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Effect of Variable Geometry Turbocharger (VGT) on Diesel Engine

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***Abstract*—**Power boosting technology of the diesel engine with no increase in the engine size has been developed with the evolution of the turbocharger which forces more air in the engine which increases more fuel injection and hence more power output. The turbocharger increases engine efficiency by using the energy of exhaust gases in the form of pressurized gas and heat, to drive the compressor. Most of the turbocharger previously used was of waste-gate type having drawbacks like volumetric efficiency limit, fix geometry. Hence the Variable Geometry Turbocharger (VGT) is used. It provides variable area of inlet orifice. It provide small orifice area for the exhaust gas during resupplying to input air due to which more boost create at lower engine speed and provides large orifice area during higher engine speed for higher exhaust pressure created during nozzeling operation. This study shows how the variable geometry obtains by the adjustable vanes which act as the nozzle around the central turbine and connected to actuator. Variable geometry turbocharger increases expansion ratio, output power, output torque. This study describes the improved full load performance of 2.5 liter DI diesel engine and its comparison with the waste-gated turbocharger. Within the same limitation of a maximum cylinder pressure as well as exhaust smoke levels, the low speed torque could be enhanced at its maximum and also reduces the exhaust smoke and improves the fuel consumption.

Keywords*—*VGT, Turbocharger, Engine Performance

I. INTRODUCTION

As the world's largest economies focus on reducing greenhouse gases (GHG), energy efficiency and it is ideally placed to help meet the most pressing challenge of making our planet a cleaner and better place to live and work. A turbocharger can meet these challenges. Turbocharger or turbo is a turbine-driven forced induction machine that improves an internal combustion engines' efficiency and power output by adding extra air into the combustion chamber. This improvement over a naturally aspirated engine's output are observed because the turbine can force more air, and thus proportionately more fuel, into the combustion chamber than atmospheric pressure alone. Turbocharger is powered by a turbine which is driven by the engine's exhaust gases. In short turbocharger uses the pressure energy of the exhaust gases and converts into kinetic energy to drive the turbines of turbocharger. There are various types of turbocharger like waste gated turbocharger, variable geometry turbocharger, twin turbocharger etc. Variable-geometry turbochargers (also known as variable nozzle turbo/VNTs), are one of type of turbochargers, usually designed to allow the effective aspect ratio (A/R ratio) of the turbine to be changed as conditions change. This change is important because, optimum aspect ratio at low engine speeds is very different from that of at high engine speeds. If the aspect ratio of turbo is too large, then it will fail to create boost at low speeds and if the aspect ratio is too small, the turbo will choke the engine at high speeds, resulting into high exhaust manifold pressures, high pumping losses, and ultimately lower power output. By altering the turbine housing's geometry, as engine accelerates, the turbo's aspect ratio can be maintained at its optimum. Because of this, VNTs have a minimal amount of lag, have a low boost threshold, and have very high efficiency at higher engine speeds. VNTs do not require a waste gate. Cross sectional view of the VGT turbocharger is shown in the fig.1.

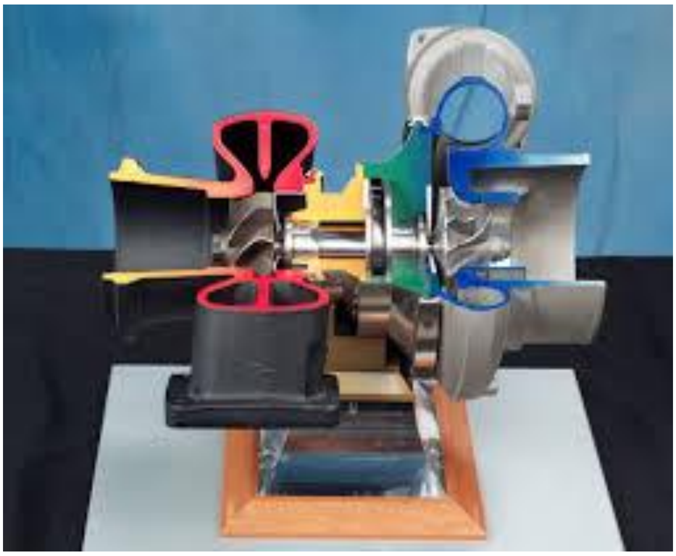

Fig. 1 Turbocharger Cross-section

VGTs tend to be much more common on diesel engines as the lower exhaust temperatures mean they are less prone to failure. The few early gasoline-engine VGTs required significant pre-charge cooling to extend the turbocharger life to reasonable levels, but advances in material technology have improved their resistance to the high temperatures of gasoline engine exhaust and they have started to appear increasingly in, e.g., gasoline-engine sports cars.[1]

II. DRAWBACKS OF TRADITIONAL TURBOCHARGER

The turbo-driven turbochargers are characterized by two chief parameters: aspect ratio (A/R ratio) and turbine radius. The A/R ratio is defined as the ratio of the area of the exhaust gas passage to the radius from the centre of the turbine wheel to a point defining the centre of that area (i.e. centroid of area).The main limitation of a traditional turbocharger is its fixed geometry. The aspect ratio (A/R ratio) of a turbo, has a direct relation to both the power increase generated and the speed of motor at which the power increase is generated. A smaller A/R ratio will produce higher boost pressure at a lower engine speed, but will fail to provide an enough high flow rate at higher engine speeds. This results into higher exhaust manifold pressures, lower pumping efficiencies, higher pumping losses and thus lower power output. A larger A/R ratio will create boost at higher engine speeds, and thus create more power, but it will fail to generate boost at lower engine speeds. So an aspect ratio must be picked either to produce power at lower engine speeds for quicker acceleration, or to produce a greater power output at higher engine speeds. Also a turbo having larger aspect ratio will have a longer lag time than a smaller A/R ratio turbo, because of its larger requirement of energy to produce boost.

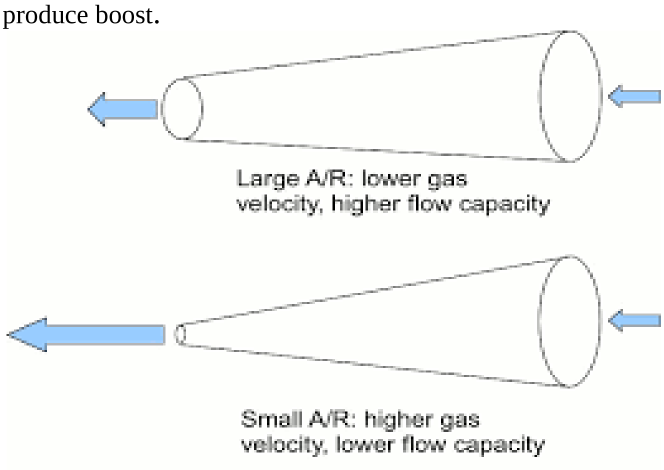

Fig. 2. Effect of A/R ratio on speed and flow

III. NEED FOR THE VGT

VGT provides the solution for all above problems. The VGT has a mechanism by which the inlet area can be varied to obtain the required A/R ratio for a given flow rate. This is obtained by varying positions of a set of aerodynamic guide vanes which direct the exhaust gas flow onto the turbine wheel. The vanes and plates move as a unit so that the plate can partially obstruct the exhaust gas inlet to the turbine, thus reduces the A/R ratio. This guide vanes can be moved such that the inlet is almost completely obstructed, or completely retracted to provide no resistance to the exhaust gas flow. Using this variability, turbine of turbocharger can work under virtually all engine speeds. By reducing the A/R ratio at low engine speed (when exhaust flow is low), and then gradually increasing, as engine speed increases (when exhaust flow is high), inlet velocity of exhaust gas can be kept high with no significant change in exhaust back-pressure. In short, this means that the VGT can function over any operating range of the engine. Since a practical diesel engines do not have a flat power curve with respect to engine speed, the turbo can be controlled in such a way that the curve get flatten out, so that the engine will have the same power output regardless of its RPM. This will make easy to design a transmission, and allows to use gear ratios designed for better acceleration, which further enhance the performance of a vehicle. It also reduces the lag by providing the same power as the engine instantaneously.

IV. TURBOCHARGER LAGS (TURBOCHARGER TRANSIENT RESPONSE TIME)

Transient response time also known as the turbocharger lag is dependent upon the inertia of the rotating parts and the efficient projection of exhaust gases onto the turbine vanes. It is defined as the time taken by the engine to change the power output in response to the throttle change. As the engine throttle is opened there will be an increased flow of mixture entering the cylinders with a corresponding exit of exhaust gas, which is directed onto the turbine blade causing the wheel assembly to accelerate rapidly. This is the main factor for the turbocharger lag. Friction and compressor load are also the factor which causes the lag.

Turbocharger lag can be reduced by reducing the rotational inertia of the turbocharger by employing the lower radius parts and using lighter parts like ceramic. Also reducing the bearing frictional losses using the foil bearing instead of the oil bearings. The main factor that can reduce the turbocharger lag is changing the aspect ratio of the turbine inlet as a large A/R ratio turbo will have a longer lag time than a smaller A/R ratio turbo because of its larger requirement of energy from the engine to generate the boost. Use of VGT can reduce the turbo lag time.

V. ASPECT RATIO (A/R RATIO)

The speed and acceleration of the turbine and compressor wheel assembly is largely influenced by the change in the A/R ratio. The A/R ratio is defined as the smallest cross sectional area of the intake passage of exhaust gas in the turbine housing (before the flow path spreads around the circumferential throat leading to the turbine wheel) divided by the distance from the centre of turbine wheel to the centroid of area. A smaller A/R ratio will produce higher boost while larger A/R ratio will produce more flow rate.

A/R ratio = smallest c.s.a.of intake passage of turbine housing /distance from central turbine wheel to centroid of area.

VI. VGTS' PARTS AND THEIR FUNCTIONS

Turbocharger consists of two main components, a turbine and a compressor. The function of the turbine is to scavenge waste exhaust heat and convert it into rotational motion. This rotational motion is then employed to drive the compressor, which compresses fresh air which is to be forced in the engine. The purpose behind the turbocharger is to overcome the limitation of the internal combustion engine's volumetric efficiency limit. Along with this there is the vanes nozzle assembly which is operated by the ECU (Electronic Control Unit) which causes the opening and closing of the vanes with respect to the speed of motor by the use of the actuators.

Turbine (as shown in fig. No. 3) is the main part of the turbocharger. The turbine is driven by exhaust gases. The temperature of exhaust gases can exceed 1875°F (1025°C) and can be very corrosive. The turbine wheels are continuously in the contact with the high speed gases. Therefore the turbine must be of high alloy steel and low in weight to reduce the inertia of the wheel so that it can move freely.

Fig. 3. Turbine

Compressor (as shown in fig. No. 4)is connected to the turbines by the shaft. As the turbine rotates compressor also rotates and forces more air in the engine. Compressor forces air having more temperature then the ambient temperature. Therefore it creates high pressure on the compressor wheels so that wheels must be made up from very high tensile strength having material.

Fig. 4. Compressor

Bearing shaft system (as shown in fig. No. 5) is also main part of the turbocharger. The bearing system supports the rotor assembly (turbine, shaft and compressor) resides in the turbocharger centre housing. That bearing system must reliably positioned and should support the rotor speed from zero to that of 150,000 RPM. In addition to the rotating loads on the bearings, there can be substantial thrust loads in either direction, regarding the operating conditions. The bearing system also has an influence on critical rotor speeds, vibration and shaft instability.

Fig. 5 Bearing shaft system

Actuator, flow control valves and speed sensors (as shown in fig. No. 6) are very important parts in the VGT. They are useful in changing the vane angle of the turbocharger as per the speed of the engine. They are directly control by the engine electronic control module (ECM). Actuator and sensors are connected to the housing of the turbine. The valves used are pneumatic valves and are control by the ECM.

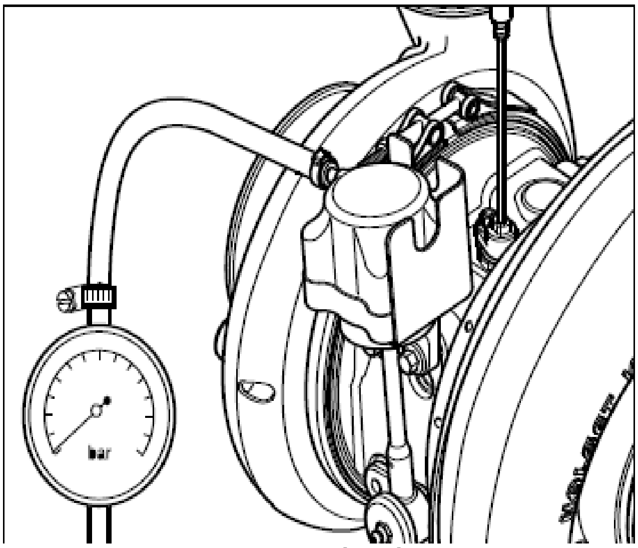

Fig. 6. Actuator and speed sensor

VII. WORKING PRINCIPLE OF TURBOCHARGER

Turbochargers are a type of forced induction system. They compress the air flowing into the engine. The advantage of compressing the air is that it lets the engine squeeze more air into a cylinder, and more air means that more fuel can be added. Therefore, we get more power from each explosion in each cylinder. A turbocharged engine produces more power overall than the same engine without the charging[3]. This can significantly improve the power to- weight ratio for the engine. In order to achieve this boost, the turbocharger uses the exhaust flow from the engine to spin a turbine, which in turn spins an air pump. In the turbocharger exhaust gases from the engines cylinders is expelled via the exhaust manifold into the turbine volute circular decreasing cross section pass way at a very high velocity, where it is directed tangentially inwards through turbine housing. The related gas kinetic energy impinges on the turbine wheel where it loss the velocity and pressure. This loss in pressure and kinetic energy of gases produces the kinetic energy in the turbine wheel and rotates. The turbine in the turbocharger spins at speeds of up to 150,000 rotations per minute (rpm) -- that's about 30 times faster than most car engines can go. And since it is hooked up to the exhaust, the temperatures in the turbine are also very high[3].

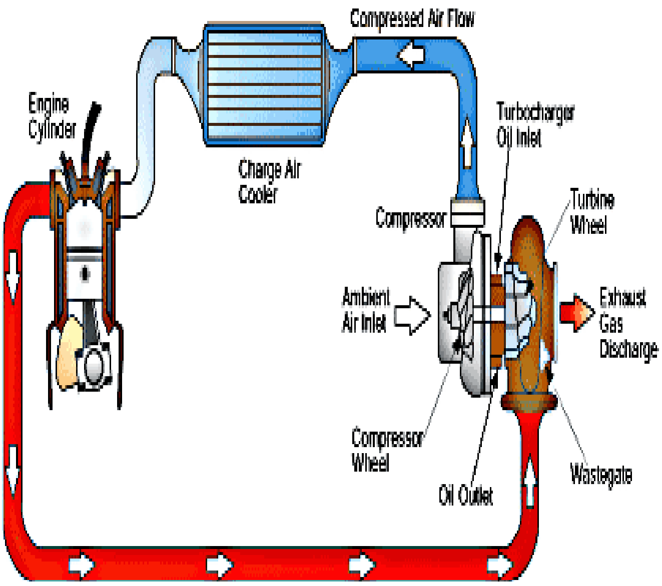

Fig. 7: Flow of air in machine

The turbine is connected to the compressor via the spindle assembly. As the turbine rotates compressor also rotates and the surrounding air gets trapped in the curved blades of the compressor wheel and the air experience the centrifugal force. The force produces the radial outward motion to the air where its velocity and pressure increases. From the wheels it goes to the periphery of the compressor wheel and the parallel diffuser (gap) form between the bearing housing and compressor wheel. From diffuser air flows to the circular volute where the air get congested and increases the pressure.

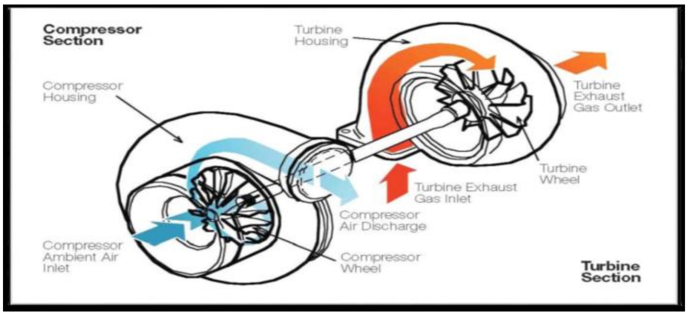

Fig. 8. Working principle of turbocharger

VIII. WORKING PRINCIPLE OF THE VARIABLE GEOMETRY TURBOCHARGER

A turbocharger equipped with variable geometry turbines have little movable guide vanes which can direct exhaust flow on the turbine blades. The guide vane angles are adjusted by an actuator. The angle of the vanes varies throughout the engine speed range to optimise turbine behavior.

In the following 3D illustration, it shows that vanes in an angle which is almost closed. This closed position of vanes is optimized for low engine speeds.

Following figure also shows that how the vanes look like in 3D when they are opened.

Fig. 9 Open and Close angle of vanes

In fig. 10 cut-through diagram shown, the direction of exhaust gas flow when the turbine vanes are almost closed. The narrow passage of which the exhaust gas has to flow through accelerates the gases towards the turbine blades, rotating them faster. The angle of the vanes also directs the gas to bombard the turbine blades at the proper angle.

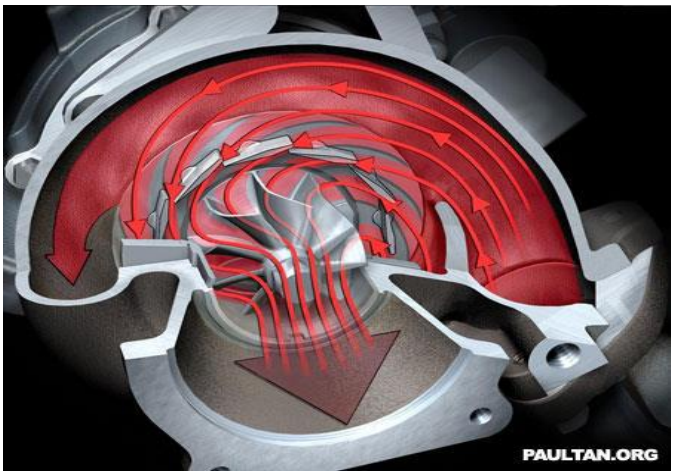

Fig. 10. Exhaust flow in closed vane

Following cut-through diagram (fig. 11) shows the exhaust gas flow when turbine vanes are fully opened. The high exhaust flow at high engine speeds are completely directed onto the turbine blades by the variable vanes.

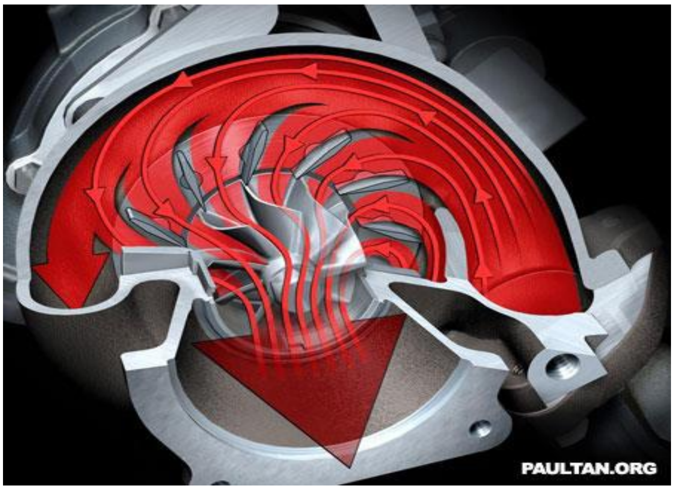

Fig. 11. Flow of exhaust in open vanes

IX. CASE STUDY

Variable geometry turbines (VGT) have particular interest to advanced diesel powertrains for future conventional trucks, since they can dramatically improve system transient response to sudden changes in speed and load, characteristic of automotive applications. The VGT technology considered as a method to eliminate turbo lag, as well as to improve low speed boost and torque because the conventional turbochargers charging effect is too poor in a low flow range below the matching point requiring a high power output at a low engine speed region. But in the VGT boost pressure can be created at the lower speed and reduction in the pumping losses at the higher speed of engine[11].

In this study applying the VGT turbo and conventional waste gated turbo to the high speed direct injection (HSDI) diesel engine and comparing the performance characteristics of the both cases. The vehicles used are international class VI 4700 series delivery truck having the vehicle and driveline specification as follow:

GVWR	7950 (kg)
Wheelbase	3.7 (m)
CG location	2.2 (in m from front)
Frontal area	5 (m^2)
Air drag coefficient	0.8
Transmission	4 speed automatic

The engine simulation used is the V8 DI 7.3 L diesel engine. The specifications of the engine are as follows:

Configuration	V8
Displacement	444 cu in.
Cylinder bore	104.4 mm (4.11 in.)
Piston stroke	106.2 mm (4.18 in.)
Power output	210-275 hp (157-205 kW)
Torque output	425-525 lb.ft (576-712 N.m)
Gove. Engine speed	2600 rpm

In the variable geometry turbocharger (VGT) flow area and the angle between the turbine volute and rotor can be changed which is not possible in the waste gated turbocharger. Therefore it increases the boost pressure at the lower speed enabling the high torque and it also reduce the fuel consumption at higher engine speed due to the high gap between the turbine volute and rotor.

As at the lower engine speeds vane angle is narrower exhaust gas get accelerated thus the boost pressure increased. This allows the More fuel delivery and higher torque is acquired. But due to the minimum, flow path turbine inlet pressure known as the engine back pressure increases. So it can be so high that fuel consumption may not be feasible. Therefore the improvement in the fuel consumption is necessary for the test. At the high pressure larger area of the flow passage is there and it can cause reduce in engine back pressure causing lower fuel consumption.

A. Experimental procedure

For the comparison study of the VGT and conventional waste gate turbocharger engine system is run at the full load covering the entire RPM range of the engine at the same boundary condition of the fuel consumption. For the study two cases are considered. In case an engine is enhanced by the VGT and in the case B it is attached with the waste gate turbocharger.

In the both the cases the engine is accelerated between the 0-60 mph and the various engine parameters are calculated. The parameter such as the fuel injection time is kept same for the both cases. in the case of the VGT initial vane angle can cause the change in the starting boost pressure therefore the starting boost pressure is kept as same for the waste gate turbocharger. At initially the engine is start at the full load with breaks applied and after the 5 seconds breaks are released to achieve the maximum demand upto the 60 mph speed of the vehicle and the engine and vehicle parameters are measured. The parameters measured during each case are engine speed (rpm), vehicle speed (rpm), boost (bar), fuel injected (g/cycle), torque converter turbine torque (transmission in peak torque in N.m), wheel slip and F/A (fuel/air) equivalence ratio.

B. Test result

From the given calculation the most important characteristics found out is the quicker response of the engine with the VGT. The slope of curve of engine speed at launch is very steep, as the result of the fact that the VGT turbocharger is able to build pressure in the intake manifold much faster; hence the injection system controller allows more fuel to be injected in the cylinder (see Fig.12).

The F/A equivalence ratio histories show spikes associated with the end of pressure build-up during the turbocharger transient (see Fig. 13). These excursions into a mixture richer that what is normally experienced under steady-state operating conditions obviously occur at different times, i.e. much earlier in the case of the engine with VGT. The unfavorable effect on emission of soot (unburnt carbon segregated) would be similar. However, with the improvement in the response so drastically, the fuel injection calibration could be changed to reduce fuelling during the critical part of the transient without sacrificing too much of the engine response. The sudden burst of engine torque combined with the increased slip ratio in the torque converter produces a much higher initial TC-turbine torque, i.e. transmission in peak torque. Hence, the time between launch and first gearshift is reduced by almost 2 seconds, and the overall 0-60 acceleration is improved considerably. The tire slip two seconds into the launch is also much higher and during that period tire wear would be increased[12].

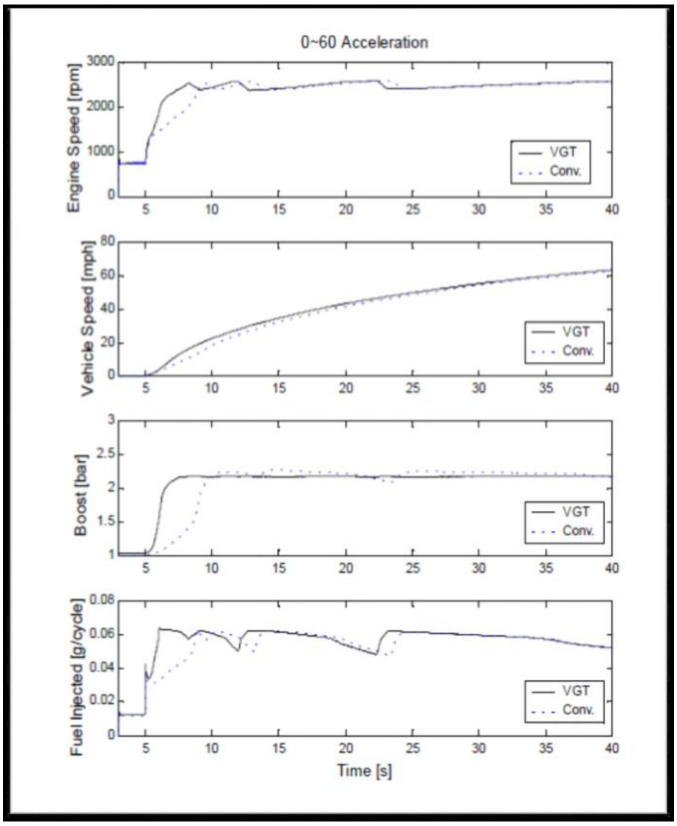

Fig. 12. Comparison between Engine speed, vehicle speed, boost pressure and fuel injected in combustion chamber of VGT and Waste gated turbocharger.

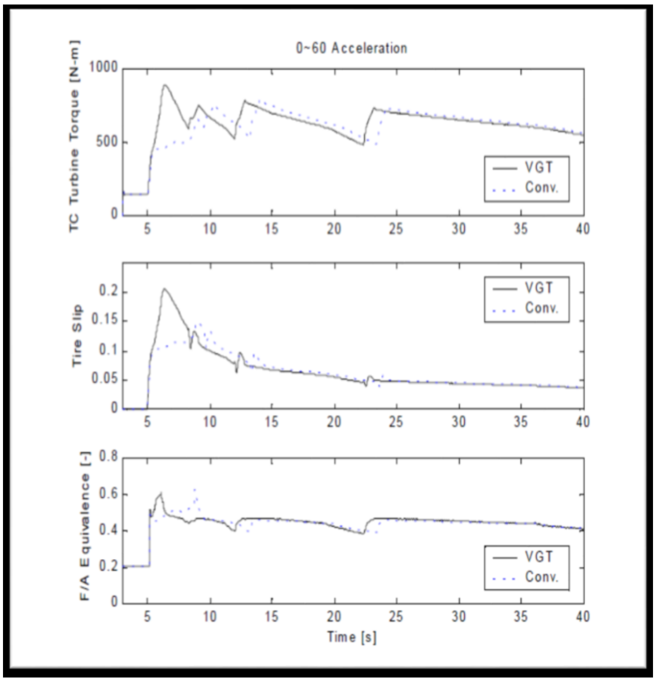

Fig. 13. Comparison between TC turbine torque, wheel slip and F/A equivalence ratio of VGT and waste gated turbocharger.

From the above data calculation observation says that due to use of the VGT charged air mass is increased by the 10-20% at low speed. Therefore exhaust smoke is reduced and the full fuel consumption will be occurred. At low speed we can see that 40% of increase in the torque. At the medium engine speed there is little gain in fuel consumption for VGT. Within the boundary condition we can say VGT can increase engine power by 8%. There will more tireslip at the low speed due to high torque generated[3][11].

X. Advantages of the VGT

A. Reducing Turbocharger Lag Time

The area between the adjustable vanes works as nozzles. These nozzles are thus varied in size as a function of engine operating conditions. By opening the nozzles at high engine speed or closing them at low speed, effectively changing the A/R with engine speed or demands, the turbo can produce boost from a low speed without restricting flow at higher speed. Since they can produce boost at lower engine speed Lag time is decreased. Also since the vanes are remotely controlled the boost pressure can be altered without changing engine speed. By adjusting the vanes you can increase exhaust manifold pressure during transients (gear changes). Coming out of a transient with a higher exhaust manifold pressure allows this stored energy, in the form of pressure, to be used to drive the turbo to a higher boost level faster. By increasing the boost level faster Lag is once again reduced.

B. Increasing Efficiency

Turbochargers in general are a very good way to improve the efficiency of an engine. By pressurizing the intake manifold, more air, and thus more fuel, is brought into the cylinder every time the intake valve opens. This creates a volumetric efficiency of greater than 1. A volumetric efficiency of even 1 is impossible in any real engine without some kind of forced induction due to friction losses. This improves the overall efficiency of the engine by allowing it to burn more air and fuel on every cycle. The high positive pressure generated also helps to overcome any casting defects in the manifold, such as surface roughness (major losses) or tight corners (minor losses), by providing a larger driving force, or pump head. Fixed geometry turbochargers (FGT) work as any other centrifugal pump and thus have a limited optimal operating range. VGTs have the advantage that many different pressure ratios can be produced at a single engine speed due to the variable vanes changing the effective area and A/R. The vanes can be manipulated to create an optimal boost pressure at any speed. By producing an optimal boost through a larger engine speed range the overall efficiency is increased.

C. Reduction in the smoke generation

Due to the increase in the intake air mass fuel in the cylinder burns completely. Therefore the smoke generated during this reduced.

XI. Disadvantages of the VGT

A. Cost and Reliability

VGTs are very complex and require complicated control systems. The small moving parts, sensors, and controllers make them more expensive to produce than FGT. All the parts are exposed to extreme temperatures of over 1000 0F making them wear quickly. Also due to the extreme temperatures they need to be made from exotic materials which increase the cost even more.

B. Availability for Gasoline Engines

Typically VGTs are only available for diesel engines. Diesel engines produce much lower exhaust temperatures than gasoline engines. These lower temperatures allow for the use of more common materials and higher reliability.

Conclusion and Future Scope

The application of VGT could provide HSDI Diesel engines with a great potential for full load performance, especially at low engine speed. By adjusting the flow area of diffuser nozzle vanes, the boost pressure can be raised higher, which results in the high mean effective pressure, most beneficial at low engine speed. In addition, because a turbine volute and wheel of VGT are designed for a larger flow region of the engine operating range, the same boost pressure can be achieved even with much lower engine back pressure, by controlling a flow angle and area. This means that a turbine could work more efficiently over a wider engine speed. Therefore, fuel consumption can be improved for most of the speed ranges. At high engine speed, engine power can be enhanced due to both the lower pumping loss and the reduced residual gas, which means more charge air flow at the same boost pressure and better combustion environment[3].

Future scope in the VGT is in the use of the light weight material for the turbine and the compressor so that it can handle more temperature and more pressure so that it can used for the gasoline engines. Research should be carried out to reduce the size of the turbocharger. There is new concept of the electric advanced turbocharger which reduces most of the disadvantages of conventional turbochargers. In this there is a electric motor at the shaft connecting the turbine and compressor. This can also work as the generator. During the acceleration engine drives turbocharger shaft. During the full load running the motor retards the turbocharger shaft so that it can ensure not more boost pressure. These turbochargers are perfect for hybrid vehicles.

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