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Variable Geometry Turbocharger Technologies for Exhaust Energy Recovery and Boosting-A Review

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ABSTRACT

As emissions regulations become increasingly demanding, higher power density engine (downsized/down-speeded and increasingly right-sized) requirements are driving the development of turbocharging systems. Variable geometry turbocharging (VGT) at its most basic level is the first step up from standard fixed geometry turbocharger systems. Currently, VGTs offer significant alternative options or complementarity vis-à-vis more advanced turbocharging options. This review details the range of prominent variable geometry technologies that are commercially available or openly under development, for both turbines and compressors and discusses the relative merits of each. Along with prominent diesel-engine boosting systems, attention is given to the control schemes employed and the actuation systems required to operate variable geometry devices, and the specific challenges associated with turbines designed for gasoline engines.

1. Introduction

In response to increasing emissions regulations, engine manufacturers around the world have adopted a wide array of turbocharging technologies in order to maintain performance when downsizing their engines. Variable geometry turbocharging represents a large portion of the technology present in today's vehicles. VGT technology (also known as VNT-Variable Nozzle Turbocharger) is employed in a huge range of applications, such as in commercial on- and off-highway, passenger, marine and rail internal combustion engine applications. Aside from the emissions and engine downsizing components, other key developmental drivers include increased transient response, improved torque characteristics, over-boosting prevention and better fuel economy.

Turbocharger growth has been substantial in the last two decades and has experienced particular growth in areas where naturally-aspirated engine domination was until recently, still viable (USA and China in particular). Substantial growth figures are posted in recent years with a significant proportion of the realized as well projected market share being taken up by VGTs. VGTs are predicted to account for 63.3% of the global turbocharging market by volume by the year 2020. In the Asia/Oceania region, the adoption of VGTs is growing rapidly, and is projected to grow at a high compound annual growth rate of 14.61% from 2015 to 2020, when calculated by volume [1].

VGTs are therefore important not only due to the market share and

value that they represent in standalone, single stage boosting terms but increasingly as cost-effective boosting devices compared to more recent and advanced technologies such as electric turbocharging and supercharging. In addition, and for the same cost-effectiveness reasons they are being increasingly encountered, as part of advanced, multi-stage (two- and three-stage) architectures.

In addition, the other part of the Variable Geometry (VG) equation, the compressor has seen little implementation but is also of significant interest especially in view of the persistent requirement for maximized boost per stage. In addition, the compressor is being asked to operate across an increasingly expanding operating envelope and this is seen as a potential enabler for advanced engine cycle (Miller/Atkinson for example).

The objective of this paper is to present the first complete review of variable geometry technologies that are available commercially, as well as those currently under development and to highlight the merits of the increasing more complex options now available to powertrain developers where VG turbochargers are encountered as components of a more complex boosting architecture. The operating principles of variable geometry are covered, initially, followed by details of the range of different VG systems for both the turbine and compressor. A summary of current control systems and strategies, actuation methods and VG efforts specific to the gasoline engine are covered before concluding with a discussion on future trends for variable geometry

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Nomenclature

AFR	Air to Fuel Ratio
ANNs	Artificial Neural Networks
AR	Aspect Ratio
BSFC	Break Specific Fuel Consumption
CFD	Computational Fluid Dynamics
CI	Compression Ignition
CTT	Cummins Turbo Technologies
EAT	Electrically Assisted Turbocharger
ECU	Engine Control Unit
EGR	Exhaust Gas Recirculation
FEA	Finite Element Analysis
FGT	Fixed Geometry Turbocharger
HTT	Honeywell Turbo Technologies
MAS	Multi-Agent Systems
MHI	Mitsubishi Heavy Industries
MVEM	Mean-Value Engine Models
NA	Naturally Aspirated
NO _x	Mono-Nitrogen Oxides
PID	Proportional-Integral-Derivative
PWM	Pulse Width Modulation

SI	Spark Ignition
VFT	Variable Flow Turbocharger
VGT	Variable Geometry
VGT	Variable Geometry Turbocharger
VST	Variable Sliding Ring Turbocharger
VNT	Variable Nozzle Turbocharger
VVT	Variable Volute Turbocharge

Variables

A	Area
\dot{m}	Mass flow rate
M	Mach number
T	Temperature
p	Pressure
γ	ratio of specific heats

Subscript notation

*	Critical value
in	Inlet

turbochargers development and implementation.

2. Turbocharger systems

The modern day turbocharger market is diverse, as manufacturers strive to provide the improved technologies to lower exhaust emissions. There are numerous technology variants available on the commercial market, as well as under development. The most basic technology is the conventional, fixed geometry turbocharger, which consists of turbine and compressor wheels connected by a common shaft. Electrically assisted turbocharging systems use electrical machines in motoring mode to impart additional power onto the common shaft during low load operation to improve upon the performance of the fixed geometry variant. VG devices are employed different designs and/or are employed in different ways to alter the cross sectional area of the housing or inlet which guides the exhaust gas into the turbine rotor; these devices can also be coupled with diffusers to effect variable geometry for the

compressor [2].

Even though not directly linked to boosting (but only to energy recovery) one additional system that can be included here is turbo-compounding. This is a waste-heat energy recovery technology using an additional power turbine to recover energy in two forms: mechanical or electrical. In electrical turbo-compounding, the energy is transferred as electrical power and transmitted to the engine or to vehicle auxiliaries through the battery; the mechanical variant feeds kinetic energy back into the engine using a high ratio transmission.

Sequential turbocharging is an additional option that involves using two (typically) or more turbochargers of different sizes operating entirely or partially in sequence. A small turbocharger is used at low speeds due to its low rotating inertia, and a second larger turbocharger is used at higher engine speeds, usually with an intermediate stage where both may be in operation. Despite clear weight, cost and thermal inertia disadvantages this technology is becoming increasingly important in meeting the increased power density demand from engines of

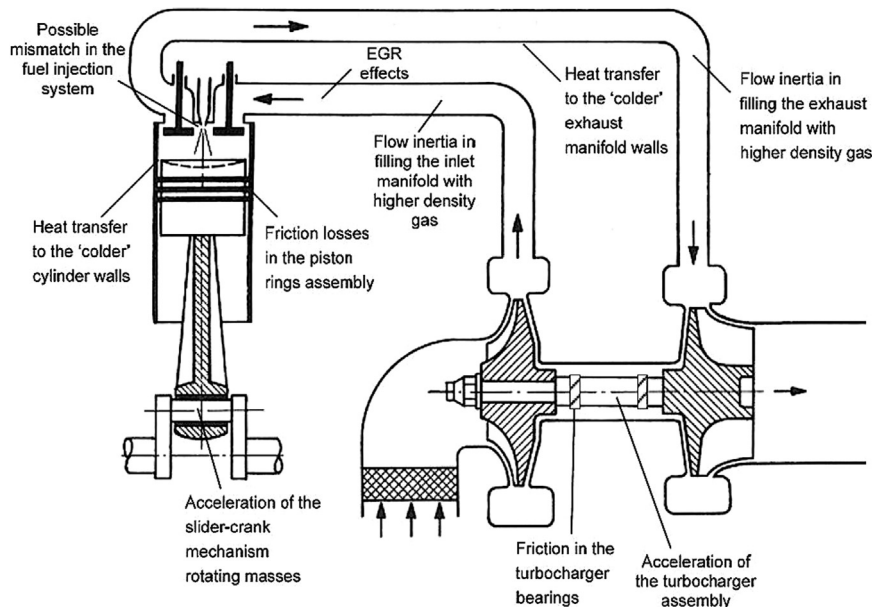


Fig. 1. A presentation of the major contribution to the system delay during transient response of a turbocharged engine [4].

the future.

3. Limitations of fixed geometry turbochargers

Downsizing engines may mean lighter, smaller and more compact powertrains, but there are limitations for turbocharging in these cases. To date, turbocharging has been far more commonly used in compression ignition engines (CI). Spark ignition (SI) engines are difficult to match with turbochargers due to the wider speed range and need to carefully control ignition timing to avoid knock. SI engines often operate at reduced compression ratios in order to prevent pre-ignition and limit knock; this makes fuel efficiency savings harder to achieve using a turbocharging. CI engines also face difficulties in matching turbochargers and engines, particularly for transient response [3,4].

The most widely recognised problem with fixed geometry devices is turbocharger lag; [5] the poor transient response of the turbocharger at low engine loads. Fig. 1 shows the major contributors to turbocharger lag for a SI engine. The biggest contributor is the rotating inertia of the turbine; this is due to the airflow not being sufficient to spool up the turbine rotor to higher speeds, a problem that is directly addressed by variable geometry systems. Analysis of Newton's second law of motion for rotational systems suggests reducing the rotor size and mass will reduce turbocharger lag [4].

In addition to the rotor size, another important parameter of turbocharger design that affects turbocharger lag and over-boosting is the aspect ratio (AR). This is the ratio of cross sectional area of the volute divided by the distance from the centre of this cross sectional area to the geometric centre of the volute. A small AR means that the velocity of the exhaust gas is increased and, therefore, a greater kinetic energy is available to the turbine rotor. Variable geometry devices in essence manipulate the AR value by altering the cross sectional area of the volute in order to increase air velocity at low engine speeds [6].

Fig. 2 shows a typical curve of turbine pressure ratio versus mass flow; the ideal relationship between these variables would be linear, but this is not possible with a fixed geometry turbocharger (fixed AR). To achieve a more linear relationship the cross sectional area of the turbine can be altered with a VGT for different load conditions. In summary, fixed geometry turbochargers are optimised with a fixed AR for a specific engine condition; for other engine conditions the system's efficiency is limited. VGT technology allows the performance of the turbocharger to be optimised across the whole engine range.

4. Operating principles of VGTs

VGT devices are designed to increase boost pressure at low speeds, reduce response times, increase available torque, decrease the boost at high engine speeds to prevent over-boosting, reduce engine emissions, improve fuel economy and increase the overall turbocharger operating range [7,8].

There are a number of different mechanical systems that are used to manipulate the AR value, and these are discussed in Sections 5 and 6 of this review. All technologies however share the common goal of using a nozzle-like system, or other movable components, to provide a variable cross sectional area. At low engine speeds the basic principle of most turbine systems is to narrow the inlet area to the rotor (reduced AR) such that air velocity is increased. Conversely, the passage is opened at higher loads. These positions are controlled by the ECU (Engine Control Unit) which is programmed to alter the nozzle geometry to achieve optimal performance at any given engine condition [9]. In simple terms, VGT systems (with the exception of a variable outlet turbine) have the ability to adjust flow conditions upstream of the turbine without altering the moment of inertia [4,10]. Early studies such as those by Lundstrom and Gall [11] highlighted the significant differences between early variable geometry devices and fixed geometry alternatives, particularly with regards to improved acceleration and response times.

The performance of a turbocharger is commonly described by non-dimensional mass flow rate and speed, which can be plotted against expansion ratio in the case of the turbine. The flow range of a radial flow turbine ($\dot{m}\sqrt{T/p}$) is limited at high pressure ratios by the choking of flow. The minimum area possible (A^*) for the nozzle section of the turbine can be defined (assuming an isentropic process with a perfect gas) as shown in Eq. (1) [2].

$$\frac{A_m}{A^*} = \frac{1}{M} \left[\frac{1 + \frac{1}{2}(\gamma-1)M^2}{\frac{1}{2}(\gamma+1)} \right]^{\frac{(0.5)(\gamma+1)}{\gamma-1}} \quad (1)$$

The area of the nozzle throat is a limiting factor in the performance of a turbocharger; many variable geometry turbocharger concepts allows for the alteration of this area. The effective area depends on the height of the passage (which can be altered in a sliding vane system) and the angle of the vanes (which can be altered in a pivoting vane system). In a vaneless system, the effective area depends on the exducer area and gas angle, this can be manipulated by changing the cross sectional area of the scroll.

Fig. 3 shows the effect of a VGT in comparison to a fixed geometry device during acceleration in second gear of a 6-cylinder, 11 L turbo-diesel engine. The solid lines on the graphs indicate a steeper curve in all three cases; VGT offers improved turbocharger rotational speed, engine speed and boost pressure than a regular turbocharger. It can also be seen at around 3 s that the nozzle is opened to reduce boost pressure and therefore prevent over-boosting; a wastegate is not needed and therefore there is no associated throttling loss.

The peak efficiency of a VGT is often lower than a FGT equivalent, partially due to leakage in the turbine casing and around the mountings of moving components [10,12]. The peak efficiency drops significantly when the nozzle is moved from its optimal position, refer to Fig. 4. Despite this the overall efficiency of a VGT is greater than that of a FGT due to the larger operating range [13].

5. Variable geometry systems for turbines

There are two main types of turbine design available on the market: radial and axial turbines. In a radial turbine, the exhaust gas enters the rotor perpendicular to the rotor blades (radially), and is redirected 90° by the rotor before exiting the housing in the axial direction. Axial variants work in the opposite manner, with exhaust gases entering the rotor axially and exiting in the radial direction. In an axial turbine the gas flow enters the turbine at zero angle, which minimises mechanical stress on the blades.

An example of an axial turbine for automotive use in the Honeywell Turbo Technologies (HTT) DualBoost™, this utilises zero-reaction aerodynamics, no nozzles and tall-bladed design to achieve a high-speed axial turbocharger. Using this technology HTT were able to reduce the mass of the turbine wheel, therefore reducing inertia by up to 40%. [15] In addition, axial turbines hold the advantage of better

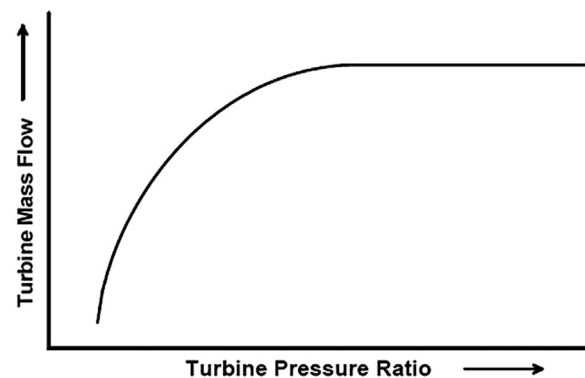


Fig. 2. Typical pressure ratio vs. mass flow curve for a FGT [4].

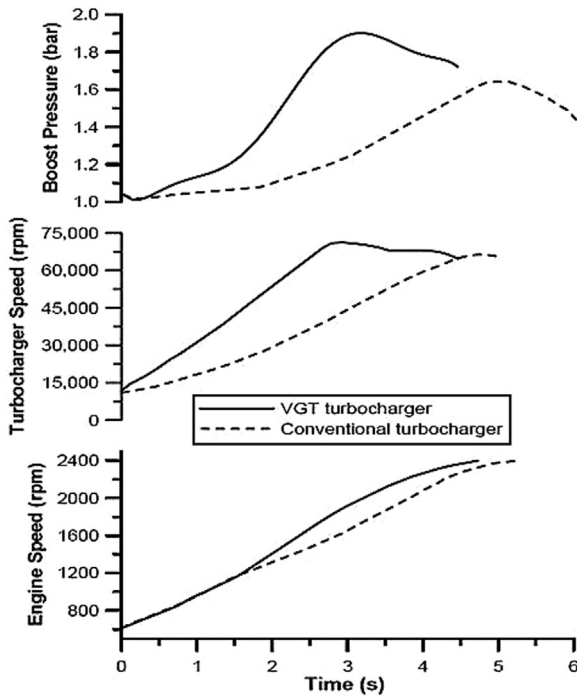


Fig. 3. Comparison of FGT and VGT [4].

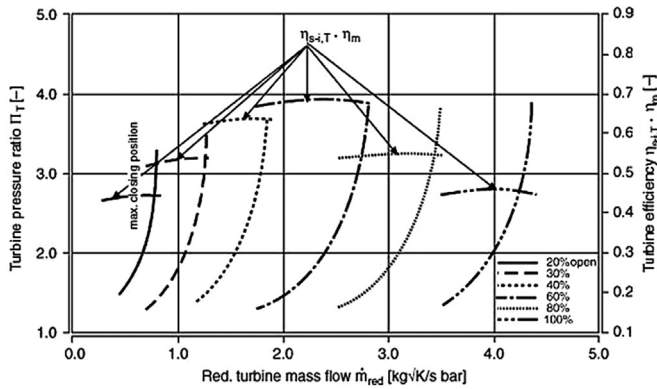


Fig. 4. Turbine pressure ratio, mass flow and efficiency for different nozzle positions [14].

efficiency at lower blade speed ratios than radial equivalents. This DualBoost™ turbocharger was tested against a conventional radial device. [16] Results showed that both were capable of achieving the target full load steady state torque and power. However the Dualboost™ device responded much faster to increasing engine load, reaching maximum torque at just 1200 rpm, the radial device didn't peak until 5000 rpm, and failed to reach the torque level of the Dualboost™ turbocharger. The results were replicated in both steady state and transient tests, with the Dualboost™ curves steeper in all instances.

Fig. 5a and b shows a comparison of radial and axial types from a study by K.H. Bauer et al. [16] for HTT. Fig. 5a indicates the efficiency curves for both rotor types, with axial devices excelling at lower normalised blade speeds and radial peaking higher in terms of efficiency and speed. Fig. 5b shows the reduced inertia of axial devices when compared with radial counterparts.

Early attempts to compare different methods of variable area devices for turbines, such as that by Flaxington and Szczupak, [17] concluded that not one VG method existed that was superior for all applications. However, the authors did note that VG methods in general did improve engine torque, widen the speed range and improve

the transient response.

5.1. Sliding nozzle

A common method of variable geometry in radial turbines is the use of a sliding vane ring. This simple and robust method is most commonly found in the turbochargers of trucks and buses due to its suitability to larger engines. The sliding nozzle method allows for higher boost at lower engine speeds, and is the best fuel-efficient means of driving EGR (Exhaust Gas Recirculation).

Sliding nozzle devices comprise of a series of vanes that are rigidly mounted on a ring, which is positioned around the rotor, as shown in Fig. 6. The purpose of the vanes is to direct the radial flow onto the rotor, and the sliding mechanism is used to narrow, or widen, the passage for the exhaust gas flow to suit the engine conditions. Since the vane ring slides axially into the flow, packaging is relatively compact. A minimal number of wear sites equates to improved durability.

Franklin [19] documented the development of Holset's VGT system, highlighting the benefits of the robust sliding vane technology at its conception. Other attempts have been made at having multiple sets of sliding vanes at different angles; a design from the Nippon Institute of Technology [20] used two sets of vanes, one with a hollow space to accommodate the other. This meant a smaller vane with a different angle setting could be used at higher speeds. At low speeds a larger second vane would slide out (with a hollow space to accommodate the initial high speed vane) to provide a greater nozzle effect.

5.2. Pivoting vanes

Similarly to sliding vane devices, pivoting vane turbochargers have a ring of vanes mounted on a flat plate. In this case however the vanes

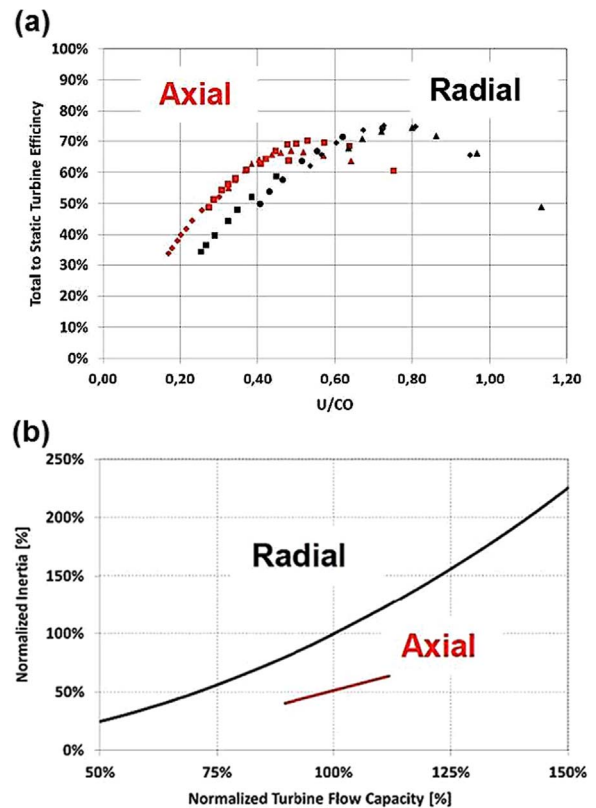


Fig. 5. a. Comparison of radial and axial turbine efficiency (a) and inertia (b), red indicates axial and black indicates radial [16]. b. Comparison of radial and axial turbine efficiency (a) and inertia (b), red indicates axial and black indicates radial [16]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

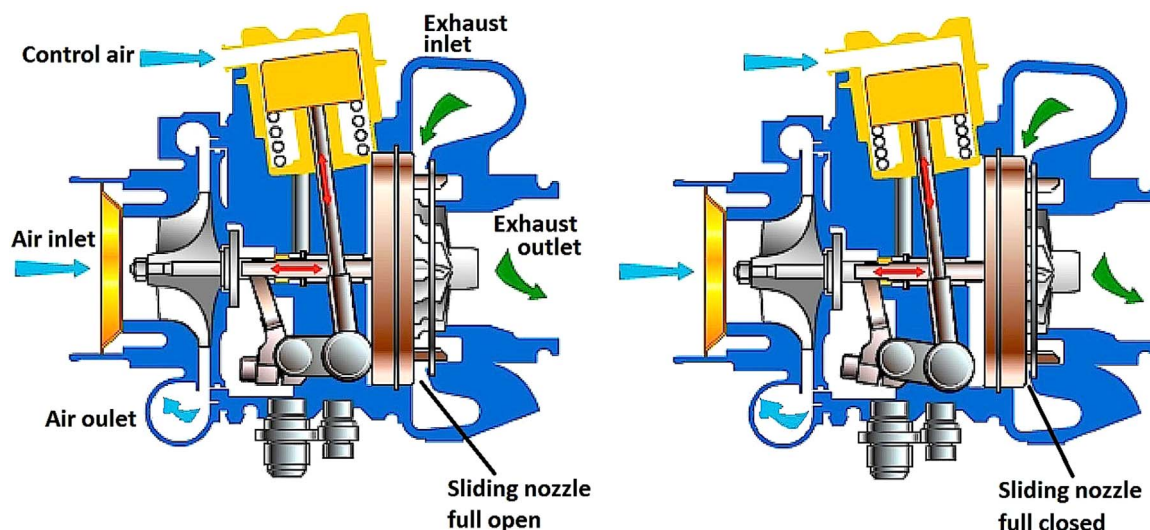


Fig. 6. Cross section view of a sliding ring turbine mechanism [18].

are mounted on pins that allow them to rotate axially. These vanes remain permanently in the gas flow with no sliding motion to narrow the flow passage. The nozzle effect here is provided by the rotation of the vanes; they can be opened and closed to allow varying amounts of air onto the rotor (refer to Fig. 7). Vanes are closed during low engine loads to accelerate the airflow. As the engine revolutions increase, the vanes open to prevent choke. The pivoting vane system has a higher overall efficiency than sliding vane variants [21].

Axially moving vanes are a well-established technology, with much of the performance development already undertaken in previous decades, such as the study from Shao et al [24].

Like sliding vane, pivoting vane mechanisms and exhaust gas recirculation (EGR) systems are a good match. The pivoting vanes provide the improved flow conditions needed for successful EGR. By pumping some exhaust gases back into the cylinder NOx emissions are reduced owing to a smaller proportion of O₂. High-pressure EGR systems [25] are most common for turbines, whereby exhaust gas is

drawn from upstream of the turbocharger. In VGT devices, the aspect ratio will determine the EGR flow, since it governs the pressure difference between the inlet manifold and exhaust manifold [4]. EGR is more commonly found on turbocharged diesel engines than petrol variants, since the exhaust gas temperatures are significantly lower; around 850 °C for diesel engines and 1000 °C for petrol engines [12,26].

Whilst the pivoting vane system is the most common for VGT devices, it is not without its drawbacks. Durability problems exist, particularly in higher temperature applications such as gasoline engines. At elevated temperatures metal-to-metal friction becomes a problem, which can cause the pivoting mechanism to stick. This will drastically reduce performance, and if over-speed occurs can lead to turbine failure.

Mitsubishi Heavy Industries (MHI) conducted research into the design of VGT vanes for their own turbochargers, designed for diesel engines [12]. Along with the shape of the vanes themselves, the issue

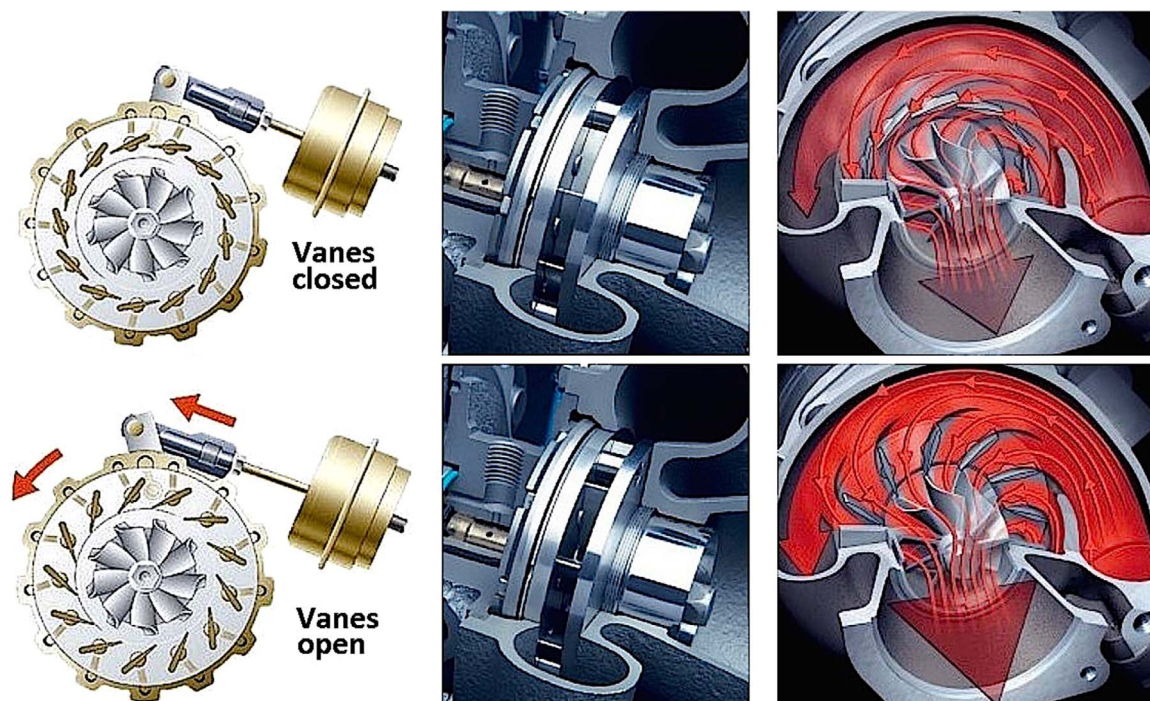


Fig. 7. Pivoting vane turbocharger in fully closed (upper) and fully open (lower) positions [22,23].

with vane-sticking was addressed. They discovered that higher temperatures lead to expansion of the metal components, causing abnormally high contact pressures being transmitted by moving components, seizing the entire VG linkage. The suggested design modifications included the introduction of a small drive ring overhang, or the redesign of the actuation mechanism.

Other studies have also included a comparison of sliding vane with pivoting vane technologies, from a control standpoint [27] and investigations into the shock waves that can occur at the nozzle exit under high inlet pressure conditions [28,29].

6. Variable geometry systems for compressors

With the increased performance of VGT devices over fixed geometry counterparts, in many cases compressor performance has to become adaptable to prevent choke or surge behavior, and this has been achieved with variable geometry compressors [30]. Compressor wheels for turbocharging are generally centrifugal by design; air is drawn in axially and accelerated before exiting in the radial direction, often through a diffuser. Axial compressors are used in jet engines and are therefore common in the aerospace industry. Axial designs can also be found in large industrial diesel engines, or heavy fuel engines that run at a constant rotational speed; such as in ships and heavy mining machinery. A comprehensive review of variable geometry systems for compressors has been published previously by Whitfield [31] and provides a good insight into vaned, vaneless and low solidity diffusers; as well as a more in-depth look at inlet swirl than is present in this review, since the author discusses passive methods.

The diameter of an axial compressor is largest at the inlet, and therefore no change in rotor diameter is needed for pressure generation. These systems are therefore destined for large air quantities at a given outer diameter. However to generate greater pressures, axial devices often require several stages; whereas radial compressors are able to obtain greater pressure levels across a single stage [14]. The design of the blade profiles is hugely important to the performance of both single and multi-stage compressors [32,33].

Cummins Turbo Technologies (CTT) have used an inverse design process to shape a new centrifugal compressor wheel [34]. Fig. 8a shows the 3D inverse design, alongside a standard impeller in Fig. 8b. 3D inverse design uses iterative processes which begin with the definition of blade angle and thickness distribution in order arrive at an optimum design solution. Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) are used to evaluate airflow and durability performance respectively.

The result of CTT's 3D inverse design process is illustrated in Fig. 9. At very low flow and pressure ratios the inverse design fares worse than

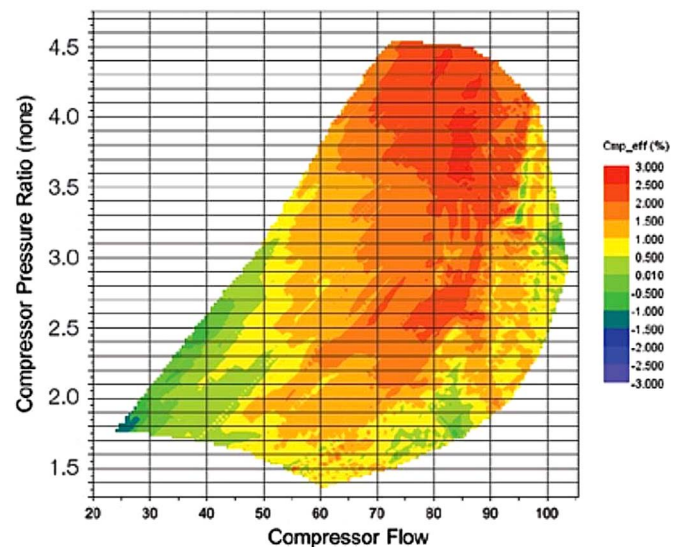


Fig. 9. Compressor efficiency improvement using inverse impeller design [34].

the standard impeller, but efficiency is largely improved across the rest of the map, with gains of up to 3% at high pressure ratios and flow rates. It was also observed that the overall trends, with regards to efficiency and pressure ratio, were closely mirrored by full stage CFD studies. This suggests that modern inverse design methods offer an efficient alternative to standard design processes [34].

6.1. Variable inlet guide vanes

Compressors can use variable geometry systems to alter performance in a similar way to turbine systems. Variable inlet guide vanes use flow regulation vanes in the inlet in order to give incoming air a swirl component. Swirl in the direction of impeller rotation is known as positive swirl, and in the opposite direction is known as negative swirl. Making these vanes variable means the relative velocity vector approaching the impeller can be controlled, eliminating the tendency of stall as flow rates are reduced. Fig. 10 illustrates the velocity triangles for both cases.

The effect of swirling flow in turbochargers has been studied, with significant publications from Whitfield et al. [35] also Whitfield et al. [36]. Additional studies focused specifically on the compressor by Simon et al. [37] also by Williams [38]. The objectives were to improve compressor pressure ratio over the turbocharger operating range, and inlet guide vanes were introduced to control the swirl angles at

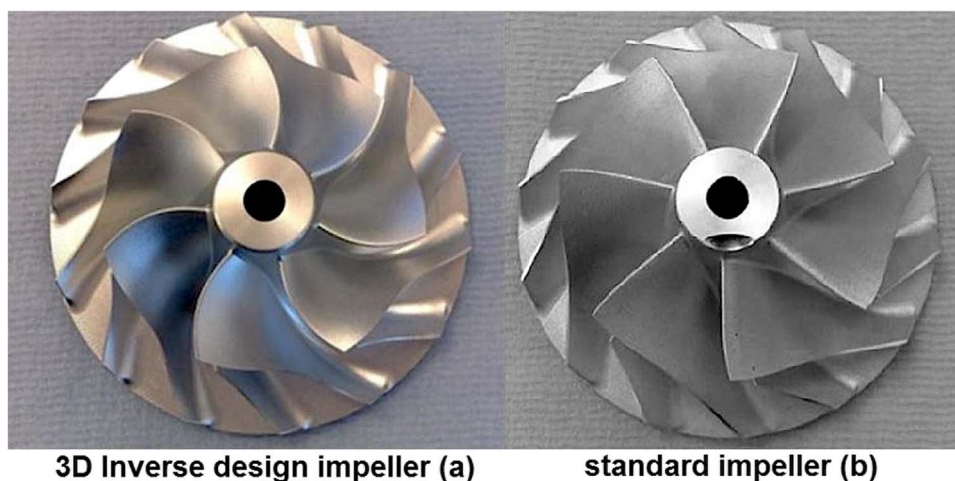


Fig. 8. 3D Inverse design impeller (a) and standard impeller (b) [34].

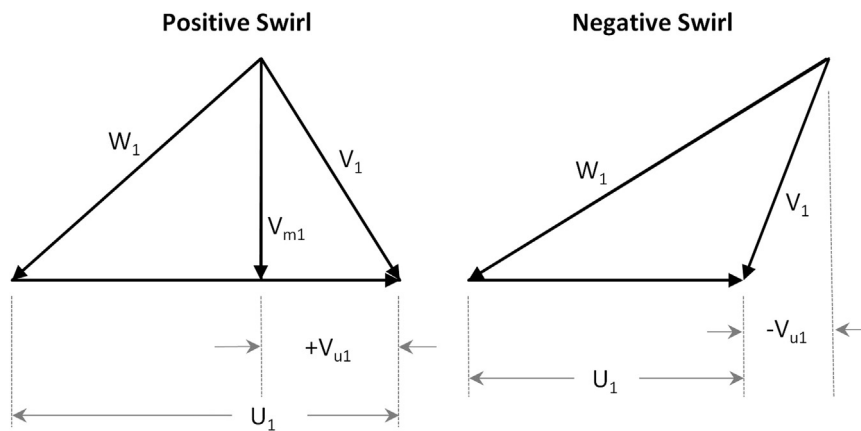


Fig. 10. Positive and negative swirl in radial compressors.

different flow rates. Whitfield et al. [35] obtained a small shift in the surge limit of the compressor by the application of 40° swirl angle at the compressor inlet. Williams [38] showed that by coupling swirl angle at the inlet with an impeller that has a large back-sweep could produce a larger expansion of the compressor surge limit at pressure ratios of 1.6–1.7. However, studies also suggest that increasing the swirl angle reduces the overall efficiency of the compressor; further investigation is needed in high swirl angles.

A tandem vane design by Swain [39] allowed the development of high swirl angles without the associated efficiency losses. CFD analysis applied to this design, along with a spherical duct arrangement, by Coppinger and Swain [40] showed a reduction in pressure loss across the vane with swirl angles up to 60° .

6.2. Variable geometry vaneless diffusers

A diffuser is a stationary component that is fitted directly around the impeller. The main function is to convert the kinetic energy of the air leaving the impeller into static pressure. There are many types of diffusers for use in turbocharger systems, and the vaneless variety is the most common when a wide operating range is required.

Ludtke [41] investigated compressor effects by narrowing the diffuser passage and suppressing surge to extend the operating range. Whitfield [42] carried out similar investigations. In both cases radial impellers were used and it was found that constant area diffusers improved surge performance with minimal impact of efficiency. Parallel diffusers were found to have the highest efficiency, but reduced surge performance. Reducing the passage width was found to reduce peak efficiency, but improved surge characteristics. Whitfield [42] also suggested improvements in surge performance by applying a flexible diffuser wall to provide variable geometry, although this is impractical.

A more practical possibility was published by Abdel-Hamid [43,44]. He considered a variable throttle ring to be used at the exit of the diffuser. This ring was applied to the compressor of a turbocharger by Whitfield and Sutton [45] and results showed better efficiency at high flow rates in surge. Hagelstein et al. [46] showed that a throttle ring used on a vaneless diffuser improved the static pressure distribution at impeller discharge.

A rotating vaneless diffuser was designed and studied by Rodgers and Mnew [47]. In this system, the shear forces between the high velocity flow and the diffuser walls are reduced by allowing diffuser walls to rotate. Rotating walls reduce friction losses by about 20% compared with the stationary wall diffuser. The rotation of diffuser walls prevents flow separation, promotes smooth flow profile from the impeller, and provides flow stability.

6.3. Variable geometry vanned diffusers

Variable geometry vanned diffusers improve efficiency and increase the operating range of turbocharger compressors. The vanes are aerodynamically shaped and can be adjusted to provide the most efficient angle for a wide range of flow rates. Simon et al. [37] used aerodynamic diffuser vane profiles and adjustable inlet guide vanes to show that the simultaneous adjustment of the inlet guide vanes and diffuser vanes provided an expansion in the operating range. Also, improvements in efficiency over the entire operating range of the compressor were achieved.

Harp and Oatway [48] investigated the wedged shaped vanes which were used for military hardware turbochargers. The vane angles were controlled by a sliding pin which was located in the slot along the chord of the vane. The leading edge of the vane was pinned. The angles of the vanes were adjusted to optimise diffuser throat area, and to achieve high flow rates. This method was adopted to create a VG diffuser that allows control and maximization of the flow over various operating ranges.

Theoretical analyses and experimental results for two unique VG techniques, conducted with pipe diffusers to enhance off-design performance, have been reported by Salvage [49]. One technique mechanically closes the diffuser throat in an unusual manner. The other allows flow recirculation to close the throat artificially while attempting to improve diffuser inlet flow characteristics. In the first design two split rings are used. By rotating one ring relative to the other, the radius is divided by 1.2 times the impeller radius. It was obtained that surge occurred at reduced flow rates with 4 degrees of rotation. In the second design the flow is recirculated from the collector back to the impeller discharge. This helps to maintain a constant flow through the diffuser as the impeller flow varies. The recirculating flow rate is controlled by a shut-off ring. Obtained results from experimental testing indicate that with the recirculating passage fully open, there was a shift of the surge line to reduced flow rates at all inlet vane positions. Moreover, the test showed that the shut-off ring had to be opened more than 10% before any positive improvements could be obtained. The maximum benefits have been achieved with recirculating passage open 50%.

6.4. Low solidity diffusers with variable geometry turbines

Vaned diffusers have a higher static pressure recovery than a vaneless diffuser, but the vaneless diffuser has flow range advantages. Therefore, Senoo, [50,51] applied a low solidity diffuser to a low specific speed centrifugal compressor and demonstrated that efficiencies of a vaned diffuser could be achieved. This was done whilst maintaining the same useful operating flow range that a vaneless diffuser offers. Low solidity diffusers have a few vanes of short length

and have no actual channel in the diffuser, as shown in Fig. 11. It provides the stable operating range at low and high flow rates. In his work Senoo [51] suggested design guidelines for low solidity diffusers, such as: diffuser vanes need to be closely coupled to the impeller, a low number of vanes should be used and that relatively flat stagger angles should be employed.

The application of low solidity diffusers to a turbocharger compressor has been investigated by Eynon and Whitfield [52,53]. They showed that the VG arrangement needs to be applied to obtain a large operating range and also investigated the effects of vane trailing and leading edge angles.

7. Actuation systems for variable geometry turbochargers

Whilst the operation of the differing types of VGT flow systems have been discussed, variation of the exhaust gas flow would not be possible without the use of an actuator. The most commonly fitted systems for VGT devices are pneumatic, hydraulic and electric variants.

7.1. Pneumatic actuation system

The most common design of these actuators is pneumatic, which uses a gas (air) to move a piston inside a closed cylinder. The movement of the piston controls the variable geometry mechanism. The major problem associated with pneumatic actuators is that the gas used is a compressible fluid; this reduces the control of the actuator, since it is difficult to predict the condition of the air once compressed. If there is any addition of heat within the actuation system, the properties of the gas change [54–56]. Subsequently, the trend for actuation of VGTs is for either hydraulic or electric systems.

The vane position is governed by a diaphragm-type actuator connected to the vanes control ring by a rod, so that the throat area can be varied continuously. The actuator runs the rod as a function of a vacuum level, counteracting against a reaction spring. As illustrated in Fig. 12, the vacuum modulation controls an electro valve, which offers a linear current against vacuum level characteristic. Vacuum can be supplied by the vacuum pump of the brake booster. Current is supplied by the battery and modulated the ECU using Pulse Width Modulation (PWM) principle. By increasing the duty-cycle of the PWM command (i.e. VGT command) it is possible to reduce the nozzle area and subsequently to enhance the boost pressure. An upper and a lower limit of duty-cycle (corresponding respectively to minimum and maximum nozzle area) define the active range of the VGT command [58].

7.2. Hydraulic actuation system

The hydraulic type of actuation device can be fed with the engine oil as means of providing movement to the nozzle ring or variable vanes. This works using the same principle as the pneumatic variant, but introducing a fluid (instead of a gas) onto a piston which then acts upon the nozzle ring or pivoting vane through a yolk or vane ring. Unlike the pneumatic variant, the fluid in hydraulic systems is not compressible, which means there is more control over the actuation [17,59].

In this mechanism a PWM vane position control solenoid valve uses engine oil pressure and the ECU signal to move the turbochargers unison ring. A hydraulic piston will move a geared rack mechanism, which in turn, rotates a cam-shaped pinion gear thereby articulating the vanes as shown in Fig. 13. An analog position sensor with a movable tip rides on the vane actuator cam and estimates the vane position to generate feedback to the ECU. Integrated in the sensor harness is a module converting the analog signal to a digital signal supplied to the engine ECU. The vanes are fully opened when no oil flow is commanded to move the servo piston and to reduce opening as oil pressure increases through the vane position control solenoid valve.

7.3. Electric actuation system

Electronic systems make the most accurate actuators. This is because voltage can provide very fine control, which, through a small selector gear, powers the VGT. However, electrical systems do require the addition of coolant pipes to avoid overheating, whereas pneumatic and hydraulic variants both use the movement of fluid to remove latent heat from the system [60].

Some variable nozzle turbochargers use a rotary electric actuator, which uses a direct stepper motor to open and close the vanes as represented in Fig. 14.

In this mechanism an electronic feedback control valve regulates the actuator position vanes through a regular rack and pinion mechanism. But in this case, the cam attached to the pinion provides displacement feedback directly to the ECU by means of a magneto-resistive sensor. When the electronic feedback control valve is de-energized, the vanes are in full open position. If, for example, the ECU intends to move the vanes to 50% closed, it will provide a current within a certain range to tell the control valve to close the vanes. When the magneto-resistive sensor confirms the vanes have reached the intended 50% closed position, the ECU will provide the “null” current to keep the control valve in its centre closed position, and therefore, maintaining the 50% commanded position. Because of the closed loop system, if the actual position drifts from the commanded position, the ECU will provide the necessary current change to bring the position back to where is desired, and then it will move back to null current to maintain it. With the elimination of the mechanical friction components mentioned earlier, the actuation system hysteresis can be significantly reduced.

8. Control systems for variable geometry turbochargers

The problem of control over the actuator of a variable geometry turbocharger is one that has received ever-increasing attention as VGT technology increased in popularity. This aspect of VGT design can be considered a novelty for a forced induction system, and focuses on the positioning of vanes for various operating conditions. Vane positions play an important part in regulating gas flow to the turbine, so decisions here can often lead to the success or failure of a VGT.

Control of a VGT is complicated by the multivariable nature of an engine coupled with a turbo, as well as other emission reducing components. Diesel engines typically enforce the use of EGR, and EGR flow has been considered of primary importance to control designers. Control in SI engines provides further issues, where engines are forced to operate near knock-boundaries to achieve stoichiometric combustion [62].

Various studies mentioned herein have attempted to implement strategies that focus on either boost performance, which is targeted by

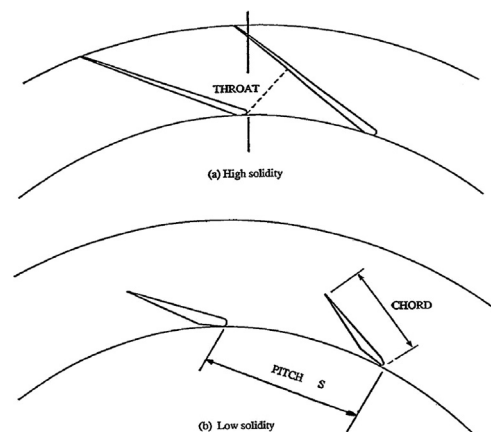


Fig. 11. Vaned diffuser throat for high and low solidity designs [52].

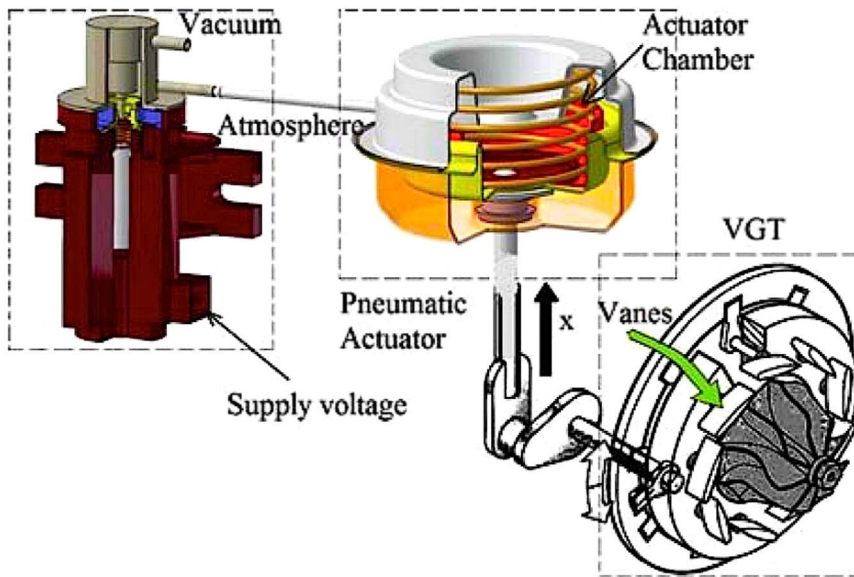


Fig. 12. Principle of pneumatic actuation mechanism in a VGT turbine [57].

regulating the pressure in the intake manifold, or emissions performance. Targeting emissions performance usually results in trade-offs, whereby designers attempt to decrease NO_x, BSFC and smoke emissions simultaneously.

The most common strategy, for finding set points at which a VGT vane can be placed, has relied on engine models and empirical data to provide reference for the controller. This method involves a feedforward controller that chooses set points from a lookup table, and employs feedback to achieve low error. The technique is flexible in allowing different control strategies and has been used to regulate boost pressure [63] and improve AFR and EGR performance [64].

In the study from He et al., [63] a lookup table of engine speed against fuel quantity was used to decide VGT positions in an open-loop

manner, with EGR flow controlled in a closed-loop fashion. In the study from Shirakawa et al. [64] it was found that using mass flow through the EGR valve versus mass flow through the exhaust manifold gave a defined strategy.

Techniques to provide a lookup table have also varied. Mean-Value Engine Models (MVEM) [65] provide an alternative method to empirical studies in finding vane and EGR actuator positions. Artificial Neural Networks (ANNs) have also been used to learn VGT performance from set maps and provide estimations for vane positions for any operating condition [66]. With the latter technique, two strategies were built based on keeping boost pressure at a designed level, and another strategy that maintains a negative pressure difference across the engine to enhance EGR flow, which was found to

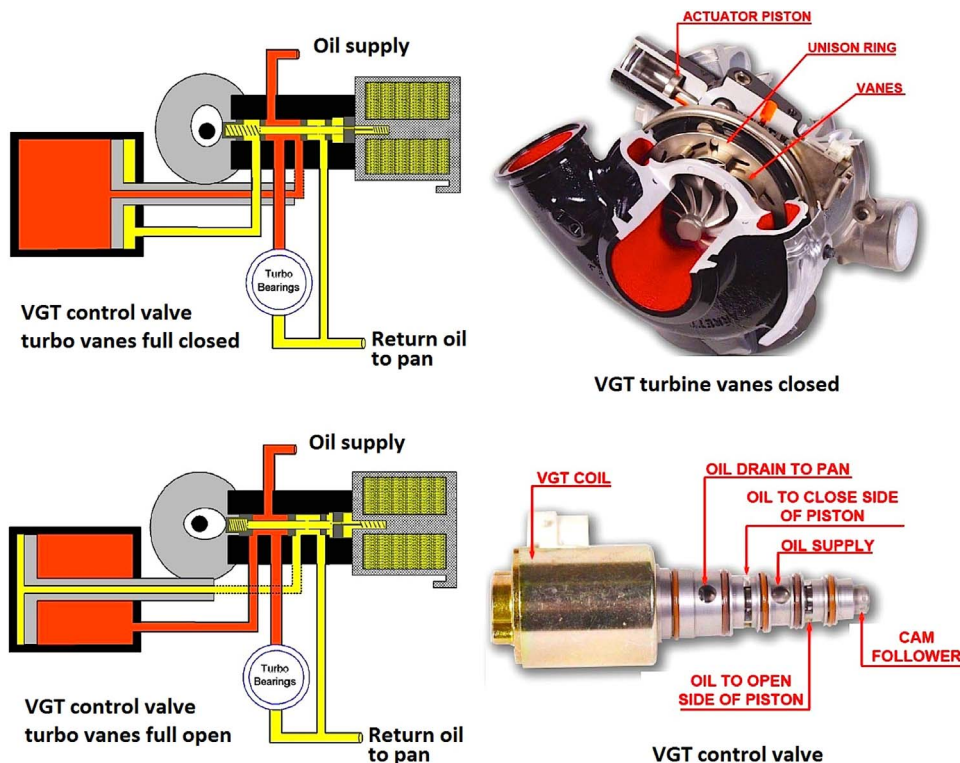


Fig. 13. Principle of hydraulic actuation mechanism in a VGT turbine [18].

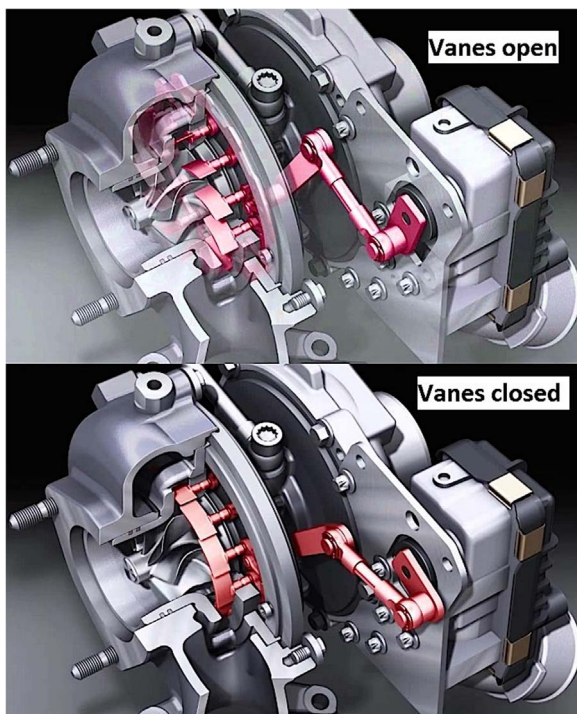


Fig. 14. Principle of electronic actuation mechanism in a VGT turbine [61].

provide 45% NO_x improvement in another study [67]. Both strategies were shown to have uses, although attempting to maintain EGR flow (by enforcing a constant negative pressure drop) resulted in overspeeding of the turbine and compressor. A better strategy should involve vane position being controlled open-loop when EGR is active [63].

Despite seeing much implementation, the use of a simple feed-forward controller has limitations in transient response. That is, when the vehicle sees high acceleration or gear changes, the VGT should react promptly. Consequently, several advances have been made in the method by which the system is controlled. Attempts at producing multivariable controllers have been made, using well-optimised control functions [68,69]. Other controllers have adopted feed-forward controllers for steady-state operation and quicker PD (Proportional-Derivative) controllers to act when the vehicle is thrust into high transient operation [58,70]. This technique involved a switching logic that switched to transient operation when the derivative of boost pressure was found to be excessive and switched back when it had returned to reference values. Another PID (Proportional-Integral-Derivative) controller used lookup tables for set points, and feedback to improve transient performance. This design is supported in theory by Van Nieuwstadt et al., [71] where it was suggested that set points provide the most effect on performance, especially in steady-state operation.

PID's and nonlinear controllers have also been taken forward for use in controlling VGT actuation in SI engines [72]. In this, a one step-ahead approach was used to extrapolate parameters and then control them with a closed-loop. A summary of this, amongst other works, by Flårdh, [73] agreed that the notion of feed-forward control being poor for transient response was also applicable to SI engines, but feedback control should only be activated for these periods to prevent excessive fuel consumption.

In the study by Lezhnev et al., [74] a comparison of controllers was made using a validated mean-value engine model (MVEM) in GT-Power (1D engine simulation software) for an SI engine. The research concluded that feed-forward control was useful, although the tendency to overshoot parameters means that feedback is absolutely necessary for transient operation. For fast torque response it was found that

closed-loop control that attempted to work VGT and throttle position were best.

Whilst PID controllers have been seen, by some [62] to be the future of control technology for VGT operation, it has its limitations when viewed over an entire load range, where it is not found to be robust enough in decision making [75]. To improve decision making, some designers have employed fuzzy logic decision-making algorithms [76]. This has been implemented with Multi-Agent Systems (MAS), [72] which works to make decisions with weighted inputs from the ECU. These have been shown to have great robustness, speed and performance, whilst not burdening the vehicle with too large an amount of computation.

9. Current and future trends for variable geometry turbocharger systems

The previous sections of this paper have highlighted the developed technologies available to turbines and compressors of diesel engines, as well as their control and actuation methods. These technologies are well established in the modern turbocharger market, which has allowed academia and industry to press forward with developing new systems and applications that incorporate a variable geometry element. The upcoming sections aim to describe more recent research developments and applications for variable geometry technologies.

Although variable geometry methods do offer considerable benefits gains over their fixed geometry counter parts, there are ways in which the established variable geometry technology can be improved upon further. Response times can be improved by adding one of a variety of assistance methods, gasoline engines offer a unique challenge for turbocharging with higher gas temperatures calling for modifications to components, and volutes themselves can contain elements which alter the geometry of the turbocharger housing during operation.

VGTs are predicted to account for 63.3% of the global turbocharging market by volume by the year 2020. In the Asia/Oceania region, the adoption of VGTs is growing rapidly, and is projected to grow at a high CAGR of 14.61% when calculated by volume (from 2015 to 2020). [1].

9.1. Variable geometry turbocharger systems for gasoline engine applications

As demands for higher specific output and decreased CO₂ emissions become more important to road vehicle manufacturers, the gasoline engine has seen a decline. Resistance to this trend has been aided by downsizing trends, which suit SI (spark ignition) engines more than CI (compression ignition) engines; many manufacturers are now looking to smaller gasoline engines, often of less than 1 liter.

In order to produce the same amount of brake power as an engine with a larger displacement, turbocharging technology is seeing more use. Turbochargers with VG properties are now being looked at for their ability to provide boost across the range of loads that are presented by this type of engine. However, VGT devices also present their own problems. The increased amount of moving components with the design and the need for them to withstand higher temperatures, up to 1050 C, [77] means that much more effort is needed to bring a reliable device to the market [62]. Furthermore, SI engines require the handling of a much more varied throughput of exhaust gases than a CI engine, so any VGT would have to be able to handle a large range of mass flow rates. As such, this type of forced induction has only been implemented, for SI engines, by a handful of companies to date.

In a study from GM Powertrain that involved a comparison of various VG-type turbochargers, [26] it was shown that most VGT's provide performance gains in several key areas, especially at low engine speeds. However, when at higher speeds, they were shown to be unable to cope with the high mass flow rate demands, with moving vane types seen to have poor efficiencies when fully open. As such, it was

recommended that a wastegate valve be employed. Although VGT's are intended to allow operation without a wastegate, this is necessary to prevent excessive backpressure.

Of the six turbochargers tested in this study, [78] a Variable Flow Turbocharger (VFT) was highlighted as having the characteristics that supported its use in gasoline engines. This VFT design involves an actuating arm that limits the inlet area of the turbo and contains a fixed vane, providing two flow areas for exhaust gases; it also supports several more fixed vanes positioned around the turbine to contain and merge gas flow. The VFT was developed by Aisin Seiki, who successfully decreased production costs for the component and resistance to high temperatures [78]. The lack of moving parts and the minimal contact of hot gases and critical components favour its use in SI engines.

In commercial use, a combination of this VFT turbo and iVTEC technology, enabled SUV vehicles to provide fuel consumption and acceleration values that are competitive with many large-engine sedans. The torque, at mid-range, is comparable to that of a naturally aspirated (NA) 3.5l engine [79]. This commercial attempt was continued in order to address the limitations of the design, by developing components that weren't limited to forced induction. Forced induction systems on SI-engines tend to increase the exhaust gas temperature, when operating within a stoichiometric range, by 50–100 °C [26] and this works to reduce catalytic light-off. This problem is not acceptable for production vehicles, which need to meet stringent emissions tests. As a result, a water-cooled aluminium manifold was introduced. To prevent problems at high mass-flow rates, a wastegate valve was also equipped to the vehicle.

Other attempts to produce VGT's capable of performing well with the varied load of an SI-engine have been developed by Borg-Warner [80]. In this, a dual-volute VGT was found to improve boost pressures at low engine speeds and increase temperature drops across the turbine through heat loss to the scroll wall employed. The two volumes of the turbocharger were linked to an ignition-sequence manifold that decoupled exhaust pulses from a four-cylinder engine so that more consistent flow could be achieved. The rotating vanes in this design provided benefits through an improved merging of gases between the separated volumes.

In another study, BorgWarner [77] also worked to recognize production methods that would enhance a VGT's performance under higher operating temperatures and stoichiometric operation. Heat-resistant austenitic steel (a material alloyed with Nickel and Chromium) was considered to be the future of design in this field, with stamping of sheet metals, being a method to reduce weight.

Despite many advances in VGT technology for use in gasoline engines, its implementation has been very limited. Standard turbochargers are still being favoured for their reliability and ability to cope with high-mass flow with a wastegate valve. With recent vehicles employing additional components to bypass VGT limitations, it has been shown that they can offer good performance gains over FGT and NA engines, although the increased cost of manufacturing such a vehicle may prevent this from catching on.

9.2. Active flow control turbocharging

Although the VGT technology accommodates systems to harness the energy in the exhaust flow at different speeds and loading conditions, it is not capable of exploiting the unsteady pulsating nature of the exhaust gases. Researchers have addressed this issue by developing a turbine design, which is able to effectively utilize the unsteady flow generated by IC engines [81]. This design is known as Active flow Control Turbine (ACT) and adapts the inlet nozzle geometry to the instantaneous pressure of the individual exhaust pulse.

The highly fluctuating pressure distribution and the related ACT nozzle area adjustment profile can be observed in Fig. 15. Building on the work carried out on VGT technology, the pivoting vane and sliding sleeve flow restriction methods were adapted to the ACT requirement

[81]. Modified the sliding sleeve mechanism and controlled its oscillatory motion by actuating it with an electromagnetic shaker. This enabled both ACT and VGT capabilities as the amplitude of the oscillation could be varied depending on the speed and loading conditions while the frequency of oscillation was matched to the pulsating pressure profile of the exhaust gases.

The second design, suggested by Rajoo [82], achieved flow restriction by using a ring of 15 pivoting vanes which could rapidly oscillate between 40° (open position) and 70° (closed position) vane angles as shown in Fig. 16, this system is also actuated by an electromagnetic shaker (PS and SS denote pressure and suction surfaces respectively). Similarly to Pesiridis' sliding wall mechanism, the oscillating pivoting vanes had coupled VGT and ACT capabilities. Overall, the pivoting vane ACT design was shown to be more efficient at extracting the exhaust gas energy although it does have the disadvantage of being more complicated mechanically due to the increased number of moving parts when compared to the sliding sleeve mechanism.

More recently, Cao et al. [83] published another variation on active control turbocharging, which the researchers named 'rotating nozzle ring'. This system allows the relative flow angle to change with the conditions within the turbine, since the nozzle ring is free to rotate in the same direction of the turbine around the same axis. This method, illustrated in Fig. 17, works best in lower mass flow rate conditions. When applied to a turbine, the biggest efficiency increase was found to be 7.2% when in the trough of a pressure pulsation, and 3.3% in the peak of the pulse [83].

9.3. Variable volute technologies

Additional turbine systems found in literature include variable volute turbines. These simply aim to alter the geometry of the volute itself as opposed to having and moving vane components, an example concept is found in the study by Chebli (illustrated in Fig. 18) [10].

Similarly, A Variable Sliding Ring Turbocharger (VST) consists of a twin (split) volute and movable wall section. The turbocharger volute is split in two; half for each of the partitioned exhaust manifold (refer to Fig. 14). The movable wall is used to close off half of the volute or opened to allow maximum flow and beyond this there is a bypass valve. During low exhaust gas flow rates, one of the volute sections is closed off to improve the rotational speed of the rotor [84]. When running at high engine speeds the system can be opened to expose the bypass valve, but this can result in some exhaust gases completely bypassing the turbine [85].

Another example of varying the geometry of the volute is the variable inlet turbocharger (also known as variable flow turbocharger). Largely developed in the 1990's, this variation uses a movable wall section on the inlet to dictate the available flow area as shown in Fig. 19.

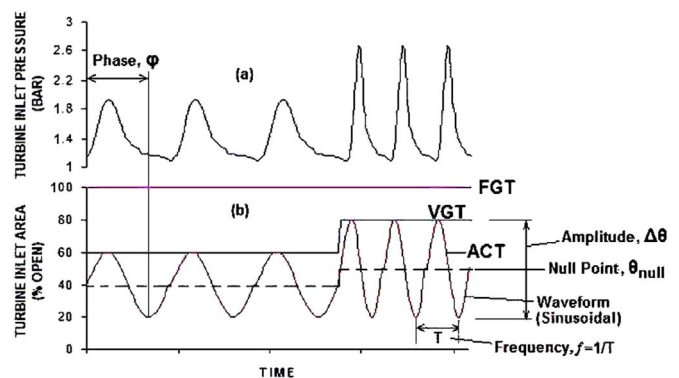


Fig. 15. Pressure distribution comparison between VGT, FGT and ACT [81].

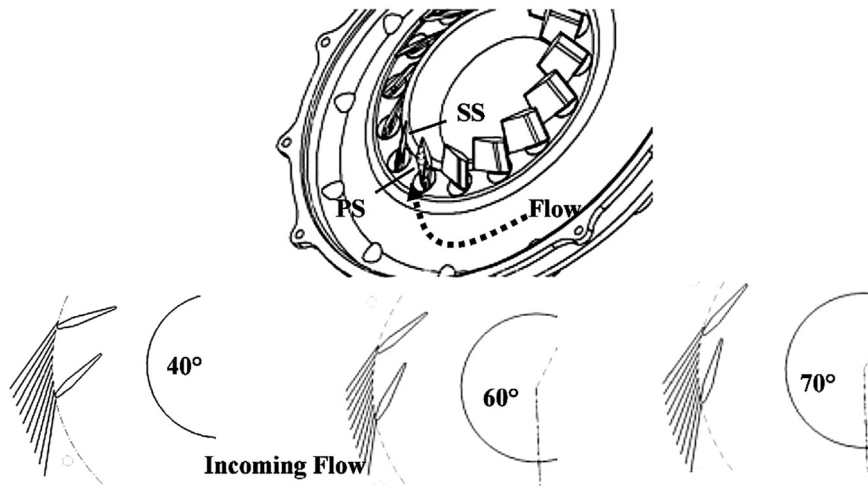


Fig. 16. ACT Vanes, rapidly variable between 40° and 70°, using an electromagnetic shaker [82].

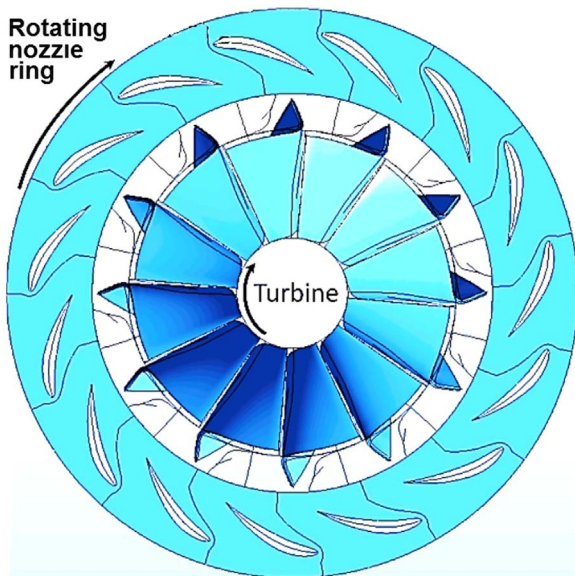


Fig. 17. Rotating nozzle ring (ACT) diagram [83].

9.4. Variable geometry twin-entry and double-entry turbocharging

Multiple-entry turbines are usually adopted to preserve the exhaust pulses within the engine exhaust pipes. This is the case for turbochargers of multi-cylinder engines where the turbine often works under off-design conditions. A fundamental distinction between the two main dual-entry designs is simply made on the basis of the flow division type

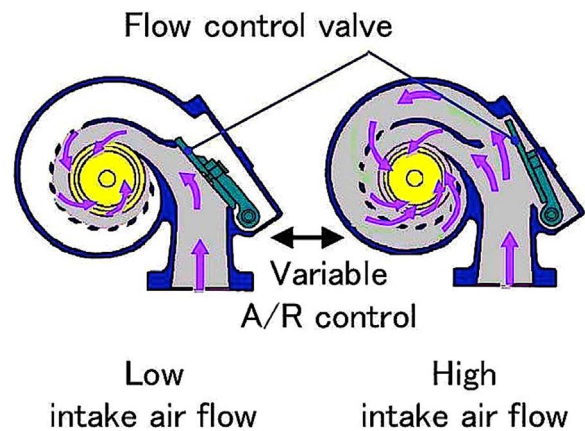
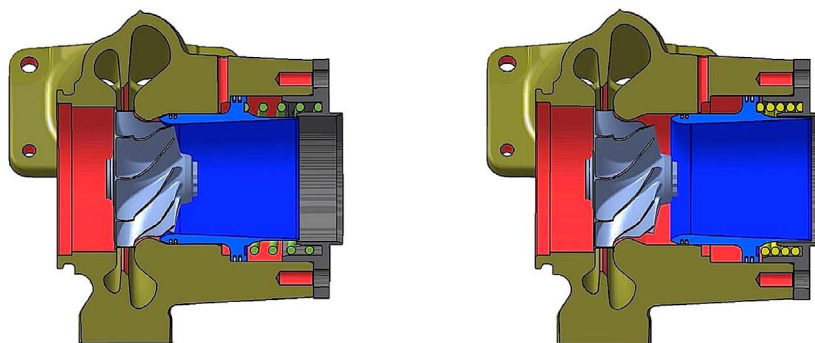


Fig. 19. Operation of a variable flow turbocharger [86].

[87]. The two configurations can be defined as:

- Double Entry: A circumferentially divided turbine: the scroll is divided such that each entry feeds a separate section of the rotor (Fig. 20)
- Twin Entry: A meridionally divided turbine: the scroll has a single divider around the entire perimeter of the housing, such that each inlet feeds the entire rotor circumference (Fig. 21)

Both turbine designs serve similar purposes, namely, to preserve exhaust gas energy and ease cylinder gas exchange. However the twin-entry turbine has traditionally seen wider use by turbocharger manu-



Sliding sleeve retracted ($z_{ss} = 0\%$) Sliding sleeve extended ($z_{ss} = 100\%$)

Fig. 18. An example of an axially sliding sleeve from Chebli Variable Outlet Turbine [10].

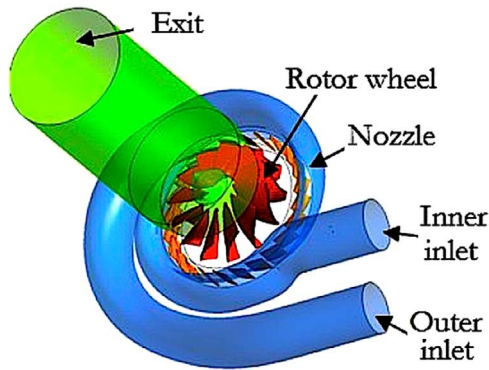


Fig. 20. Configuration of a double-entry turbine [88].

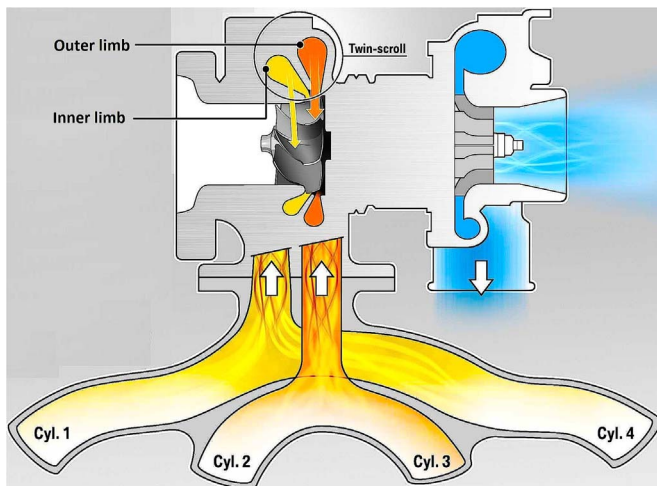


Fig. 21. Configuration of a twin-entry turbine [89].

fabricators due to its inexpensive and simple design.

An early study on twin-entry turbines was conducted by Pischinger and Wunsche [90], who performed a direct comparison between double-entry and twin-entry turbines by retaining the same equal admission effective area. They concluded that the efficiency loss under unequal admission is dependent on the volute geometry and design. The twin-entry turbine was found to perform better than the double-entry turbine; however the twin-entry turbine shows a penalty in the maximum efficiency achievable. Dale and Watson [91] continued work on the twin-entry design and found that although the turbine housing was symmetrical in the axial direction, and the measured mass flow characteristics for the two entries were almost coincident, their influence on the turbine efficiency was such that the peak efficiency point occurred when the mass flow rate of the shroud side entry was more than the hub side (not at full admission). In addition to this, the minimum efficiency was obtained under partial admission conditions when the entry on the shroud side was fully closed. Baines et al. [92,93] directly measured the performance and the flow field of a vaneless twin-entry radial turbine under full and partial admission conditions. The outcomes of their work showed that under equal admission conditions, the flow angle is unaffected by changes in turbine operating conditions. However, they found that under unequal admission conditions, the variation of flow velocity is much greater in the spanwise direction. In the extreme case where one entry is blanked off (known as partial admission), strong evidence of flow recirculating from one limb to the other was observed; consequently there was a large efficiency penalty. Steady and unsteady flow performance of a twin-entry automotive turbocharger turbine was also measured under full and partial admission by Capobianco and Gambarotta [94]. They found that the two entries appeared to be significantly different, both in terms of

mass flow rate and efficiency characteristics. Full and partial admission tests showed that flow capacity and efficiency were always higher for outer entry from the centre housing (shroud). They explained this dissimilar behavior by taking into account the housing and rotor geometry, which showed an apparent asymmetry with reference to the meridional dividing plane. Highest efficiency was reached in partial admission conditions with a very high difference in the mass flow rate between the two turbine entries. This was later confirmed by Aghaali and Hajilouy-Benisi [95] who also developed meanline models for twin-entry turbines [96,97]. The performance could be predicted with good degree of approximation under full admission while under partial and unequal admission the effectiveness of the models as predictive tools deteriorated significantly.

There is very little research available regarding performance of the double-entry turbine under unequal admission conditions. A work which focuses exclusively on double-entry turbine was conducted by Mizumachi et al. [98] using both numerical and computational analysis. The partial admission was achieved using a single entry turbine and blocking the admission to half of the rotor inlet and recorded a significant drop in efficiency between full and partial admission condition. Also, the mass flow characteristics of the partial admission turbine were approximately equal to half of the full admission parameter. Benson and Scrimshaw [99] tested a double-entry a turbine under full and unequal admission. Wallace and Blair [100] focused on three-entry circumferentially divided designs. Copeland et al [101–103] produced a number of different publications considering the performance of the double-entry turbine under a range of unequal and unsteady (pulsating) operating conditions. The analysis was both experimental and computational.

9.5. Variable geometry and multi-stage turbocharging

To further increase waste energy recovery and to improve engine performance, two turbochargers of different sizes can be connected to form a two-stage turbocharging system [104,105]. In one of the simplest systems, the two turbochargers are placed in series with bypass control and inter stage cooling; as shown in Fig. 22. The engine exhaust gas first goes through a relatively small turbine (high pressure or HP turbine), or partially through a bypass valve. After the HP stage, the entire exhaust gas then flows through a relatively large turbine (low pressure or LP turbine). The air is first compressed by a relatively large, compressor (low pressure or LP compressor), which after inter stage cooling, is further compressed by a relatively small compressor (high pressure or HP compressor).

At low engine speeds, the bypass valve remains completely closed, and all the engine exhaust gas goes through the HP turbine, resulting in a quick boost pressure rise on the air side. At high engine speeds, the bypass valve opens to reduce engine backpressure, and the exhaust

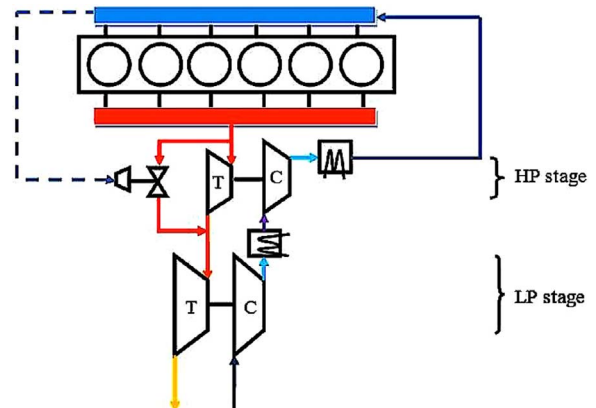


Fig. 22. Schematic of a simple, regulated two-stage turbocharging system [3].

goes through both the HP turbine and the LP turbine, to provide high boost for engine power requirement. Many other two-stage configurations are possible by using the two turbochargers differently, for example in parallel rather than in series, and each configuration has its own unique characteristics that suit a particular engine architecture and type of application. VGT is often used in the HP stage to enhance low speed performance. Note that a LP compressor often has a higher pressure ratio compressor compared with the HP compressor.

Compared with single stage turbocharging, two-stage turbocharging provides flexibility to meet engine requirements at both low and high speeds. Because of load split, both LP and HP stage can operate at reduced flow and pressure ratio ranges. This enables more efficient turbines and compressors to be specifically designed for two-stage turbocharging. The disadvantages of two-stage turbocharging are complex piping, valve and seal systems, and a considerable weight penalty. Control of the turbocharger is more complicated than that of single stage turbocharger, to achieve a smooth operation during stage switching. Two-stage systems also have larger flow passage volume and more metal surface than single stage systems, and this can affect the time taken by the turbocharger to warm up from cold start, thus affecting the operation of the downstream catalyst converter and engine cold start emissions.

9.6. Variable geometry and electric turbocharging

Leading manufacturers and academic institutions are pressing ahead in developing new, more effective VGT systems. The push for not only better efficiency and engine emissions, but also transient response times, means that variable geometry alone may not be enough in the future.

Electrically Assisted Turbochargers (EAT) comprise of an electric motor/generator that is mechanically coupled to the turbocharger shaft is one such new technology. The main purpose of EAT is to improve engine transient response, but this also results in a reduction in fuel consumption [106] (Fig. 23).

In 2013, researchers [107] tested one such EAT system on a dynamometer to extend manufacturers turbine maps, and separate the heat losses from aerodynamic performance. The test results showed a peak turbine efficiency of 69% with the vanes in a 60% open position. The peak efficiency of the motor/generator was found to be over 90% both in motoring and generating modes whilst running at 120,000 rpm.

Another research study [108] identified another turbocharger assist method, which uses engine simulations to compare EAT with Compressed Air Assist Turbocharging. Fig. 24 shows selected results from the test, with pre-compressor air assistance providing better engine response. The paper also highlights the benefits of avoiding compressor surge by using pre-compressor assistance.

BorgWarner have been working on the eBooster™ system, which unlike other ETA devices, works as two turbo-machines connected in series [109]. An additional compressor is matched to an existing turbo machine and powered by an electric motor, and in doing so expands the entire power curve. This also has the advantage of less thermo-mechanical stress than other electrically assisted devices. Another interesting development at BorgWarner is the movement away from cast steel housings to sheet metal turbine housings for gasoline turbochargers. This innovation saves weight whilst offering air-gap insulation and the flexibility of being constructed for either single or double flow.

The next generation of CTT automotive turbochargers will be produced with a 20% weight saving, cost saving materials and better reduction of CO₂; [110] as well as two stage technologies with improved turbine control and extended flow rate flexibility. For the heavy duty sector, a turbine expander is being developed to recover waste heat and in turn increase thermal efficiency; this system will deliver energy directly into the drive train system whilst reducing fuel

consumption and emissions.

Another major focus of industry is the downsizing turbocharger products to accommodate smaller engines. The world's smallest 2 cylinder engine, was released in India in 2010, boasting a 25% power gain, significant fuel efficiency improvements and lower emissions [111]. Another aim, for HTT, is to extend the VNT DualBoost technology (as previously mentioned) from light and medium-duty trucks to cover more applications.

The cost of a typical VGT, in the same production volume, is from 270% to 300% the cost of the same size, fixed geometry turbocharger. This disparity is due to a number of pertinent factors from the number of components, the materials used, the accuracy required in manufacturing and machining of the components, to the speed, accuracy, and repeatability of the actuator. However, for this increased cost, VGTs can offer gains of around 20% over comparable FGT systems [112].

As emissions regulations continue to tighten around the world, engine downsizing will drive the development of turbocharging systems, and VG at its most basic level is the first step up from standard fixed geometry turbocharging systems.

10. Conclusions

The present paper discussed has discussed the current and short-term future application of variable geometry systems for application in turbocharger compressors and turbines. From the review, the following conclusions were obtained:

1. VGTs are a popular technology, whose development and increased usage is driven by the tightening of worldwide emissions regulations.
2. There is a cost penalty in choosing a VGT above a FGT, but it comes with many performance improvements. The various technologies discussed can provide improved fuel efficiency, transient response, emissions and torque characteristics.
3. The two key VG technologies for turbines are sliding and pivoting vane systems. Both are suitable for mating with EGR systems.
4. The trend of actuating VGT devices is shifting further towards electrical and hydraulic variants which allow finer control than pneumatic.
5. VG systems will continue to play an important role in future energy recovery and boosting applications for internal combustion engines.
6. Cost-benefit considerations will dictate many of the choices embedded in the development of such systems.

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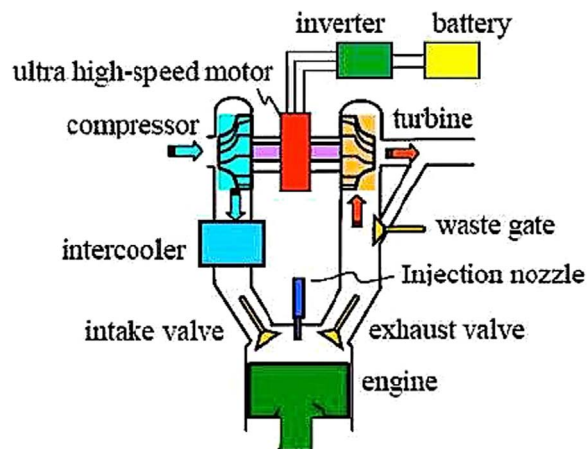


Fig. 23. Diagram of an Electrically Assisted Turbocharger (ETA) [3].

Boost Assistance Method	Acceleration Time - s
No assist	8.70
Intake manifold air-assist	8.40
Electric turbocharger assist	7.49
Exhaust manifold air-assist	7.54
Pre-compressor air-assist	6.16

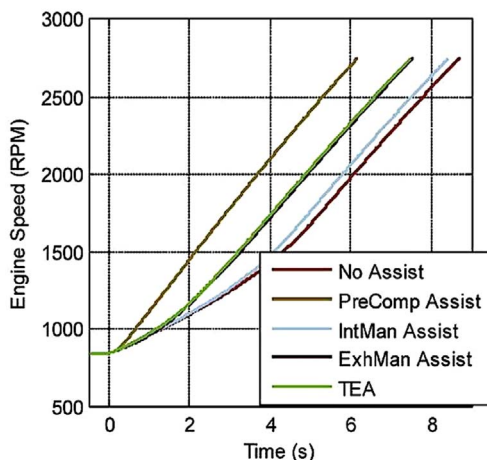


Fig. 24. Chart showing engine speed response to a full-load tip-in for each turbocharger assistance method [108].

members of the award winning VGT project team at Brunel University London in 2013/14 – who collated many of the resources required for this review.

References

- Markets R. Turbocharger Market by Vehicle Type (On-Highway (Passenger Car, LCV, & HCV), Off-Highway (Agricultural Tractors & Construction Vehicles)), Locomotive, Technology (VGT/VMT & Wastegate), Fuel Type (Gasoline & Diesel), & by Region – Forecast to 2020. Dublin, Ireland; 2015.
- Watson N, Janota M. Turbocharging the internal combustion engine. Basingstoke: Palgrave Macmillan; 1982.
- Pesiridis A, editor. Automotive Exhaust Emissions and Energy Recovery. Hauppauge, NY, USA: NOVA Science Publishers; 2014.
- Rakopoulos CD, Giakoumis EG. Diesel engine transient operation: Principles of operation and simulation analysis, 1st ed.. Athens, Greece: Springer; 2009. <http://dx.doi.org/10.1007/978-1-84882-375-4>.
- Saidur R, Rezaei M, Muzammil WK, Hassan MH, Paria S, Hasanuzzaman M. Technologies to recover exhaust heat from internal combustion engines. Renew Sustain Energy Rev 2012;16:5649–59. <http://dx.doi.org/10.1016/j.rser.2012.05.018>.
- Veltman T. Variable geometry turbochargers. USA: Stanford Univ; 2010, [accessed 30.10.13] (<http://large.stanford.edu/courses/2010/ph240/veltman1/>).
- Aghaali H, Ångström H-E. A review of turbocompounding as a waste heat recovery system for internal combustion engines. Renew Sustain Energy Rev 2015;49:813–24. <http://dx.doi.org/10.1016/j.rser.2015.04.144>.
- Hatami M, Ganji DD, Gorji-Bandpy M. A review of different heat exchangers designs for increasing the diesel exhaust waste heat recovery. Renew Sustain Energy Rev 2014;37:168–81. <http://dx.doi.org/10.1016/j.rser.2014.05.004>.
- Shu G, Liang Y, Wei H, Tian H, Zhao J, Liu L. A review of waste heat recovery on two-stroke IC engine aboard ships. Renew Sustain Energy Rev 2013;19:385–401. <http://dx.doi.org/10.1016/j.rser.2012.11.034>.
- Chebli E, Casey M, Muller M, Sumser S, Hertweck G, Schmid W. Innovative variable turbine concept for turbochargers. In: Proceedings ASME Turbo Expo 2011, Vancouver, Canada: ASME; 2011. p. 1–11.
- Lundstrom R, Gall J. A comparison of transient vehicle performance using a fixed geometry, wastegated turbcharger and a variable geometry turbocharger. SAE Tech Pap Ser 1986. <http://dx.doi.org/10.4271/860104>.
- Jinnai Y, Armizua H, Tashiro N, Tojo M, Yokoyama T, Hayashi N. A variable geometry (VG) turbocharger for passenger Cars to Meet European Union emission regulations. Mitsubishi Heavy Ind Tech Rev 2012;49:17–26.
- Schmitt F. Future Passenger Car R2S Charging Systems – using VTG and Low Pressure EGR? 2008. p. 1–41.
- Hiereth H, Preninger P. Charging the internal combustion engine. Wien New York: Springer; 2003.
- Honeywell Turbo Technologies. Gasoline DualBoost Turbochargers n.d. (<http://turbo.honeywell.com/our-technologies/gasoline-axial-dualboost-turbochargers/>) [accessed 21.10.13].
- Bauer K-H, Balis C, Donkin G, Davies P. The next generation of gasoline turbo technology. In: 33 International Wiener Mot. 2012, Vienna, Austria; 2012.
- Flaxington D, Szczupak DT. Variable Area Inflow Turbine. In: Proceedings Conference Turbocharging Turbochargers 1982, London, UK: IMechE; 1982. p. 55–62.
- Dieselclass. Turbochargers: Variable Geometry n.d. (<http://dieselclass.com/EngineFiles/VGTTurbochargers9-05.pdf>) [accessed 14.10.16].
- Franklin P. Performance development of the Holset variable geometry turbocharger. SAE Tech Pap Ser 1989. <http://dx.doi.org/10.4271/890646>.
- Ogura M, Shao J. Research development of variable nozzle turbocharger Part 1: a new axially movable turbocharger. SAE Tech Pap Ser 1995;952102. <http://dx.doi.org/10.4271/952102>.
- Garrett SE, Parker JF. Variable Geometry Turbine. US 8,291,703 B2; 2012.
- Solediesel.com. What is a Turbocharger and How Does it Work? n.d. (<http://blog.solediesel.com/en/what-is-a-turbocharger-and-how-it-works/>) [accessed 14.10.16].
- Epi-Eng.com. Turbochargers – EPI Inc., 2014. (http://www.epi-eng.com/piston_engine_technology/turbocharger_technology.htm) [accessed 14.10.16].
- Shao J, Ogura M, Liu Y, Yoshino M. Performance development of a new axially moveable vane turbocharger. SAE Tech Pap Ser 2013. <http://dx.doi.org/10.4271/961747>.
- Park Y, Bae C. Experimental study on the effects of high/low pressure EGR proportion in a passenger car diesel engine. Appl Energy 2014;133:308–16. <http://dx.doi.org/10.1016/j.apenergy.2014.08.003>.
- Andersen J, Karlsson E, Gawell A. Variable turbine geometry on SI engines. SAE 2006 World Congr 2006. <http://dx.doi.org/10.4271/2006-01-0020>.
- Brace CJ, Wijetunge RS, Hawley JG. Transient investigation of two variable geometry turbochargers for passenger vehicle diesel engines. SAE Tech Pap Ser 1999;1–12. <http://dx.doi.org/10.1243/0954407991526766>.
- Zhao B, Hu L, Sun H, Yi J, Yang C, Xin S, et al. Numerical investigation of a novel approach for mitigation of forced response of a variable geometry turbine during exhaust braking mode. In: Proceedings of the ASME Turbo Expo 2016 Turbomach. Tech. Conference Expo., Seoul, Korea; 2016. p. 1–10.
- Yang D, Dazhong L, Yang C, Hu L, Sun H. Investigations on the generation and weakening of shock wave in a radial turbine with variable guide vanes. In: Proceedings of the ASME Turbo Expo 2016 Turbomach. Tech. Conference Expo., Seoul, Korea, p. 1–9; 2016.
- Jiao K, Sun H, Li X, Wu H, Krivitzky E, Schram T, et al. Numerical simulation of air flow through turbocharger compressors with dual volute design. Appl Energy 2009;86:2494–506. <http://dx.doi.org/10.1016/j.apenergy.2009.02.019>.
- Whitfield A. Review of variable geometry techniques applied to enhance the performance of centrifugal compressors. International Compressor Engineering Conference, Bath, UK: Purdue University; 2000. p. 63–70.
- Lebele-Alawa BT, Hart HI, Ogaji SOT, Probert SD. Rotor-blades' profile influence on a gas-turbine's compressor effectiveness. Appl Energy 2008;85:494–505. <http://dx.doi.org/10.1016/j.apenergy.2007.12.001>.
- Chen L, Luo J, Sun F, Wu C. Design efficiency optimization of one-dimensional multi-stage axial-flow compressor. Appl Energy 2008;85:625–33. <http://dx.doi.org/10.1016/j.apenergy.2007.10.003>.
- Cummins Turbo Technologies. Improving Compressor Efficiency; 2010.
- Wallace FJ, Whitfield A, Atkey RC. Experimental and theoretical performance of a radial flow turbocharger compressor with inlet prewhirl. In: Arch Proc Inst Mech Eng 1847–1982. vols 1–196(189); 2006. p. 177–86. doi: (http://doi.org/10.1243/PIME_PROC_1975_189_024_02).
- Whitfield A, Doyle MDC, Firth MR. Design and performance of a high pressure ratio turbocharger compressor. Part 2: experimental performance. In: Arch Proc Inst Mech Eng Part A J Power Energy 1990–1996. vols. 204–210(207); 1993. p. 125–31. doi: (http://doi.org/10.1243/PIME_PROC_1993_207_021_02).
- Simon H, Wallmann T, Mönk T. Improvements in performance characteristics of single-stage and multistage centrifugal compressors by simultaneous adjustments of inlet guide vanes and diffuser vanes. J Turbomach 1987;109:41. <http://dx.doi.org/10.1115/1.3262068>.
- Williams R. An examination of the methods used to vary the output of centrifugal compressors with particular reference to part-load efficiency. In: Proceedings of the IMechE Eur. Conference Dev. Ind. Compressors, London, UK: IMechE; 1989. p. 37.
- Swain E. The design of an inlet guide vane assembly for an industrial centrifugal compressor. IMechE Semin. S351/002/96, London, UK: IMechE; 1996.
- Coppinger M, Swain E. Performance prediction of an industrial centrifugal compressor inlet guide vane system. In: Proc. Inst. Mech. Eng. Part A J. Power Energy, London, UK: IMechE. vol. 214; 2005. p. 153–64. doi: (<http://doi.org/10.1243/0957560001538254>).
- Ludtke K. Aerodynamic tests on centrifugal process. J Eng Gas Turbines Power 1983;105:902–9. <http://dx.doi.org/10.1115/1.3227499>.
- Whitfield A, Wallace FJ, Atkey RC. The effect of variable geometry on the operating range and surge margin of a centrifugal compressor. In: Am Soc Mech Eng Gas Turbine Conf Prod Show 1976, New Orleans: ASME; 1976.
- Abdelhamid AN. Effects of vaneless diffuser geometry on flow instability in centrifugal compression systems. In: Am Soc Mech Eng Gas Turbine Conf. Prod. Show, Houston, Texas: ASME; 1981.
- Abdelhamid AN. Control of self-excited flow oscillations in vaneless diffuser of centrifugal compressor systems. ASME Pap No 82-GT-188 1982.
- Whitfield A, Sutton AJ. The effect of vaneless diffuser geometry on the surge margin of turbocharger compressors. In: Arch. Proc. Inst. Mech. Eng. Part D Transp. Eng. 1984–1988 (vols 198–202), vol. 203, London, UK: IMechE; 2006. p. 91–8. doi: (http://doi.org/10.1243/PIME_PROC_1989_203_154_02).

- [46] Hagelstein D, Van den Braembussche R, Keiper R, Rautenberg M. Experimental investigation of the circumferential static pressure distortion in centrifugal compressor stages. In: Proceedings of the 1997 International Gas Turbine Aeroengine Congr. Expo., Orlando, Florida; 1997.
- [47] Rodgers C, Mnew H. Rotating Vaneless Diffuser Study. San Diego, California; 1970.
- [48] Harp JL, Oatway TP. Centrifugal compressor development for a variable area turbocharger. SAE Tech Pap Ser 1979. <http://dx.doi.org/10.4271/790066>.
- [49] Salvage JW. Variable geometry pipe diffusers. J Turbomach 1997;119:831–8. <http://dx.doi.org/10.1115/1.2841194>.
- [50] Senoo Y. Low solidity circular cascade for wide flow range blower. In: Proc. Adv. Concepts Turbomach., Hanover, New Hampshire: Fluid Dynamics Institute; 1981.
- [51] Senoo Y. Low solidity cascade diffusers for wide flow range centrifugal blowers. Von Karman Inst Lect Ser 1984.
- [52] Eynon PA, Whitfield A. Performance of a Turbocharger Compressor With a Range of Low Solidity Vaned Diffusers. SAE Tech Pap Ser 980772 1998. doi:10.4271/980772.
- [53] Eynon PA, Whitfield A. The effect of low-solidity vaned diffusers on the performance of a turbocharger compressor. Proc Inst Mech Eng Part C J Mech Eng Sci 1997;211:325–39. <http://dx.doi.org/10.1243/0954406971522088>.
- [54] McCutcheon ARS, Brown MWG. Evaluation of a variable geometry turbocharger turbine on a commercial diesel engine. In: Proceedings of the 3rd International Conference Turbocharging Turbochargers, London, UK: IMechE; 1986.
- [55] Hartwell DP. Turbochargers and the military vehicle. In: Proceedings of the 4th International Conference Turbocharging Turbochargers, London, UK: IMechE; 1990.
- [56] Walsham BE. Alternative turbocharger systems for the automotive diesel engine. In: Proceedings of the 4th International Conference Turbocharging Turbochargers, London, UK: IMechE; 1990.
- [57] Laghrouche S, Mehmood A, Bagdouri M El. Study of the nonlinear control techniques for single acting VGT pneumatic actuator. Int J Veh Des 2012;60:264. <http://dx.doi.org/10.1504/IJVD.2012.050084>.
- [58] Buratti R, Carlo A, Lanfranco E, Pisoni ADI. Diesel engine with variable geometry turbocharger (VGT): a model based boost pressure control strategy. Meccanica 1997;32:409–21.
- [59] Okazaki Y, Matsudaira N. A case of variable geometry turbocharger development. In: Proceedings of the 3rd International Conference Turbocharging Turbochargers, London, UK: IMechE; 1986. p. 191–5.
- [60] Wallace FJ. Variable GEometry Turbocharging – Optimization and Control under Steady-state Conditions. In: Proceedings of the 3rd IMechE international conference turbocharging turbochargers; 1986.
- [61] Arbore L. Turbocompressori: gli attuatori pneumatici ed elettronici della geometria variabile (VNT). Ital; 2015. (<http://www.notiziariomotoristico.com/approfondimenti/6223/turbocompressori-gli-attuatori-pneumatici-ed-elettronici-della-geometria-variabile-vnt>) [accessed 14.11.16].
- [62] Mitianiec W. Rodak. control problems in a turbocharged spark-ignition engine. J KONES Power Transp 2011:18.
- [63] He Y, Lin C, Gangopadhyay A. Integrated simulation of the engine and control System of a turbocharged diesel engine. SAE Tech Pap Ser 2009. <http://dx.doi.org/10.4271/2006-01-0439>.
- [64] Shirakawa T, Itoyama H, Miwa H. Study of strategy for model-based cooperative control of EGR and VGT in a diesel engine. JSAE Rev 2001;22:3–8. [http://dx.doi.org/10.1016/S0389-4304\(00\)00100-4](http://dx.doi.org/10.1016/S0389-4304(00)00100-4).
- [65] Eriksson L, Wahlström J, Klein M. Physical modeling of turbocharged engines and parameter identification. Lect Notes Control Inf Sci 2010;402:53–71. http://dx.doi.org/10.1007/978-1-84996-071-7_4.
- [66] Filipi Z, Wang Y, Assanis D. Effect of variable geometry turbine (VGT) on diesel engine and vehicle system transient response. SAE 2001 World Congr 2001:1–19. <http://dx.doi.org/10.4271/2001-01-1247>.
- [67] Hawley J, Wallace FJ, Cox A, Horrocks R, Bird GL. Reduction of steady state NOx levels from an automotive diesel engine using optimised VGT/EGR schedules. SAE Tech Pap Ser 1999. <http://dx.doi.org/10.4271/1999-01-0835>.
- [68] Jankovic M, Jankovic M, Kolmanovsky I. Constructive Lyapunov control design for turbocharged diesel engines. IEEE Trans Control Syst Technol 2000;8:288–99. <http://dx.doi.org/10.1109/87.826800>.
- [69] Stefanopoulou AG, Kolmanovsky I, Freudenberg JS. Control of variable geometry turbocharged diesel engines for reduced emissions. IEEE Trans Control Syst Technol 2000;8. <http://dx.doi.org/10.1109/87.852917>.
- [70] Zhang HG, Wang EH, Fan BY, Ouyang MG, Xia SZ. Model-based design of a variable nozzle turbocharger controller. Int J Automot Technol 2011;12:173–82. <http://dx.doi.org/10.1007/s12239-011-0021-0>.
- [71] Nieuwstadt MJ, Van , Kolmanovsky IV, Moraal PE, Stefanopoulou A, Jankovic M. Experimental Comparison of EGR-VGT control schemes for a high-speed diesel engine. Control Syst IEEE 2000;20. <http://dx.doi.org/10.1109/37.845039>.
- [72] Flårdh O, Mårtensson J. Nonlinear exhaust pressure control of an SI engine with VGT using partial model inversion. In: Proceedings of the IEEE conference decision control; 2010, p. 6433–8. doi: (<http://doi.org/10.1109/CDC.2010.5717243>).
- [73] Flårdh O. Modeling, control and optimization of the transient torque response in downsized turbocharged spark ignited engines. KTH, Stockholm; 2012.
- [74] Lezhnev L, Kolmanovsky I, Buckland J. Boosted gasoline direct injection engines: comparison of throttle and vgt controllers for homogeneous charge operation. Direct Inject. SI Engine Technol. 2002, Detroit, Michigan: SAE; 2002. p. 75–88.
- [75] Dotoli M, Lino P. Fuzzy adaptive control of a variable geometry turbocharged diesel engine. In: Ind Electron 2002 ISIE 2002 Proc 2002 IEEE Int Symp. vol. 4; 2002. p. 1295–300. doi: (<http://doi.org/10.1109/ISIE.2002.1025977>).
- [76] Mastrovito M, Gaballo L, Dambrosio L. Diesel engine variable-geometry turbine turbocharger controlled by a multi-agent-based algorithm. Proc Inst Mech Eng Part D J Automob Eng 2008;222:1459–70. <http://dx.doi.org/10.1243/09544070AUTO493>.
- [77] Simon V, Oberholz G, Mayer M. Exhaust gas temperature 1050 °C. An engineering challenge Academy; 2000.
- [78] Ishihara H, Adachi K, Kono S. Development of VFT Part 2. SAE Tech Pap Ser 2002. <http://dx.doi.org/10.4271/2002-01-2165>.
- [79] Ito N, Ohta T, Kono R, Arikawa S, Matsumoto T. Development of a 4-cylinder gasoline engine with a variable flow turbo-charger. SAE Tech Pap Ser 2007. <http://dx.doi.org/10.4271/2007-01-0263>.
- [80] Sauerstein R, Dabrowski R, Becker M, Schmalzl H-P, Christmann R. The Dual-Volute-VTG from BorgWarner; 2009.
- [81] Pesiridis A. Turbocharger turbine unsteady aerodynamics with active control. London: Imperial College; 2007.
- [82] Rajoo S. Steady and pulsating performance of a variable geometry mixed flow turbocharger turbine. London: Imperial College; 2007.
- [83] Cao K, Yang M, Martinez-Botas RF. Control method for turbocharger turbine performance improvement under pulsating condition. In: Proceedings of the ASME Turbo Expo 2015 Turbine Tech Conference Expo, Montreal, Canada: ASME; 2015. p. 1–10.
- [84] Woolenweber W. Variable geometry turbocharger turbine. 4,776,168; 1988.
- [85] Hoecker P, Pfluger F, Jaisle JW, Munz S. Modern turbocharging turbocharging designs for passenger car diesel engines. n.d.
- [86] Ecompt Inc. Variable geometry turbochargers. Diesel Net 2013, (https://www.dieselnets.com/tech/air_turbo_vgt.php), [accessed 12.11.14].
- [87] Romagnoli A, Copeland CD, Martinez-Botas R, Seiler M, Rajoo S, Costall A. Comparison between the steady performance of. J Turbomach 2012;135:11042. <http://dx.doi.org/10.1115/1.4006566>.
- [88] Newton P, Martinez-Botas R, Seiler M. A three-dimensional computational study of pulsating flow inside a double entry turbine. J Turbomach 2014;137:31001. <http://dx.doi.org/10.1115/1.4028217>.
- [89] Darding G. Valeo: le compresseur électrique bientôt de série. (In French); 2015. (<http://www.guillaumedarding.fr/valeo-le-compresseur-electrique-bientot-de-serie-9736673.html>) [accessed 14.11.16].
- [90] Pischinger F, Wunsche A. The characteristic behaviour of radial turbines and its influence on the turbocharging process. In: Proceedings of the institution of mechanical engineering, Tokyo, Japan: IMechE; 1977. p. 545–68.
- [91] Dale A, Watson N. Vaneless radial turbocharger turbine performance. In: Proceedings of the institution of mechanical engineering 3rd International conference turbocharging turbochargers, London, UK: IMechE; 1986.
- [92] Baines NC, Lavy M. Flows in vaned and vaneless stators of radial inflow turbocharger turbines. Institution of mechanical engineering turbochargers turbocharging conference Pap. No. C405/005, London, UK:IMechE; 1990, p. 7–12.
- [93] Baines NC, Hajilouy-Benisi A, Yeo JH. The pulse flow performance and modelling of radial-inflow turbines. In: Proceedings IMechE international conference turbochargers turbocharging. London, UK: IMechE; 1994. p. 209–18.
- [94] Capobianco M, Gambarotta A. Performance of a twin-entry automotive turbocharger turbine. In: Proceedings of the ASME Turbo Expo. 93-ICE-2., Cincinnati, OH; 1993.
- [95] Aghaali H, Hajilouy-Benisi A. Experimental and theoretical investigation of twin-entry radial inflow gas turbine with unsymmetrical volute under full and partial admission conditions. Turbo Expo 2007, Parts A B, ASME. vol. 6; 2007. p. 1099–107. doi: (<http://doi.org/10.1115/GT2007-27807>).
- [96] Ghasemi S, Shirani E, Hajilouy-Benisi A. Performance prediction of twin-entry turbocharger turbines. Turbo Expo 2002, ASME. vol. 1; 2002. p. 1087–95. doi: (<http://doi.org/10.1115/GT2002-30576>).
- [97] Hajilouy-Benisi A, Rad M, Shahhosseini MR. Flow and performance characteristics of twin-entry radial turbine under full and extreme partial admission conditions. Arch Appl Mech 2009;79:1127–43. <http://dx.doi.org/10.1007/s00419-008-0295-5>.
- [98] Mizumachi N, Yoshiki D, Endoh TA. A study on performance of radial turbine under unsteady flow conditions. Rep Inst Indust Sci, Univ Tokyo. vol. 28; 1979. p. 1–77.
- [99] Benson RS, Scrimshaw KH. An experimental investigation of non-steady flow in a radial gas turbine. In: Proc Inst Mech Eng Conf Proc 1964–1970 (vols 178-184). vol. 180; 1965. p. 74–85. doi: (http://doi.org/10.1243/PIME_CONF_1965_180_283_02).
- [100] Wallace FJ, Blair GP. The pulsating-flow performance of inward radial-flow turbines the pulsating-flow performance of inward radial-flow turbines. In: ASME Gas Turbine Conference, Washington: ASME; 1965.
- [101] Copeland CD, Martinez-Botas R, Seiler M. Comparison between steady and unsteady double-entry turbine performance using the quasi-steady assumption. vol. 7 Turbomachinery, Parts A B, ASME; 2009, p. 1203–12. doi: (<http://doi.org/10.1115/GT2009-59290>).
- [102] Copeland C. The evaluation of steady and pulsating flow performance of a double-entry turbocharger turbine. London: Imperial College; 2010.
- [103] Copeland CD, Martinez-Botas R, Seiler M. Unsteady performance of a double entry turbocharger turbine with a comparison to steady flow conditions. J Turbomach 2012;134:21022. <http://dx.doi.org/10.1115/1.4003171>.
- [104] Pfluger F. KKK's new charging system for commercial diesel engines. In: Proceedings of the 6th international conference turbocharging air management system C554/035/98, London, UK: IMechE; 1998.
- [105] Weber O, Christmann R, Gauckler V, Sauerstein R R2S – modelling and consequences for the boost control. In: Proceedings of the 10th IMechE international conference turbochargers turbocharging, London, UK: IMechE; 2012, p.

- 43–53.
- [106] Terdich N, Martinez-Botas RF, Romagnoli A, Pesiridis A. Mild hybridization via electrification of the air. *J Eng Gas Turbines Power* 2013;136:31703. <http://dx.doi.org/10.1115/1.4025887>.
- [107] Terdich N, Martinez-Botas R. Experimental efficiency characterization of an electrically assisted turbocharger. *SAE Tech Pap Ser* 2013. <http://dx.doi.org/10.4271/2013-24-0122>.
- [108] Darlington A, Cieslar D, Collings N, Glover K. Assessing boost-assist options for turbocharged engines using 1-D engine simulation and model Predictive control. *SAE Tech Pap Ser* 2012. <http://dx.doi.org/10.4271/2012-01-1735>.
- [109] BorgWarner. Turbocharger for an exhaust temperature of 1050 °C n.d. (<http://www.turbos.bwauto.com/products/turbochargerExhaustTemperature.aspx>) [accessed 27.10.13].
- [110] Cummins Turbo Technologies. Future Technologies n.d. (http://www.cumminsturbotechnologies.com/ctt/navigationAction.do?Url=SiteContent+en+HTML+ProductsAndTechnologies+Next_generation_products) [accessed 27.10.13].
- [111] Honeywell Turbo Technologies. Small Wastegate Turbos n.d. (<http://turbo.honeywell.com/our-technologies/small-wastegate-turbo/>) [accessed 27.10.13].
- [112] Martinez-Botas RF, Pesiridis A, Yang MY. Overview of boosting options for future downsized engines. *Sci China Technol Sci* 2011;54:318–31. <http://dx.doi.org/10.1007/s11431-010-4272-1>.