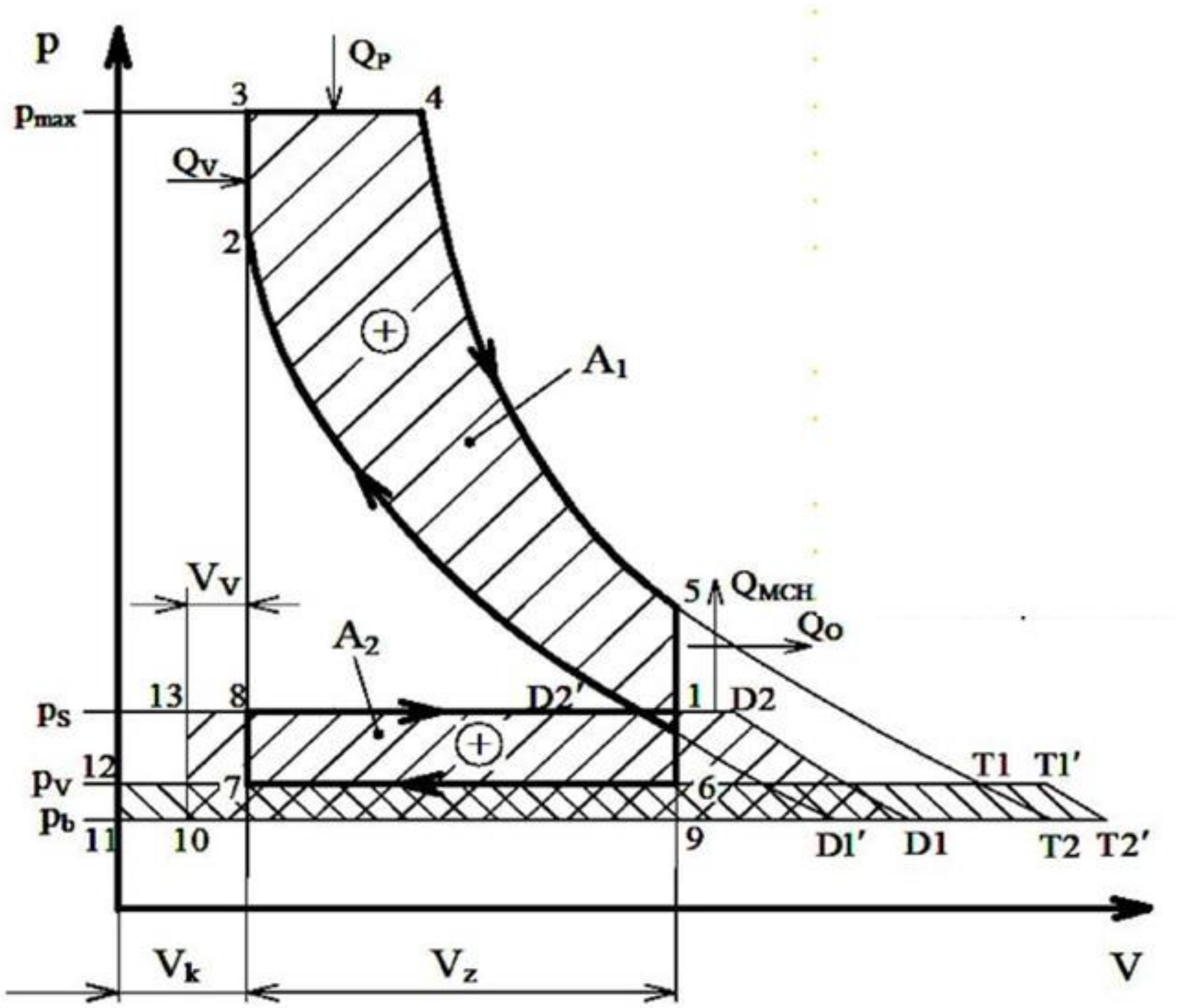
Turbochargers

Turbocharging is the most common used technology in internal combustion engines for forced intake air induction. The main components of a turbocharger are the turbine and the compressor. The role of the turbine is to use the thermal and kinetic(twin-scroll turbochargers) energy of the exhaust gases and convert it into mechanical energy. The role of the compressor is to use the mechanical energy and compress the intake air in order to increase its density.

The basic effect is on fig.



From fig define:

$$\varepsilon_M = \frac{V_5}{V_2} \;;\varepsilon_M = \frac{V_{D1'}}{V_5} \;;\rightarrow \varepsilon_C = \varepsilon_M . \varepsilon_D = \frac{V_{D1'}}{V_2}$$

Compression Ratio in compressor parts:

$$\pi_D = \frac{p_{D2}}{p_{D1}}$$

Expansion Ratio in turbine parts:

$$\pi_T = \frac{p_{T2}}{p_{T1}}$$

Cooling Ratio in intercooler:

$$\omega_{CH} = \frac{V_1}{V_{D2}}$$

The generali from p-V fig.:

$$A_T = A_{i1} + A_{i2}$$

Total effeciency:

$$\eta_t = \eta_{t1} + \eta_{t2}$$

Types of turbochargers

The architecture of the exhaust manifold has a very important role in the performance of the turbocharger, in terms of efficiency and response time (the time taken to spin faster). The exhaust manifold must be designed taking into account the following requirements:

- the interference between the exhaust process of the cylinders needs to be kept at a minimum, ideally without having any pressure interference between the connected cylinders (during the exhaust process)
- the energy of the exhaust gas should reach the turbine with minimum losses
- the deployment of the exhaust gas into the turbine must be done consistently over time, to insure maximum efficiency

From the exhaust gas energy point of view, there are two types of turbocharging systems:

- constant-pressure turbocharging
- pulse turbocharging

Constant-pressure turbochargers are mainly used in diesel engines for passenger vehicles. Having the exhaust ducts for all the cylinders integrated in the same component has the advantage of a compact design which can be easily integrated in any engine application.
Constant-pressure turbochargers are also called single-scroll, because all the exhaust gas flow goes into the turbine through a common (single) duct (scroll).

Figure 1 Exhaust manifold (single-scroll turbocharger)

A constant-pressure turbocharging system has a common pipe/exhaust manifold for all the cylinders. The exhaust ports of each cylinder are connected to a common volume, called a collector. Thus, before reaching the turbine, the exhaust-gas pressure waves from each cylinder interfere with each other and dampen out the pressure peaks. The exhaust gas pressure before the turbine will only have small fluctuations around a constant value.
Because of the integrated design, in a constant-pressure turbocharging system, the number of cylinders of the engine does not play a significant role. For example, from the turbocharging point of view, the behavior of a 4 cylinder turbocharged engine will be the same with the one of a 6 cylinder engine.

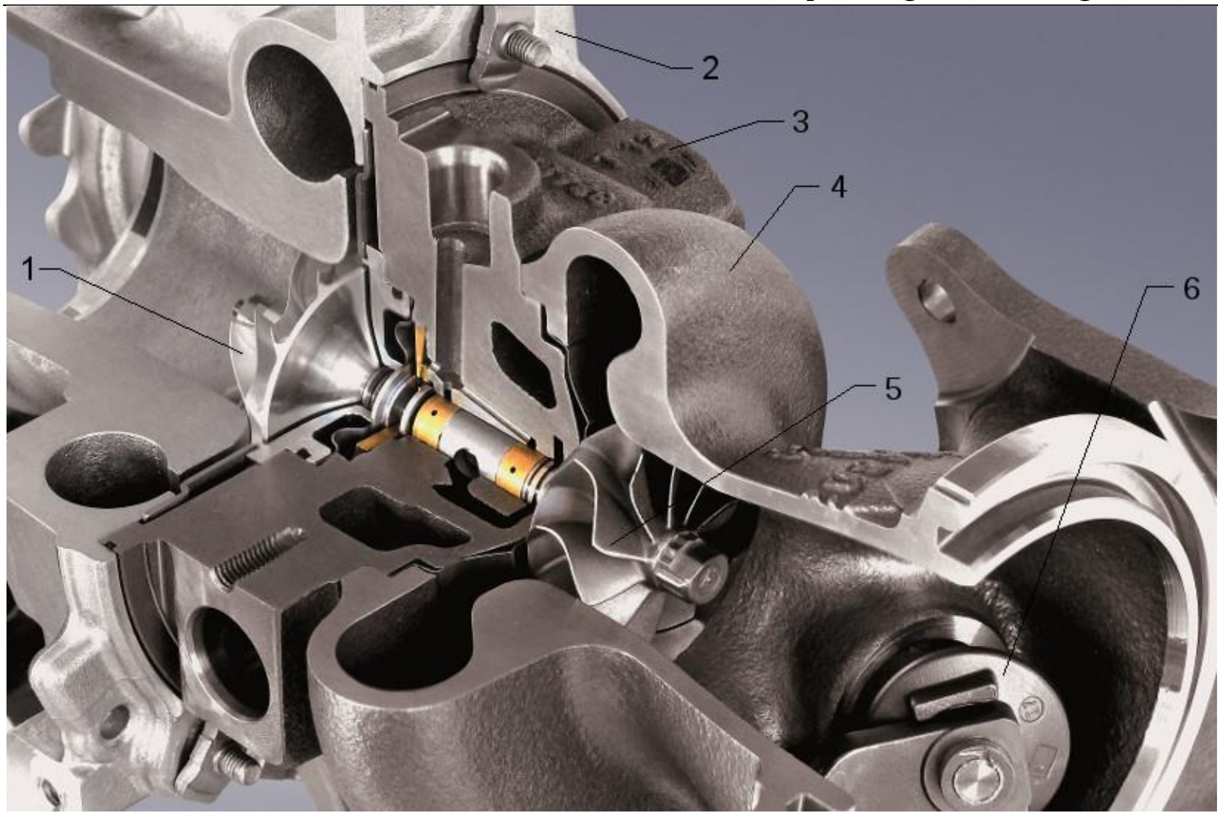
Constant-pressure turbochargers are also called single-scroll turbochargers because the use a single common pipe (scroll) to transport the exhaust gas from the cylinders to the turbine.

The advantages of single-scroll (constant-pressure) turbocharging systems are:

- high turbine efficiency, given by the steady flow of exhaust gas
- good performance at high load (high exhaust gas flow)
- simple, easy to manufacture and cost effective exhaust manifold and turbine casing

The disadvantages of single-scroll (constant-pressure) turbocharging systems are:

- lower exhaust gas energy at the turbine inlet
- poor performance at low – medium engine speed and load
- poor performance during transient engine operation (acceleration)



1. Figure 2 Single-scroll turbocharger (1. Compressor, 2. Compressor housing, 3. Bearing (central) housing 4.Turbine housing (single-scroll), 5.turbine, 6.wastegate)

Twin-scroll turbochargers

In a pulse-turbocharged system, depending on the number and firing order of the cylinders, different routing pipes connect the exhaust ports of the cylinders with the turbine. In this case, the pressure interference between cylinders is eliminated and the pressure waves (high peak pulse) travel up to the turbine inlet.

For a 4 cylinders engine, with the firing order 1-3-4-2, the cylinders 1 and 4 have a common exhaust pipe and cylinders 2 and 3 have a second exhaust pipe. Both pipes transport the exhaust gas up to the turbine inlet. Since it uses two pipes for the exhaust gas, the system is called twin-scroll turbocharging.

Figure 3 Exhaust manifold for twin-scroll turbocharger

Twin-scroll turbocharging takes full advantage of pulse energy, which means that the exhaust gas energy available for conversion to useful work in the turbine is bigger.

Compared to a single-scroll (constant-pressure) turbocharger, a twin-scroll (pulse) turbocharger has the following advantages:

- higher turbine inlet energy due to exploitation of pressure waves (pulse energy)
- good performance at low – medium engine speed and load
- good performance during transient engine operation (acceleration)

The disadvantages of twin-scroll (pulse) turbocharging systems are:

- poor efficiency at high engine load and speed
- complex and expensive exhaust manifold and turbine casing

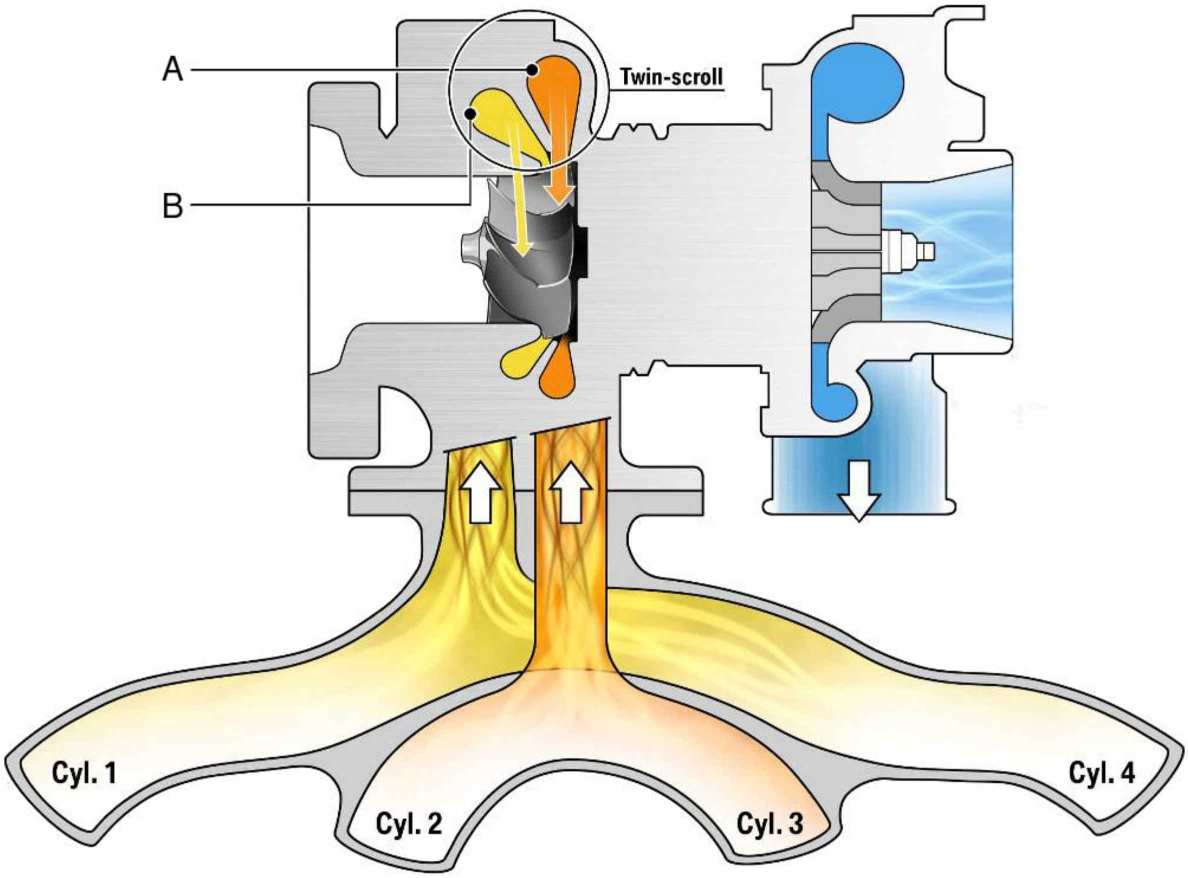


Figure 4 Twin-scroll turbocharger

The exhaust streams from the two pairs of cylinders are routed to the turbine via separated spiral-shaped channels (scrolls) of different diameter.
The larger channel (A), which connects the exhaust of the cylinders 2 and 3, directs one exhaust stream to the outer edge of the turbine blades, helping the turbocharger to spin faster.
The smaller channel (B), which connects the exhaust of the cylinders 1 and 4, directs the other exhaust stream to the inner surfaces of the turbine blades, improving the response of the turbocharger during transient operations (engine acceleration).
Twin-scroll technology combines optimal low-end response with excellent top-end power increase.

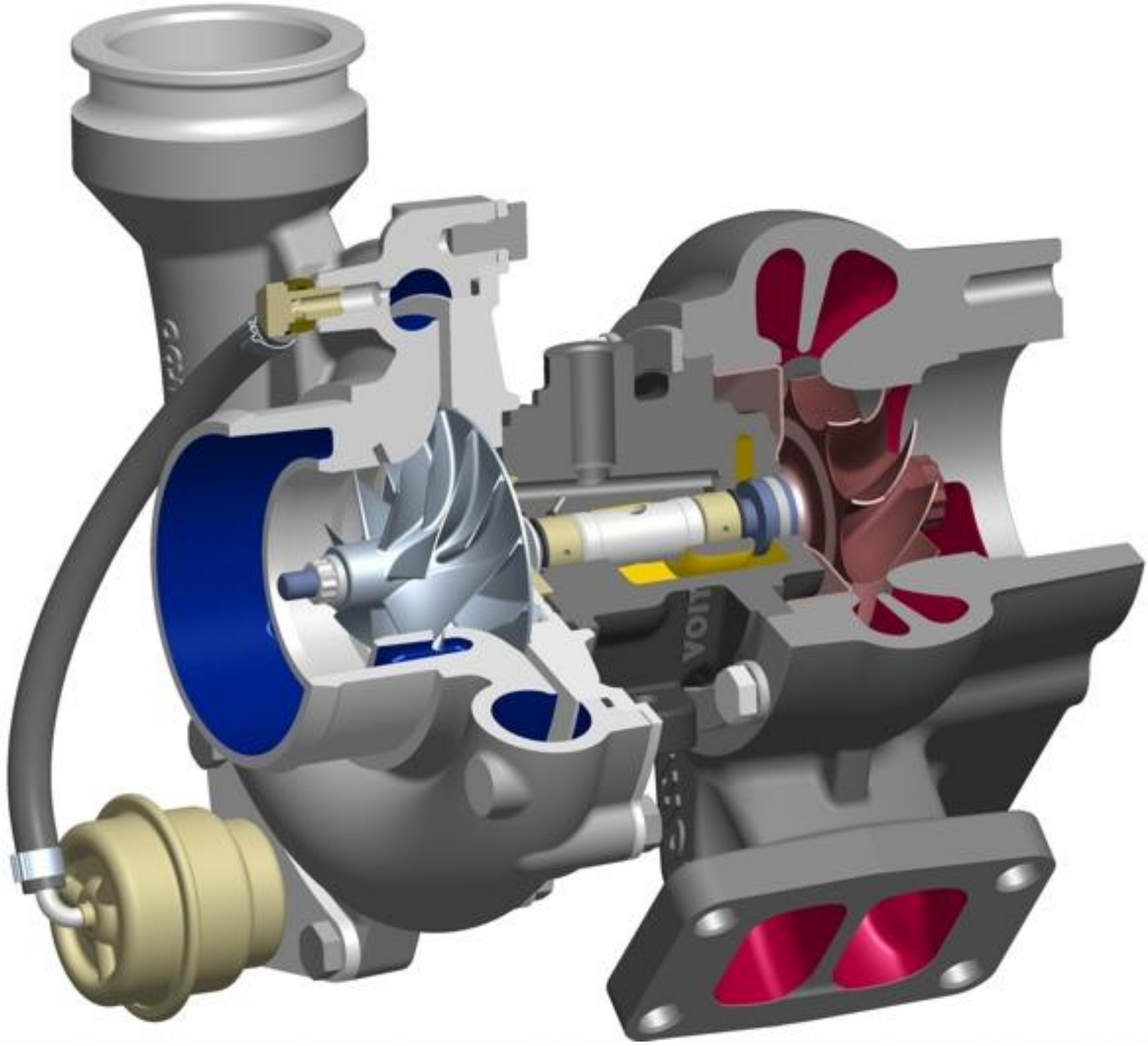


Figure 5 Twin-scroll turbocharger

Single-scroll turbochargers are only using the thermal energy of the exhaust gas in order to compress the intake air through the compressor.
Twin-scroll turbochargers are using both thermal and pulse (pressure wave) energy of the exhaust gas in order to obtain mechanical work to drive the intake air compressor.

https://www.youtube.com/watch?v=VZuTDZiJaMs&ab_channel=JCMedia

Variable Geometry Turbocharger (VGT)

Due to the geometry and different speed range operation, there is a mismatch between the exhaust gas flow of the internal combustion engine and the radial flow of the turbocharger. If the geometry (flow area) of the turbine is designed to match the full speed and load of the engine (large area), at low and medium speeds, the response of the turbocharger will be poor. If the geometry of the turbine is matched for a fast response (small area), when the engine will operate at high speed, the choke limits might be reached and the turbocharger might overspeed or the intake air pressure may exceed the maximum limit.

An ideal turbocharger should be able to provide the required intake air pressure (boost) regardless of the operating point of the engine (speed and torque). This is not possible due to the fact that the speed of the turbocharger shaft depends on the mass flow of the exhaust gases, which depends on the engine operating point.

For a fixed geometry turbocharger, at low engine speed, the exhaust gas mass flow is low, therefore the speed of the turbocharger shaft is low, which means low air boost. On the other hand, at high engine speed, the exhaust gas mass flow rate is high, the speed of the turbochrger shaft high as well, which translates in high intake air boost (pressure).

Types of variable geometry turbochargers

Variable geometry turbocharger means variable A/R ratios. The only plausible way of getting a variable A/R ratio is by varying the cross-sectional area A of the exhaust gas flow. The radius R will always be constant.
Compared with fixed geometry turbochargers, variable geometry turbochargers are designed to:

- increase intake air boost pressure at low engine speed
- improve the response time of the turbocharger during transient engine operation phases
- increase the availability of the maximum engine torque
- prevent over-boosting at high engine speed
- reduce exhaust gas emissions and improve fuel economy

Depending on the turbocharger manufacturer, there are several technical solutions available in the automotive industry. Regardless of the mechanical system used, the outcome is the same: use movable components to provide a variable cross sectional area A, to get an overall variable A/R ratio.

The most common types of variable geometry turbochargers are:

- pivoting vanes
- moving wall
- sliding ring
- variable area

Pivoting vanes variable geometry turbochargers

Pivoting (rotating) vanes turbochargers are widely used in passenger vehicles applications and they are the most common type of variable geometry turbochargers (VGT).

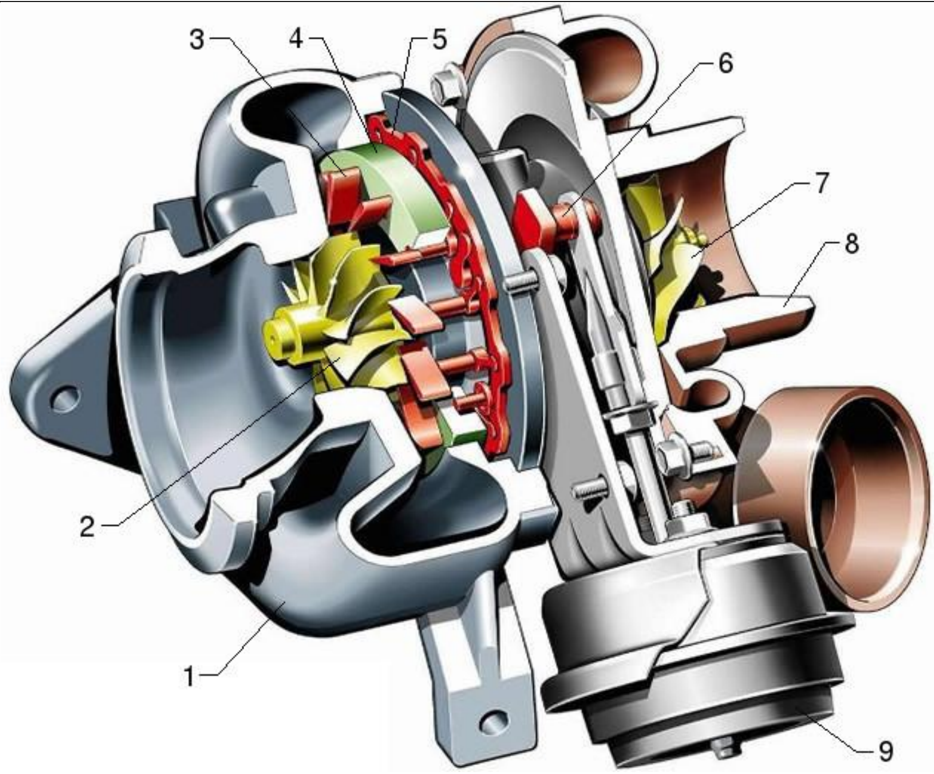


Figure 6 Variable geometry turbocharger – components (1 .turbine casing, 2.turbine wheel, 3.vanes, 4.unison ring, 5.adjustable ring, 6.lever system, 7.compressor wheel, 8.compressor casing, 9.pneumatic actuator)

The variation of the cross-sectional flow area of the turbine is achieved by the rotating vanes (3). These are mechanically linked to an adjustable ring (5), which is controlled by the pneumatic actuator (9) through a mechanical lever system (6).

Depending on the operating point of the engine, the engine control module (ECM) is adjusting the air pressure in the pneumatic actuator, which is closing or opening the pivoting vanes.

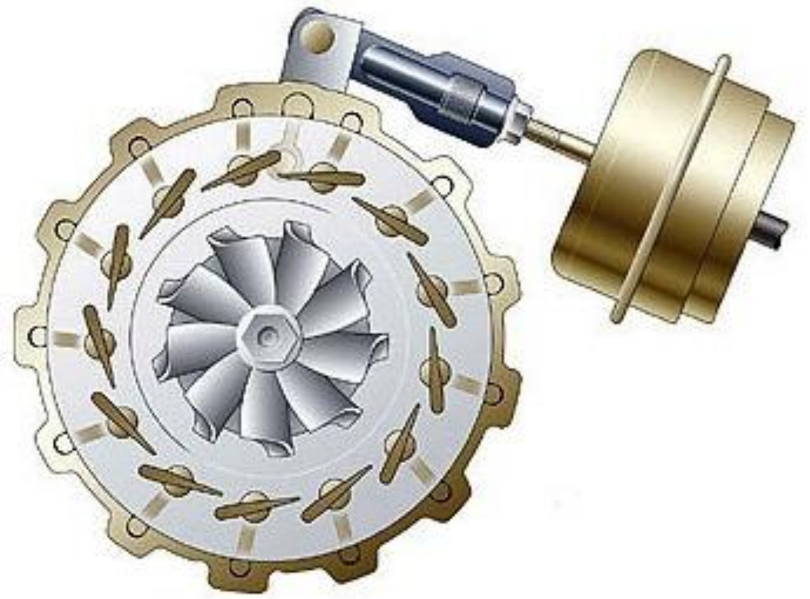


Figure 7 Wide vane opening

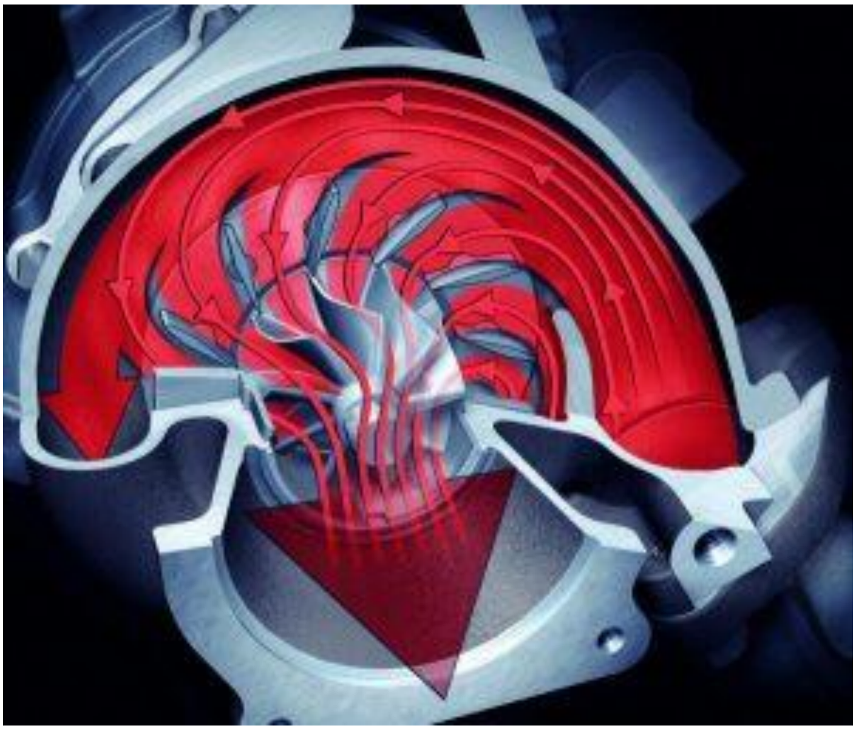


Figure 8 Exhaust gas flow (wide vane opening)

At **high engine speeds**, the vanes are in a wide position, the cross-sectional area for the exhaust gas flow is large, the A/R ratio is at its maximum value and the velocity of the exhaust gas through the turbine at its minimum. The compressor speed will be slower but enough to provide the required intake air boost.
Also, the flow capacity of the turbine is increased, which will decrease the exhaust gas backpressure and allow the engine to "breathe" normally.

The position of the vanes (A/R ratio) can be controlled between a minimum (fully closed) and a maximum (fully open) position. The exact position of the vanes depends on the operating point of the internal combustion engine (speed and torque) and is regulated by the engine control module (ECM) or powertrain control module (PCM).

The most common design of variable geometry turbochargers are using rotating vanes (airfoils) arranged like slats in a window blind around the turbine wheel. These vanes are moved to regulate the cross-sectional area of the exhaust gas flow through the turbine. The vanes are mounted in the turbine housing with one end pinned to the housing. The other end of the vane is connected through a pin to a plate called a unison ring. Rotation of this unison ring causes the all the vanes to revolve around the fixed pivot point.

Figure 9 Variable geometry turbocharger (VGT) – pivoting vanes assembly

The pivoting vanes assembly is also known as a **nozzle ring**.
At high exhaust gas temperatures, the metal-to-metal dry friction between the vanes, pivots and ring can be problematic and cause the pivoting mechanism to stick. If they get stuck in an open position, the engine performance will be poor at low speeds. If the vanes get stuck in a closed (narrow) position, at high engine speeds there will be a significant exhaust gas backpressure, which will lead to over-speed and even to turbine failure.

The pivoting vanes design is most of the time used in diesel and gasoline applications for passenger vehicles.

Moving wall variable geometry turbocharger

Another way of obtaining a variable A/R ratio is by using a moving wall inside the turbocharger. The variable cross-sectional area will be created between the moving wall and the turbine casing.

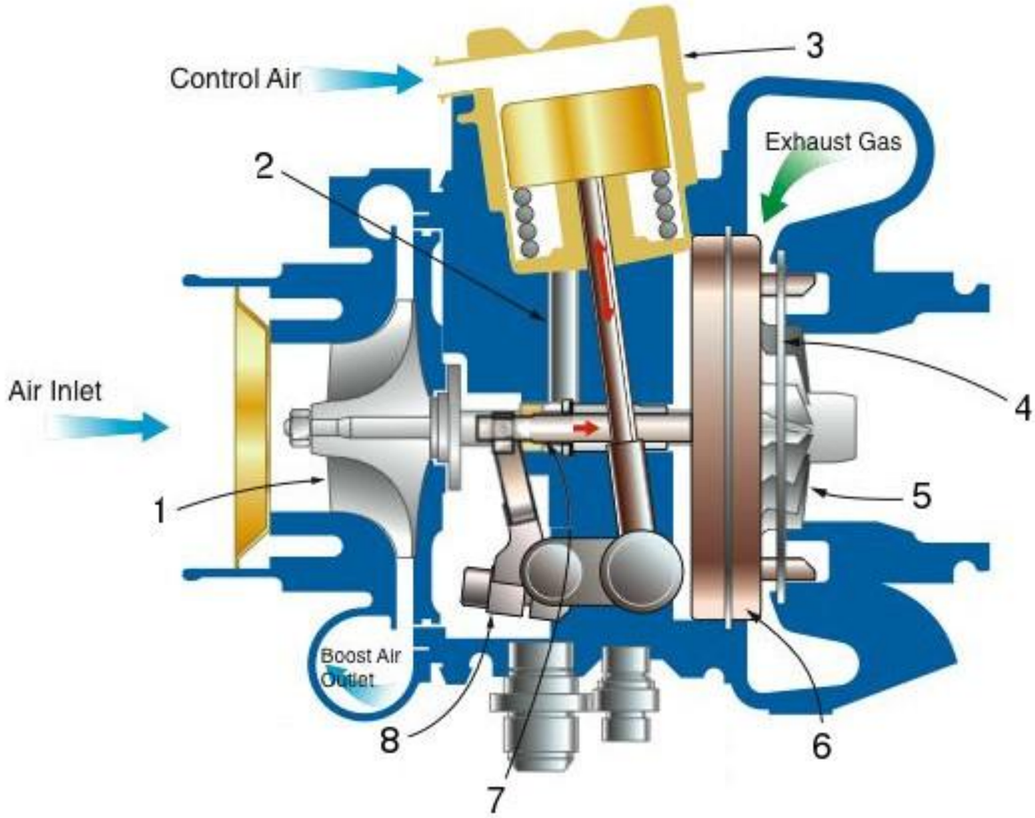


Figure 10 Moving wall variable geometry turbocharger (VGT) (1.compressor wheel, 2.shaft speed sensor, 3.pneumatic actuator, 4.fixed shroud plate, 5.turbine wheel, 6.sliding nozzle ring and vanes (moving wall), 7.push rod and bushes, 8.operating yoke)

In this design the moving wall (6) contains the nozzle ring, with the vanes being fixed at a constant angle. The position of the nozzle ring is relative to the turbine casing, its position being adjusted by the pneumatic actuator (3). When reducing the cross-sectional area, the vanes of the nozzle ring are entering in a fixed wall (4) through radial slots.

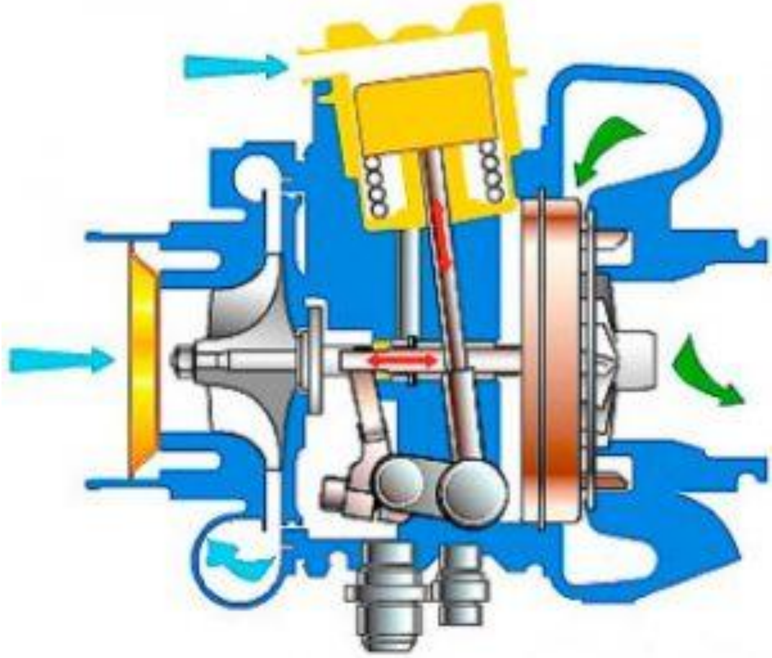


Figure 11 Sliding nozzle turbocharger – narrow

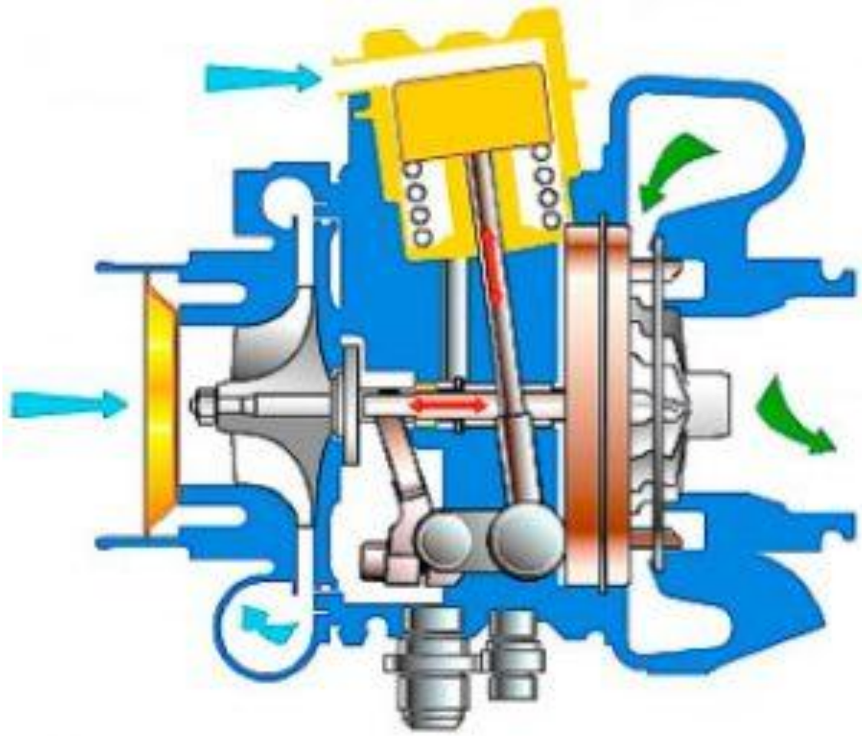


Figure 12 Sliding nozzle turbocharger – wide

At **low engine speed**, the nozzle ring is pushed to the right, reducing the cross-sectional area and the A/R ratio. This will force the increase of the exhaust gas speed, the turbocharger will spin faster and the intake air boost will increase.

When the nozzle ring (moving wall) is at its maximum left position, the cross-sectional area for the exhaust gas flow is at its maximum. The A/R ratio is also at its maximum value, with the engine operating at **high speed**.
Compared to the pivoting vanes desing, the moving wall variable geometry turbochargers have the advantage of less moving parts, which means less wear points and better reliability (less chances to fail). Moving wall design has the potential of a better efficiency at high exhaust flow. Not having multiple pivoting points, the exhaust gas leakage is reduced and the overall efficiency improved. The main disadvantage of the moving wall design is high manufacturing costs, mainly due to tight clearance and minimum contact between the nozzle ring vanes and the shroud plate openings.

The moving wall design is most of the time used in diesel applications for commercial vehicles. For example, Scania is using on its diesel engines applications a sliding nozzle variable geometry turbocharger (VGT).

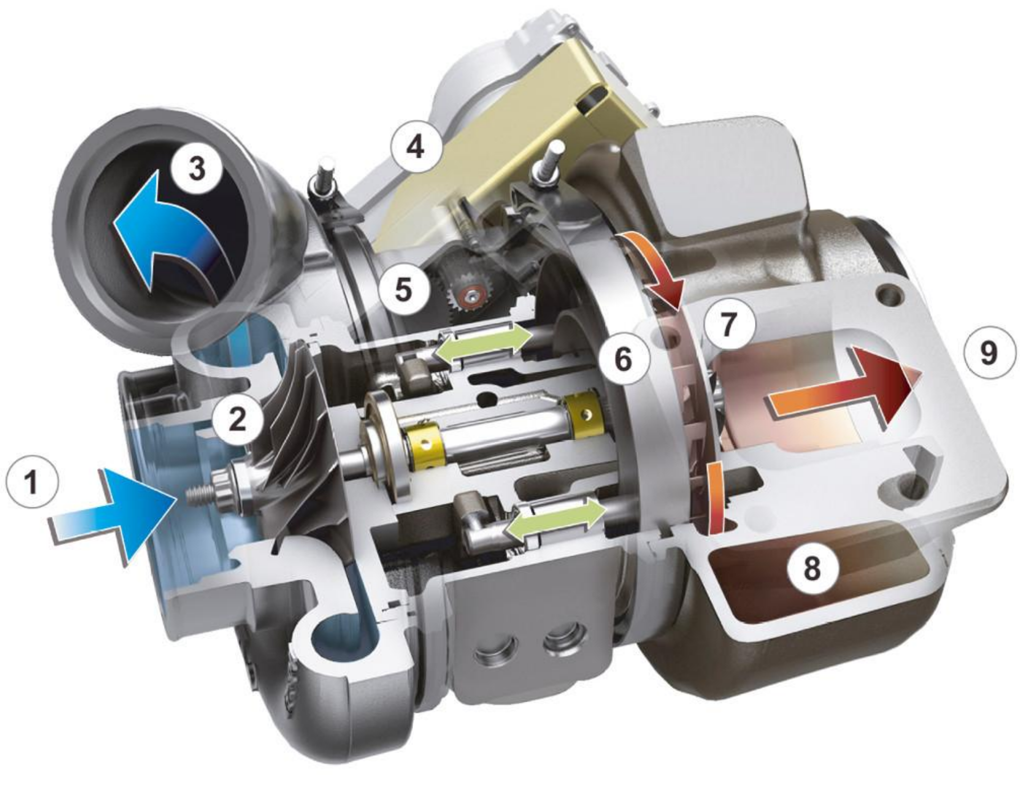


Figure 13 Variable geometry turbocharger (VGT) – slidevane

Sliding ring variable geometry turbocharger

The siding ring design is similar to the moving wall architecture. The main difference is that the vanes are fixed in a static nozzle plate. The variation of the cross-sectional exhaust gas flow area is done by a moving (axial) ring.

Figure 14 Sliding ring turbocharger

In **closed (narrow) position** the sliding ring is close to the nozzle plate and all the exhaust gas flow is forced through the vanes. This is the position with the smallest A/R ratio, high shaft speed and high intake air boost.
When the sliding ring **moves away** from the nozzle plate, the exhaust gas partially bypasses the vanes assembly and enters the turbine directly. In this position the turbine has a higher A/R ratio, lower shaft speed and the compressor provides a lower air boost.

Variable area turbocharger

The pivoting vanes variable geometry turbocharger obtains a variable A/R ratio by rotating the vanes around their pivoting point. The main disadvantage of this technology is the complicated and high cost mechanical system.

Aisin Seiki designed a variable geometry turbocharger which has a much simpler mechanical system, therefore lowering the manufacturing cost and increasing reliability. The **variable flow turbocharger** (VFT) developed by Aisin Seiki is based on a variable area principle. The turbine casing has two scrolls, an inner scroll and a outer scroll. A central pivoting valve guides the exhaust gas flow through the inner vane, outer vane or both, depending on the operating point of the engine (speed and torque).
Along the turbocharger wall, between the inner scroll and the outer scroll, there are also some stationary vanes which help redirecting the exhaust gas flow in the turbine wheel.

Compared to a pivoting vanes variable geometry turbocharger, the number of components in a variable flow turbocharger is smaller. Also, there is only one moving part, the central valve, which allows the engine control module (ECM) to employ a simple control algorithm, similar to the one used for fixed geometry turbochargers with wastegate.

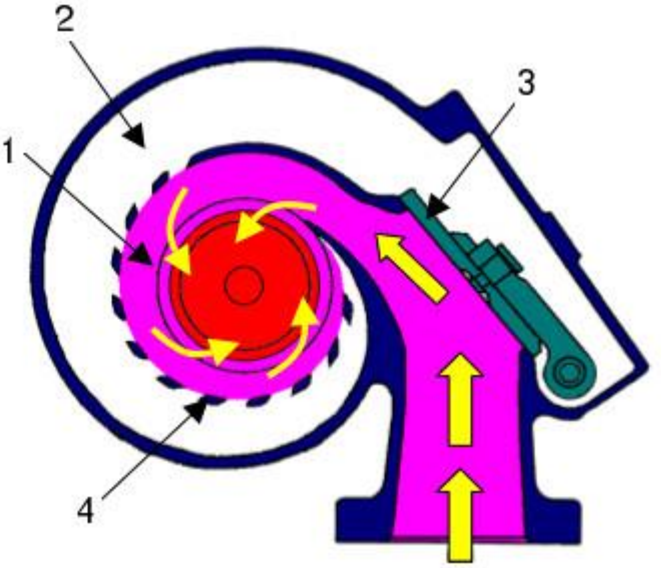


Figure 15 Variable flow turbocharger (VFT) – low flow rate (1.inner scroll, 2.outer scroll, 3.central flow control valve, 4.stationary vanes
)

Figure 16 Variable flow turbocharger (VFT) – high flow rate

At **low engine speed** (low exhaust gas flow rate), the central valve (3) is fully closed and the exhaust gas is forced through the inner scroll (1), which has a smaller cross-sectional area and A/R ratio. In this state, there is no exhaust gas flow into the outer scroll although there are passages between the outer and inner scrolls, as the outer scroll (2) is regarded as a statically pressurized chamber.

At **high engine speed** (high exhaust gas flow rate), the central valve controls the amount of the exhaust gas entering the outer scroll. The gas entering the outer scroll is fed to the inner scroll through the stationary vanes and merged with the flow in the inner scroll. The direction of the flow to the turbine rotor is a combination of the vectors of the two flows. Varying the flow angle to the turbine rotor can control the turbine speed, and hence control the turbine inlet pressure (exhaust back pressure of the engine).

The variable flow turbocharger (VFT) is a much simpler and lower cost option compared to a pivoting vane or moving wall turbine variable geometry turbocharger. Japanese automotive manufacturers (Honda) have integrated the VFT in both gasoline and diesel engines.

In terms of **actuation systems**, variable geometry turbochargers have a **pneumatic** actuator or an **electrical** actuator. Despite the higher cost, electrical actuated turbochargers have faster response time and more precise actuation of the moving elements.

Advantages of variable geometry turbochargers

- **higher low-end maximum torque**: a variable geometry turbocharger can improve the maximum torque of the engine in the low-end area due to the ability of the turbocharger to provide a higher air mass quantity; this translates into more fuel being injected, hence a higher mean effective pressure and torque
- **faster engine torque response**: especially in the low speed area, the torque lag of the engine is minimized due to ability of the turbocharger to accelerate faster and provide the required intake air boost
- **higher air-fuel ratio at low engine speed**: the extra intake air boost gives a higher air-fuel ratio (more air available for combustion) which could help reducing exhaust gas emissions
- **reduced throttling losses in the exhaust manifold**: a variable geometry turbocharger doesn't need a wastegate, since the exhaust gas flow is regulated by the pivoting vanes, sliding ring or central valve; therefore the throttling losses of the exhaust manifold are reduced, which increases the ability of the engine do "breathe" (perform gas exchange) with fewer losses
- **improves exhaust gas recirculation (EGR) rates**: for high pressure EGR systems, when the EGR valve is open, it's important that the exhaust gas pressure is higher that the intake air pressure in order to have a gas flow; being able to increase the backpressure in the exhaust manifold, a variable geometry turbocharger improves the efficiency of an EGR system
- **improves engine braking performance**: when the engine is in overrun state (engine braking), if the A/R ratio of the turbine is small, the backpressure in the exhaust manifold will be higher; in this case, the engine braking torque will be higher since it would need to compress the air in the exhaust at a higher level

Sources

- https://x-engineer.org/automotive-engineering/internal-combustion-engines/ice-components-systems/variable-geometry-turbocharger-vgt/
- https://x-engineer.org/automotive-engineering/internal-combustion-engines/ice-components-systems/twin-scroll-turbochargers/
- https://www.youtube.com/watch?v=VZuTDZiJaMs&ab_channel=JCMedia
- https://www.youtube.com/watch?v=SG6knfcTyM4&ab_channel=JCMedia