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Application of variable geometry turbine turbochargers to gasoline engines- A review

S Dasgupta¹ P Sarmah^{1*}, P P Borthakur¹

¹Department of Mechanical Engg., Dibrugarh University, PIN - 786004, India.

Email: pksnit07@gmail.com

Abstract. An ideal engine today is considered to be one with low emission, low fuel consumption and high specific power output. Engine downsizing by turbocharging provides an answer to all the three. Though the traditional problems of poor low end torque and inadequate transient response have been overcome to a great extent using variable geometry turbine turbocharger in diesel engine, the application of variable geometry turbine turbocharger is in quite a nascent stage when it comes to gasoline engine. This article primarily describes all the important aspects of application of VGTs to gasoline engines right from when VGT's were restricted to only very expensive research prototypes to the very recent application in cost sensitive production engines. Also at the same time, it highlights the need and development in the flow range of the turbocharger compressor, addressing problems of choke and surge in the turbochargers compressor.

1. Introduction

Owing to the emphasis on environmental issues, improvement in emission quality and reduction in fuel consumption have become the main driving forces of engine development and research. As per modern day standards, an ideal engine is supposed to have both high power and a low fuel consumption. Although turbocharging historically started as a means to increase the power output of an engine, it is today serving greatly as a means to achieve the emission standards along with lower fuel consumption [1]. The European Union has always been the front runner in achieving emission standards. Figure 1 shows the historical development and future targets for emission standards in the EU [2]. Similarly, most of the large economies have specified converging emission targets for new vehicles. Figure 2 explains the global scenario a bit further. To achieve these emission targets, engine downsizing via forced induction is quite inevitable.

The objective of obtaining more power from an existing engine size, can also be achieved by increasing the thermal efficiency by increasing the compression ratio, especially in case of a CI engine. However, an increase in compression ratio is also accompanied by an increase in maximum cylinder pressure and the rate of increase in maximum cylinder pressure is comparatively less than the rate of increase in break mean effective pressure. This, therefore, implies that, for a given maximum allowable cylinder pressure, greater power can be obtained by increasing the pressure at intake as compared to that obtained by increasing the compression ratio [3].

Owing to the aforementioned briefing, turbocharging has been the primary method of engine downsizing. Moreover, from an environmental point of view, turbocharging and lean boosting reduces carbon Dioxide emissions [4] and also leads to lower fuel consumptions [5, 6, and 7], not to mention the reduction of engine weight, thereby leading to lower production cost.



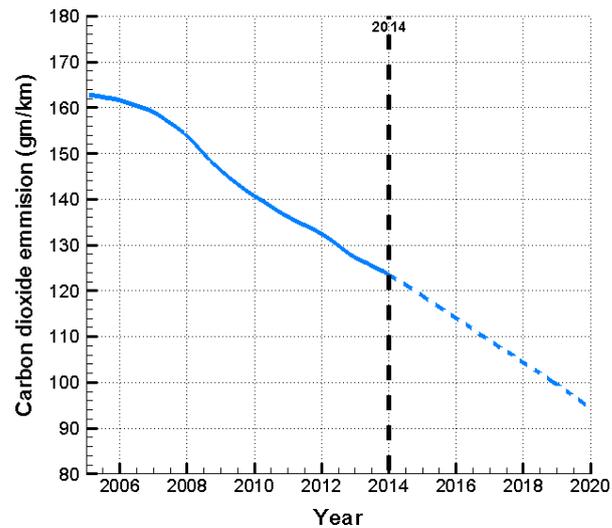


Figure 1. Historical development and future targets for CO₂ emission levels of new passenger cars in the EU. [2]

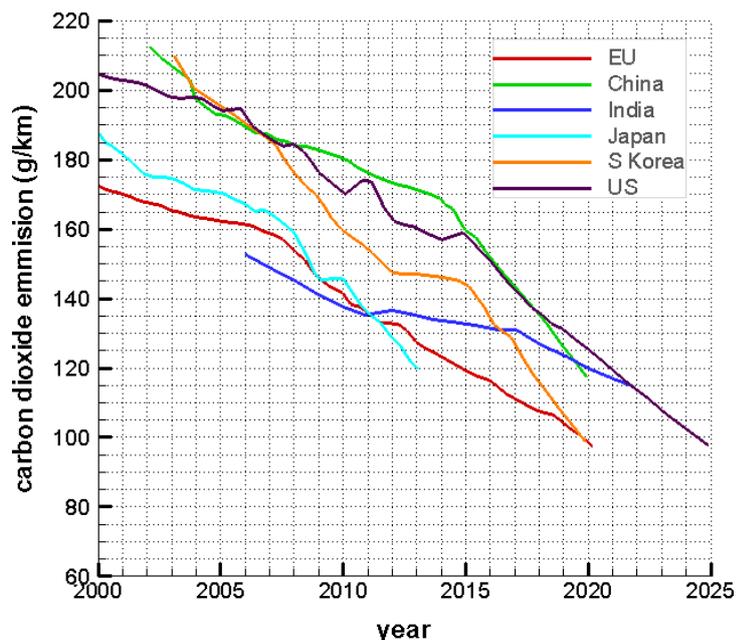


Figure 2. Comparison of global CO₂ regulations for new passenger cars. [2]

The degree of turbocharging of a SI gasoline engine is primarily limited by knocking rather than thermal or mechanical loads (a major constraint case in a diesel engine) [8]. Furthermore, SI engines use the throttle to control load in contrast to its CI counterpart, which controls load by governing the amount of fuel injected. This, therefore makes turbocharging of a gasoline engine much more challenging, as the intake manifold pressure increased during turbocharging plays a vital role in load control.

Traditionally, the main problem with turbocharging, be it a gasoline or a diesel engine, has been inadequate low end torque and poor transient response (or ‘turbo lag’ as it is more popularly known). This lag is due to the additional inertia added to the induction system by the turbocharger. This makes a turbocharged system, with a fixed geometry turbine turbocharger less responsive than its naturally aspirated counterpart. The problems of transient response and low end torque have been addressed by two stage turbo charging or by altering the flow dynamics using different types of variable geometry turbocharger [9, 10] or by using the assistance of an electric motor [11] at low

engine speeds. Casing treatment has also proved beneficial in improving the choke and surge limit of the compressor [12, 13]. Apart from these, various synergies of the mentioned techniques have been used to obtain optimum results as per the desired engine requirement. A classic example of these synergetic techniques is the Volkswagen 1.4 liter TSI engine which uses a two stage boosting system using a supercharger along with a fixed geometry turbine (FGT) turbocharger. However, Volkswagen plans to replace the 1.4 liter TSI engine with the new 1.5 liter EA211 TSI evo gasoline engine [34, 35], which makes use of a variable geometry turbine turbocharger.

This review primarily deals with the following:

- Section 2 deals with the short comings of the traditional fixed geometry turbine (FGT) turbochargers and highlights the correlation between throat area to radius ratio ($A: R$ ratio) of the turbine housing and boost pressure.
- Section 3 is a discussion about the various types of variable geometry turbine (VGT) turbocharger and their application to gasoline engine downsizing.
- Section 4 deals with casing treatment for surge limits, choke flow improvement methods and other method to obtain a wide flow range in the turbocharger compressor.

2. Short comings of FGT turbochargers

The conventional or fixed geometry turbine turbo chargers have had some inherent short comings like turbo lag and inadequate low end torque [8]. This lack of transient response which is due to the inertia of the turbine rotor can be reduced to an extent by using lighter materials.[14] But as the turbine is constantly subjected to a highly oxidizing environment and extreme high temperatures of the exhaust gases, reducing the mass of the rotor material has proved to be rather difficult. However, they have become much lighter over the years, and the turbine rotors today are much lighter than what they used to be. One way to obtain a better transient response is by using fixed geometry turbine (FGT) turbo chargers in a two stage turbo charging system, using a low pressure turbo charger at low engine speeds and high pressure turbo charger at high engine speeds. This means using turbocharger turbine housing with a smaller throat area to radius ratio at low speeds and a turbocharger turbine housing with a larger throat area to radius ratio at high engine speeds [15, 16]. Lowering the $A: R$ ratio increases the exhaust gas velocity in the turbine increasing the kinetic energy of the gas and thereby leading to a better throttle response.

Taking the concept of matching the $A: R$ ratio of the turbocharger with the engine speed a step forward leads us to variable geometry turbochargers (VGT) [17, 18, and 19]. The VGTs unlike FGTs provide a whole range of $A: R$ ratios as per the engine speed rather the just two sets of $A:R$ ratios as in the case of two stage turbo charging. Moreover, in some cases, the usage of waste gates can be completely eliminated while using a variable geometry turbocharger [17]. However, it should be advisable to maintain an external waste gate in case of abnormal boost pressure over shooting. The various types of VGTs, their mechanisms, characteristics and usage to gasoline engine downsizing have been further described in the next section.

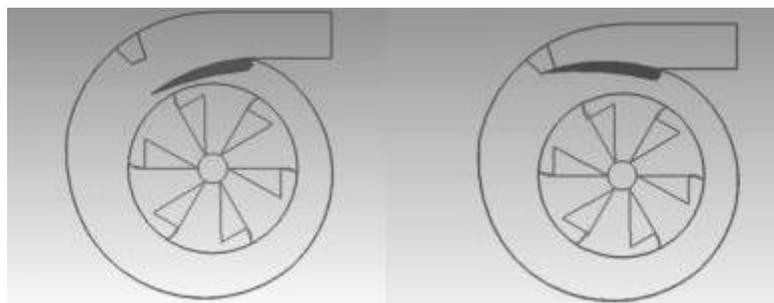


Figure 3(a)

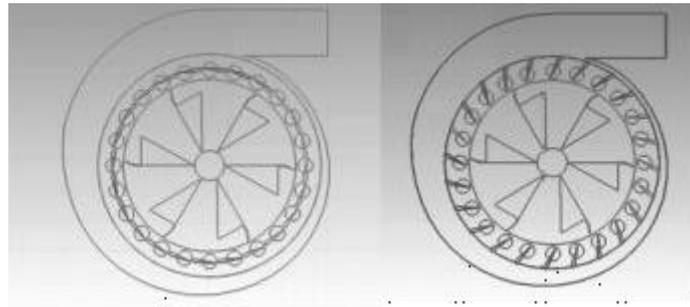


Figure 3(b)

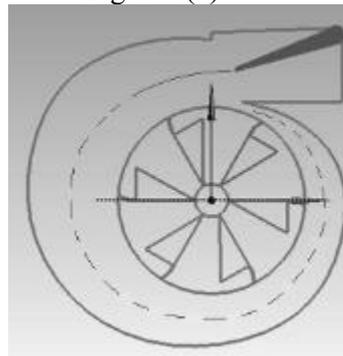


Figure 3(c)

Figure 3. Types of VGT: (a) variable turbine housing throat area (VAT), (b) variable geometry nozzle turbine (VNT) (c) variable flow turbine (VFT).

3. Variable Geometry Turbine (VGT) Turbochargers: scope, studies and gasoline engine applications

The variable geometry turbines have proved to be the best way of matching the A: R ratio of the turbine as per the engine speed. The various types of VGTs mainly include; variable throat area turbine (VAT) [20], variable flow turbine (VFT) [21] and variable nozzle turbine (VNT) [22].

Kawaguchi et al. reported a variable flow turbine (VFT), as novel technique to vary turbine inlet area [21]. In a VFT, the task of altering the flow dynamics as per the engine speed is achieved by the movement of a flow control vane on the radial plane as shown in figure 3(b). In addition to that, the flow within the turbine casing is confined within two scrolls, one primary and one secondary scroll in the axial direction. The wall separating the two scrolls within the turbine housing is an array of strategically well positioned stationary vanes [24]. The flow of the exhaust gases into the turbine is governed by the position of the flow control vane at the throat as mentioned above. At low engine speeds, when the exhaust flow is low, the vane directs the exhaust towards the primary (inner) scroll and as the flow increases with the engine speed, the vane gradually opens, thereby, increasing the throat area and directing more of the flow towards the secondary scroll. When the control vane comes to its fully opened position, the VFT starts behaving like a conventional FGT as the flow is now controlled by the waste gate.

Kawaguchi et al. [21] suggested the major positive point of the VFT to be the single moving component (the flow control valve) compared to the multiple nozzle vanes movement in a VNT. Kawaguchi et al. [21] also documented a 10 kPa boost pressure improvement in the VFT compared to an equivalent VGT under similar inlet exhaust pressure.

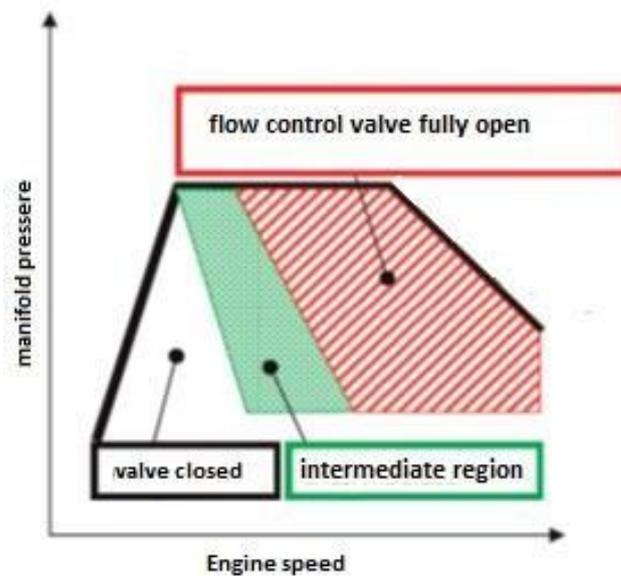


Figure 4. Flow control strategy of the VFT. [23]

The above mentioned flow control strategy of a VFT becomes more clear from figure 4 extracted from Ito et al. [23] (2007) which divides the flow into three regions, namely the closed, the intermediate and the fully open zone. Such VFT systems have been used in Honda Acura RDX 2.3 liter production engines along with variable valve timing (VVT) to obtain a further better engine aspiration [24]. Also a water cooled exhaust manifold (WCEM) to control the turbine inlet temperature is used. One problem with water cooled exhaust manifolds is that, cooling the exhaust also reduces the energy available at the turbine especially at low engine speeds. A solution to this problem could be – a slight delay in ignition timing. This could lead to a higher exhaust temperature at low engine speeds leading to better low end torques.

The VFT, which is kind of a synergy between a small (small A:R) and a large (large A:R) provide a better low end torque at low engine speeds and a better high end torque at higher engine speeds as compared to a large and a small FGT turbo charger respectively. The plot between engine speed and output break torque for a 4-cylinder gasoline adapted from Ito et al. [23] (figure 5) explains it better. A much wider torque plateau can be seen for the VFT.

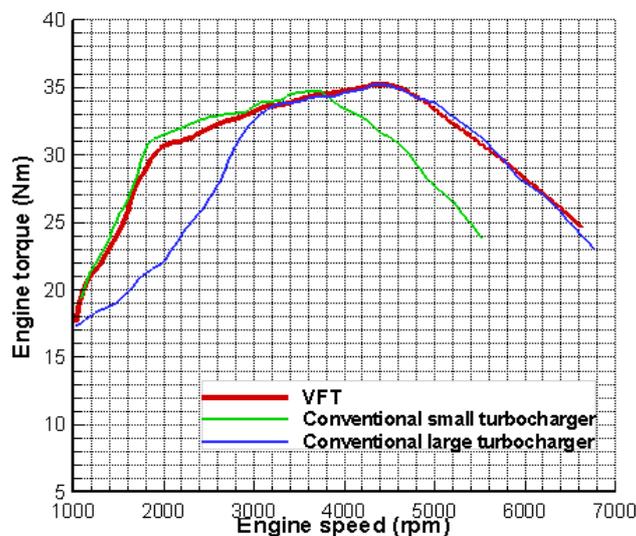


Figure 5. Comparison of VFT with conventional small and large FGT turbochargers. [23]

Moving towards variable throat area turbine (VAT). Flaxington and Szczupak [25] studied some

methods of variable area devices for turbines. These include, in general, the variable area via regulation of the rotor exit area, volute exit area and volute tongue area (throat). They further investigated the latter two methods, which are shown in Figure 6 and 7 with its relevant engine performance results. They concluded, in general, an improved torque, wider speed range and improved transient performance. It was, however, concluded that no single method to area control was superior for all application, and each has its superiority in particular operating regions.

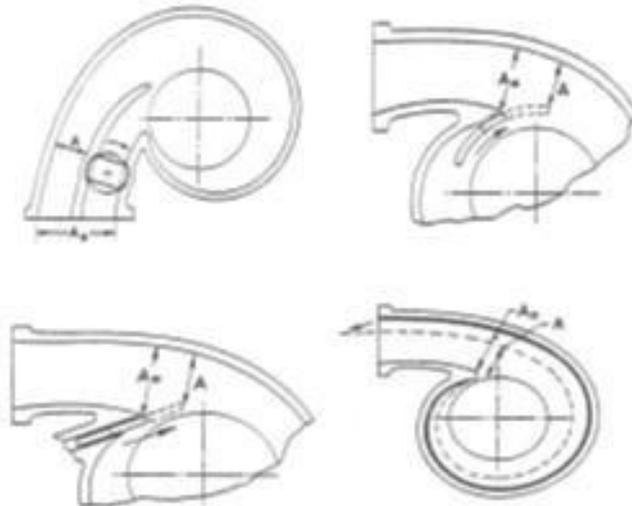


Figure 6. Methods of volute tongue area control studied by Flaxington and Szczupak.[25]

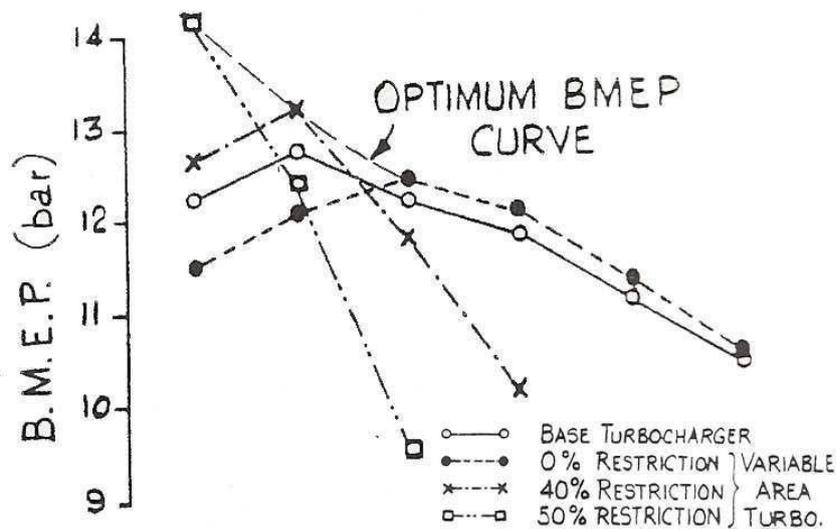


Figure 7. Engine performances under the various methods of volute tongue area control studied by Flaxington and Szczupak. [25]

VATs have been considered as a better and efficient approach to turbocharger- engine matching as compared to FGTs, and in some cases, better than FGT compounding. VATs can provide satisfactory boost over a wider range by varying the turbine housing throat area. At lower speeds, the reduction of the turbine inlet area increases the momentum impact on the rotor while at higher speeds the increase in throat area controls over boosting in the intake manifold. However, the scope of an internal or external waste gate cannot be eliminated.

Two of most widely used methods used to vary the throat area of VAT include the pivoting nozzle vane [20,26,27] and the sliding wall technique[27,28], the latter being a bit less popular due to causes of non-aerodynamic shape and subsequent efficiency losses[28]. In the first type, the flow rate is governed by the movement of the vane, and in the second, by movement of the sliding wall.

Pesiridis and Martinez- Botas [28] (2007) presented a technique to continuously regulate a turbine inlet area so as to adapt to the continuous exhaust gas pulsation. This system was called Active Control Turbocharger (A.C.T.). Here, a variable throat area turbine operation was extended to consider the pulsating nature of the exhaust flow. The throat inlet area opens progressively as the exhaust pressure increases and closes gradually at the end of the pulse. Some power improvements were seen, but efficiency losses contributed largely by the aerodynamically poor sliding nozzle employed was a drawback. Figure 8 further explains the mechanism.

Petitjean et al. [29] in 2004 also proposed a method of varying the turbine inlet area using a mechanism similar to Pesiridis and Martinez- Botas for application in gasoline engines, and claimed an advantage over variable nozzle turbine (VNT) in terms of durability. In a variable nozzle turbine (VNT), the flow dynamics of the exhaust gases is controlled by the movement of the vanes as shown in figure 3(a). The movement of the vanes increases or decreases the area between the vanes so as to alter the flow speed and angle of impingement on the rotor. At low engine speeds, reducing the area between the vanes increases the velocity at the expense of pressure, making the vanes function as sub sonic nozzles, and vice-versa. The VNTs therefore provide a better engine – turbocharger matching over a wider engine speed range. This may also lead to a complete elimination of a waste gate as well.[17,20]

Capobianco and Gambarotta analyzed a variable area turbine (VAT), a variable nozzle turbine (VNT) and a fixed geometry turbine (FGT) under steady and pulsating flow conditions and established relative aerodynamic performances. The VNT showed a better engine turbo matching with a wider operating range but with a loss in efficiency at the top end. The VNT unit, thus, proved to be a little better than its VAT counterpart. The FGT, VAT and VNT units used were Garrett TB025, Garrett VAT025 and Garrett VNT025, respectively. The aforementioned would become more clear from figure 9 adapted from Capobianco and Gambarotta [20].

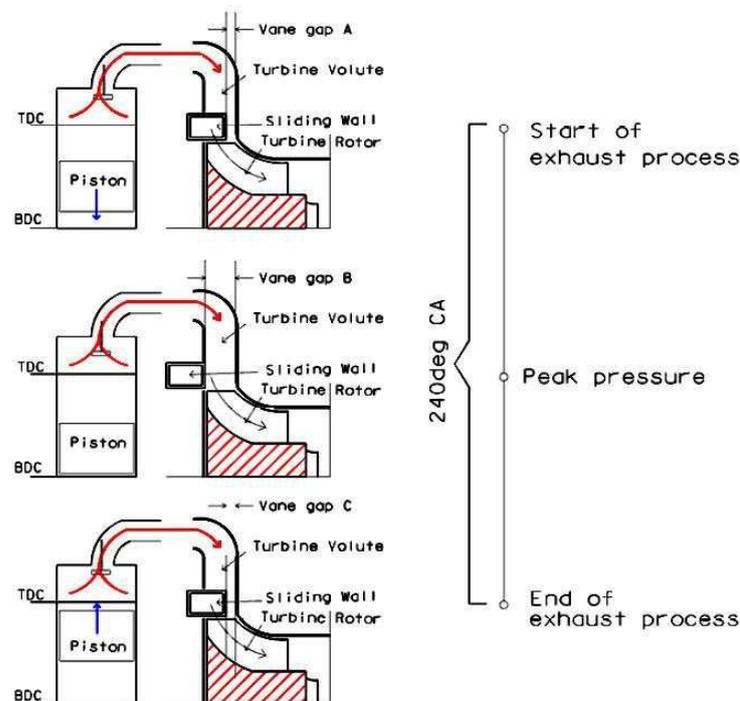


Figure 8. Active Control Turbocharger (A.C.T.); nozzle gap progressively opens towards the peak pressure and closes lower end of the pulse. [28]

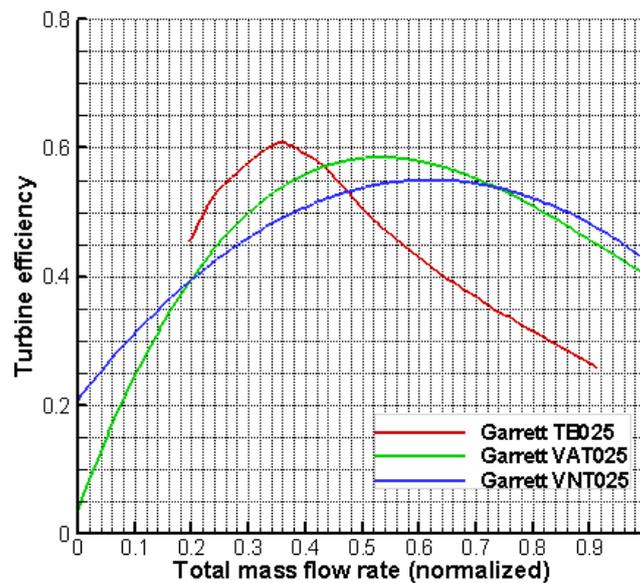


Figure 9. efficiency comparison of same sized VAT, VNT and FGT, the control vanes are at fully open and fully closed at one and zero respectively on the abscissa .[20]

However, in the study conducted by Capobianco and Gambarotta [20], only the static pressure at turbine inlet and outlet were measured and the rest were just time average values. Therefore, no conclusive correlation could be established for the entire flow range. However, a decreasing mass flow rate factor with increasing pulse amplitude was deduced.

Again, Gabriel et al. [17] in 2007, highlighted that exhaust gas pulsation damping at low vane position resulted in an increased turbine inlet temperatures leading to pumping losses. However, it was also claimed that exhaust gas pulsation damping gave way to transient compressor surge reduction, thereby having a positive end to it. It can also be seen from the plot in figure 9 that the peak efficiency of a FGT is slightly better than that of a VFT or even VNT. This is mainly due to the fact that a FGT has comparatively less hindrances in the flow passage. Even though a FGT (with waste gates) provides a better peak efficiency, it fails to provide sufficient boost pressure at higher engine speed levels as compared to its VGT counterparts [20].

Arnold et al. [30] highlighted the need for clearance between vane and housing of a VNT in order to prevent the sticking of vanes. Again in 2011, Hu Liangjun et al. [31] presented a research which showed dramatic decrease in turbine performances with increasing nozzle clearances. Various simulations were carried out with different nozzle clearances and also with no clearance. It was reported that an increase of 1% nozzle clearance led to a drop of 2.5% in turbine efficiency. This drastic drop in turbine efficiency can be further realized from the curve in figure 10 adopted from Liangjun et al. [31]. This dramatic drop in turbine performance is credited to two reasons. Firstly, the inclusion of clearance towards the hub and shroud side of the nozzle leads to back flow of the fluid (exhaust gases) from the pressure side to the suction side. This reverse flow tends to induce a component of flow velocity opposite to the direction of rotation of the rotor, leading to a fall in rotor efficiency. Secondly, due to the nozzle clearance and the above mentioned back flow, the fluid at impeller hub has comparatively low energy and is therefore unable to overcome the centrifugal forces of the rotor. The fluid hence has a tendency to migrate from the hub to the shroud side at the impeller inlet. As a result, low energy fluid occupies greater amount of flow passage as compared to a VNT without clearance.

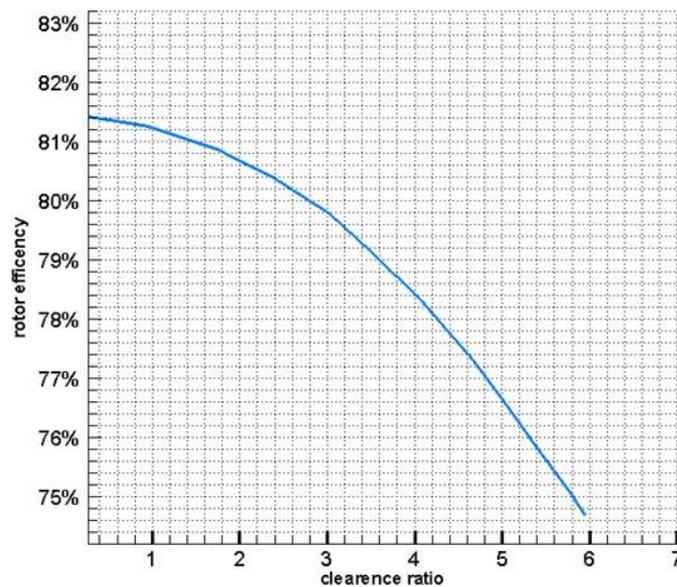


Figure 10. drastic fall of rotor efficiency with increasing clearance ratio in a VNT. [31]

As discussed previously the working mechanism of VNTs is much more complex than other VGTs (VFTs and VATs). This is greatly due to the greater number of moving parts. [28, 31] Also in case of high speed gasoline engine with a VNT complete elimination of a waste gate may not be possible due to a wide range of flow rates [32]. Again, in a simulation conducted by Yang and Wang, it was claimed that using a VNT in a gasoline engine may lead to increased knocking at the beginning of combustion [33]. Moreover, in case of a gasoline engine, the exhaust temperature is higher than a diesel engine which makes the application of VNTs to gasoline engines much more difficult. These hindrances to gasoline VNT application have largely restricted the use of VNTs on gasoline production engines. Most of the VNT gasoline engines today are in prototype stage with massive future scope. In spite of all the hindrances, Porsche and Volkswagen have been quite successful in their gasoline VNT ventures.

One of the very few production gasoline engines using a VNT turbocharger can be seen in the Porsche 911 Turbo S [22] engine, which uses two VNTs in parallel. It is a 3.8 liter engine which shows an enormous specific power of 112 kW/l. Other gasoline VNT applications include the new Volkswagen 1.5l EA211 TSI evo gasoline engine [34, 35]. The engine is expected to replace the 1.4l TSI and is expected to be 10% more efficient than its predecessor. Thanks to the VNT, the turbocharged four-cylinder engine that makes its maximum torque available really early, offering 200 Nm from just 1300 rpm in the 128 hp versions.

More recently in 2016, the 2.5 liter Porsche 718 Boxster S [36] and 718 Cayman S [37, 38] have been equipped with VNTs. This resulted in a power output of 256 kW (235hp) at 6500 rpm and a maximum torque of 420 Nm available across a wide range from 1900 rpm to 4500 rpm. As compared to the 2 liter base model (718 Boxster and 718 Cayman) the 2.5 liter S model with the VGT provides an improvement of 25 kW (35hp) and 100 Nm but with a 14% decrease in fuel consumption and emissions, thanks to the VGT. The turbochargers used in the 2.5 liter Porsche 718 Boxster S and 718 Cayman S have been derived from the majestic 3.8 liter Porsche 911 Turbo S and adapted for the 718 S to obtain excellent transient response at low engine speeds and maximum power output.

4. Increasing the flow range of the VGT turbocharger compressor

As discussed in the previous sections, variable geometry turbine turbochargers have helped largely in better turbocharger – engine matching and to overcome, to a great extent, the problems of transient response. But, the compressor of the turbocharger has a surge limit related to the flow rate of the compressor on the low flow side and choke on the high flow side. Lowering the flow rate below the surge limit leads to pressure fluctuations characterized by loud noises. Solutions involving two or three turbochargers have been developed and put to production but issues like

packaging, durability and high heat dissipation have been a major hindrance in its way. Therefore using a single turbocharger with a compressor that has a wide flow range seems to be a better alternative. One way to prevent the flow rate from going below the surge limit is increasing the rotational speed of the turbocharger, either by using a variable nozzle turbine (VNT) or by using motor assistance a lower engine speeds [39].

The surge limit can be improved by what is known as the casing treatment. Yamaguchi et al. [40] in 2002 developed a casing treatment for turbocharger compressors. There have also been many other works on improving the surge limit of a turbocharger compressor. Uchida et al. [13] made use of casing treatment and variable inlet guide vane (VIGV) to develop a turbo charger compressor with wide flow range and improved surge limits. Figure 11[13] shows the structure of compressor with VIGV and casing treatment. The VIGV located upstream to the casing treatment was able to control the pre-whirl of the inlet flow to the impeller. It was found from CFD analysis that vortexes were formed at the side of the shroud at the surge limits. This problem was catered by casing treatment i.e. by re-circulating the air from the impeller to point downstream of the variable inlet guide vane. The casing treatment implemented by Uchida et al.[13] had spoon type guide walls and was able to reduce the surge flow rate by 30% as compared to a conventional compressor at a pressure ratio of 2.5, not to mention the increment in compressor efficiency. Moreover the excellent synergy of the VIGV with the casing treatment yielded a reduction in surge flow rate by 59% as compared to a conventional compressor at a pressure ratio of 2.5. The structure of the compressor with the VIGT and the casing treatment is shown in figure 11(a) and the improvement in the surge limit has been shown in figure 11(b). It was also seen that the installation of a rib led to improvement in the surge limits at higher engine speeds.

Other studies on the effect VIGT on the flow range of a turbocharger compressor include, Fraser et al.[41], Mohtal et al.[42], Yamaguchi et al.[40]. Even though, the VIGT successfully widens the compressor's operating range, problem of throttling losses due to the variable inlet guide vanes are seen as low flow rates.

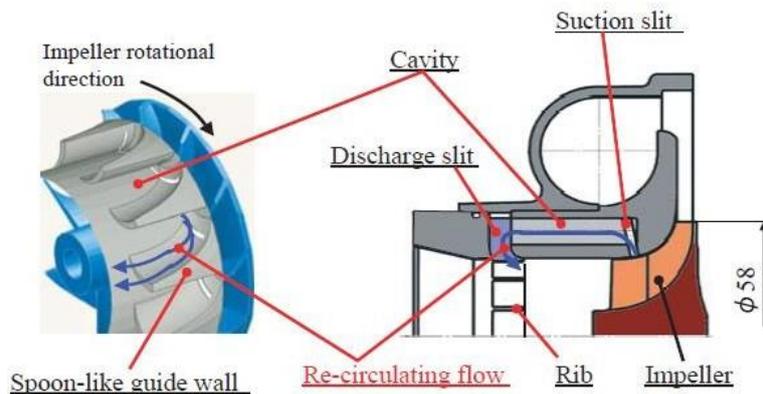


Figure 11(a). Structure of the casing treatment studied by Uchida et al.[13]

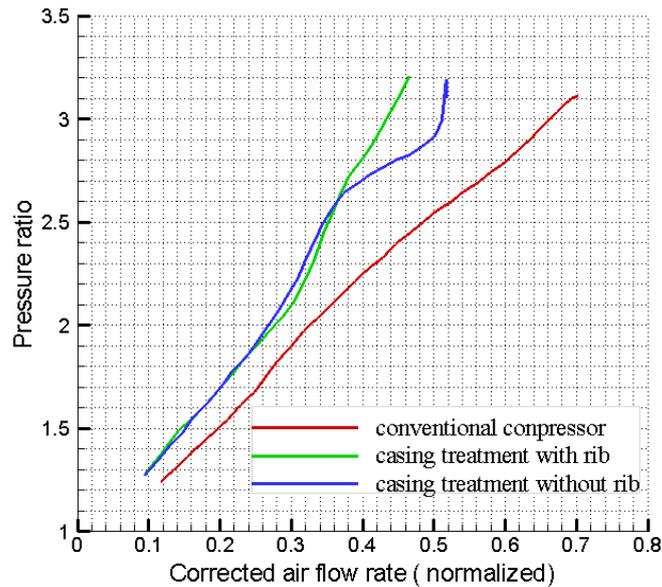


Figure 11(b). Effect of casing treatment (with and without rib installed in the discharge slit) on the surge limit of the compressor.[13]

Xinqian Zheng and Chaunjie Lan [43] improved the performance of a turbocharger compressor by a successful synergy of self-recirculation casing treatment (SRCT) and blade bowing. Six cases of blade bowing were studied which included both positive and negative bowing. It was reported that the negative bowing decreased the surge mass flow rate as well as the choke mass flow rate. Significant effects of blade bowing were seen at high rotational speeds. At near-coked conditions negative blade bowing enlarged the throat area, thereby changing the choke mass flow rate. With the synergy of SRCT and negative blade bowing improvements were seen on the surge flow rate of the compressor. An increase of 5.84% in the surge flow rate of the compressor was reported.

H Sun et al.[44] proposed a dual port casing treatment scheme (aka active casing treatment) to enhance the turbocharger compressor's operating range. It was an enhancement over the classical ported shroud recirculation casing treatment which successfully obtained a 12% additional flow capacity. The surge and choke were addressed separately with two different slots on the compressor shroud. Figure 12 further explains the design.

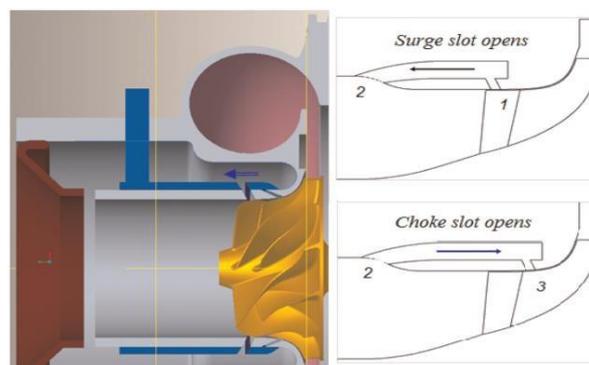


Figure 12. Dual-port casing treatment with bleeding and injection slot to extend the surge margin and the choke flow capacity of the compressor.

The slot between the full blades and the splinter blades serves to provide optimum surge control and the other slot downstream enhanced the choke flow capacity. As a shock wave involves a compression wave followed by expansion wave, the introduction of a second slot downstream could successfully take advantage of the following expansion and improve the choke flow capacity. An improvement in the flow capacity by 12% compared to aforementioned classical re-

circulation casing treatment without any compromise in low end efficiency and surge performance was reported.

Table 1 gives a brief description to recent gasoline production engines making use of VGT turbochargers. Apart from those mentioned in the table 1, Honda equipped the Legend with a VGT system starting in 1988, but it was only in production for two years. Chrysler equipped the Dodge Shelby SCX with a VGT in the late 1980s, but this was a very limited production run. With the recent trend in VGT application in gasoline production engines, it seems that VNT would be leading the way in the coming future. Though VGTs gasoline engine application seems to have been quite successful in few gasoline production engines, issues of production costs and durability still need some addressing. Also there seem to be scope for further development by addressing the issues of optimum vane clearances and vane sticking. Also some synergies of VGTs with Energy Recovery Systems may lead to a better control over the boost pressure. A brilliant application of the synergy Energy recovery system and turbocharger can be seen in the 2014 Mercedes Formula-1 engine.

Table 1. Recent gasoline production engines featuring VGTs

| Engine | No of cylinders | Displacement | Boosting system | Compression ratio | Fuel consumption | CO2 emission | Specific power | torque | Power |
|------------------------------------|-----------------|--------------|-----------------|-------------------|------------------------------------------------------|-------------------------------------|------------------|----------------------------------------------------------------------------|-----------------------------|
| Porsche 911 turbo S Coupé | 6 | 3.8 liter | VGT (VNT) | 9.8:1 | 9.1 liter/100km | 212 g/km | 112.3 kW/liter | 700 Nm (2,100–4,250 rpm) 750 Nm (2,250–4,000 rpm (with over boost) | 427 kW (580hp) 6,750 rpm |
| Porsche 718 Boxster and 718 Cayman | 4 | 2.5 liter | VGT (VNT) | 9.5:1 | 8.1 liter/100km (manual) 7.3 liter/100km (PKD)*** | 184 g/km (manual) 167 g/km (PKD) | 102.8 kW/liter | 420 Nm (1900 rpm to 4500 rpm) | 257 kw (300hp) at 6500 rpm |
| 911 Turbo S Cabriolet | 6 | 3.8 liter | VGT (VNT) | 9.8:1 | 9.3 liter/100km | 216 g/km | 112.3 kW/liter | 700 Nm (2,100–4,250 rpm) 750 Nm (2,250–4,000 rpm (with over boost****)) | 427 kW (580hp) 6,750 rpm |
| Volkswagen EA211 TSI evo | 4 | 1.5 | VGT (VNT) | 12.5:1 | Not released yet* | Not released yet* | 73.33 kW/liter | Not released yet** | 96 kW and 110 kW |
| Honda acura RXD 2.3L engine | 4 | 2.3 | VGT (VFT) | 8.8:1 | 19/24/21 mpg (2WD) 17/22/19 mpg (SH-AWD) | Not released yet | Not released yet | 260 ft-lbs at 4500 rpm. | 240hp 6000rpm |

*Volkswagen claims the new EA211 TSI evo to have efficiency benefits of up to 10 per cent compared with the previous 1.4l TSI (92 kW).

**Volkswagen claims that compared with a 1.4l TSI (92 kW), the step change in load to the maximum torque takes place some 35 per cent faster.

*** Porsche Doppelkupplung (PDK) is 7- speed transmission which offers extremely fast gear changes. . The engine is decoupled from the transmission to avoid deceleration caused by engine braking

****over boost function gives the Porsche 911 Turbo an extra 37 lb.-ft. of torque for up to 10 seconds.

5. Conclusion

In the past VGT turbochargers have already proven their worth in diesel engine downsizing. Today, with the stringent emission norms and with the heavy reliance of gasoline engine

downsizing on turbocharging, VGT application to gasoline engines seem inevitable. The VGT benefits of increased fuel economy, improved low end torques, better transient response, better steady state performances, increased power density and greater boost pressure over a wider range would be quite difficult to overlook in the next generation gasoline engine designs. VGTs have also proven to be a better solution over the more complex two or three stage turbocharging in many ways.

Though the high exhaust gas temperatures of gasoline engines and the perception of VGT (VNT) gasoline applications not being cost efficient have historically been taken as a hindrance to VGT (VNT) application to gasoline engines, Volkswagen 1.5 liter TSI evo engine seems to have successfully overthrown this perception by being a cost sensitive gasoline with a VNT turbocharger.

Despite all hindrances of high exhaust gas temperature and cost constraints, VGT turbochargers have successfully paved their way to gasoline engine application and have been wonderfully successful in providing a better transient response along with better steady state performance, not to mention the contribution of technologies like WCEM, variable valve timing etc. towards making this possible. At the same time, various improvements in the flow range of the turbocharger compressor have also been instrumental in the development of the VGTs so far. It therefore, seems that VGTs would possibly be a major driving force in the near future gasoline engine downsizing process.

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