Effect of Variable Geometry Turbocharger on HSDI Diesel Engine

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Power boosting technology of a High Speed Direct Injection (HSDI) Diesel engine without increasing the engine size has been developed along with the evolution of a fuel injection system and turbocharger. Most of the turbochargers used on HSDI Diesel engines have been a wastegated type. Recently, the Variable Geometry Turbocharger (VGT) with adjustable nozzle vanes is increasingly used, especially for a passenger car in European market. This study describes the first part of the experimental investigation that has been undertaken on the use of VGT, in order to improve full load performance of a prototype 2.5 liter DI Diesel engine, equipped with a common rail system and 4 valves per cylinder. The full load performance result with VGT is compared with the case of a mechanically controlled wastegated turbocharger, so that the potential for a higher Brake Mean Effective Pressure (BMEP) is confirmed. Within the same limitation of a maximum cylinder pressure and exhaust smoke level, the low speed torque could be enhanced by about 44% at maximum.

Keywords: VGT, HSDI, Turbocharger

INTRODUCTION

In power boosting of engines, the application of conventional turbochargers could realize only a limited improvement because it is effective in a narrow flow range. Charging effect of a conventional turbocharger is too poor in a low flow range below the matching point to realize a high power output at a low engine speed region. The wastegated turbochargers that bypass some portion of an exhaust gas are generally used for boosting high speed Diesel engines. But, recently, VGT (Variable Geometry Turbocharger) is increasingly used in HSDI Diesel engines, which makes it possible to raise the boost pressure even at lower engine speeds, together with the reduction of pumping losses at higher engine speeds, compared with a wastegated turbocharger. In this study, a VGT was applied to an HSDI Diesel engine, and the improvement of a full load performance over the case with a mechanically controlled wastegated turbocharger is confirmed. The test engine is a prototype 2.5 liter direct injection Diesel engine, equipped with a common rail fuel injection system with a maximum rail pressure of 1350 bar and 4 valves per cylinder. The VGT tested in this study was a Variable Nozzle Turbine (VNT) type, and the vane angle of the turbine nozzle can be varied, as shown in Fig. 1.

EXPERIMENTAL STUDY

VGT is a device that can vary the flow area and flow angle between the turbine volute and rotor channel. Compared with a wastegated turbocharger, it is possible not only to increase a boost pressure and charge air flow rate with VGT at low engine speeds, enabling a higher torque, but also to reduce fuel consumption at higher engine speeds, due to lower pumping losses with full utilization of the exhaust flow.

At low engine speeds, by making the flow passage between turbine nozzle vanes narrower, the exhaust gas approaching the turbine rotor channel can be accelerated. By this acceleration, a boost pressure and, therefore, a charge air flow rate can be increased. This allows more fuel delivery, and the higher torque can be acquired. However, as a negative effect of throttling the flow path between nozzle vanes, a turbine inlet pressure, so called an engine back pressure, could rise so high to the level where the improvement in fuel consumption might not be feasible any more. Therefore, if the boost pressure is not raised more than necessary, there should be an improvement in fuel consumption because Indicated Mean Effective Pressure (IMEP) increases more than Pumping Mean Effective Pressure (PMEP). In other words, higher combustion efficiency can still overcome the pumping loss, just like the case that the fuel consumption of a turbocharged engine is better than that of a naturally aspirated engine. Thus, the improvement in fuel consumption may depend on test conditions.

At high engine speeds, a larger area of the flow passage between nozzle vanes, acquired by manipulating a vane angle adequately, results in a reduced engine back...
pressure. This results in the reduced pumping loss, which is the primary reason of the lower fuel consumption with VGT at high engine speeds. In the turbocharger point of view, a large portion of the exhaust gas enthalpy at the turbine inlet is wasted by wasting and incidence loss provoked from an inadequate flow angle relative to the rotor vane. This is relatively big in the case of a mechanically controlled wastegated turbocharger. On the contrary, there is no bypassing of an exhaust gas for VGT. Thus, the exhaust gas enthalpy is not wasted at all, but used more efficiently for boosting. Furthermore, the approach angle of the exhaust gas flow to the turbine rotor blade can be adjusted appropriately, so that the incidence loss may be reduced to the minimum level with the higher turbine efficiency. As a result, the fuel consumption can be improved. With an increased fuel delivery at high engine speeds, power increase can also be acquired within the same boundary conditions of an exhaust smoke level and peak cylinder pressure, which is due to not only the reduction of pumping loss but also the improved smoke limited torque resulted from the less residual gas due to the better gas exchange.

In a medium speed range, with raising a boost pressure and increasing a charge air mass, higher torque can also be acquired. But, the performance level in this region is already limited to the maximum cylinder pressure. Hence, the torque improvement by VGT is not so dramatic as at low engine speeds, compared with the case of a well-matched wastegated turbocharger. Nevertheless, because VGT does not waste any exhaust gas energy, at the same boost pressure, a turbine inlet pressure for VGT must be lower than that of a wastegated turbocharger. By careful setting of an injection timing and boost pressure, it can be possible to enhance the power output to a certain extent.

**TEST METHOD**

To find out the extent of the improvement in fuel consumption, the change in a power output was measured with the same fuel delivery, as Case A. In addition, in order to see how much power can be enhanced by VGT, Case B was executed with the same boundary conditions.

In Case A, the test purpose is to see the effect of changes in a boost pressure and turbine inlet pressure, whereas the other dominant parameters on fuel consumption are fixed as the same with the case of using a wastegated turbocharger, such as a start timing of fuel injection. In this case, it is important how to set the nozzle vane angle according to the speed variation. It may be one way to vary the boost pressure, in order to find out the point at which the improvement in fuel consumption appears. The other way is to just set the boost pressure at the same level as in the case of using a wastegated turbocharger. At low engine speeds where full load performance is limited mainly by charge air mass, the former method is used to show the improvement in exhaust smoke and fuel consumption, according to the increase of charge air mass. However, at high engine speeds, the latter method is adopted to observe the effect of the reduced turbine inlet pressure.

In Case B, it is necessary to set the injection timing carefully to prevent the cylinder pressure from rising over the limit allowed. At low engine speeds, as in Case A, the boost pressure is raised to get more air flow, compared with the case of using a wastegated turbocharger, and then the fuel delivery is increased to see how much the full load performance can be enhanced with the same smoke level. In a medium engine speed range, because of the limitation of the cylinder pressure, it is impossible to raise the boost pressure by as large an extent as in the case of a low speed region, compared to the case of using a wastegated turbocharger. But, in spite of this fact, it is possible to enhance the power output, within the cylinder pressure limit, by an increased fuel delivery with a injection timing retarded. At high engine speeds, it is intended to see a power increase mainly caused by reduced pumping losses resulting from lower back pressure and by an increasing fuel delivery, which is possible due to the reduction of an internal EGR rate, rather than by an increase of a boost pressure or charge air mass. However, the cylinder pressure, exhaust smoke, and gas temperature at the turbine inlet must be kept within the limits.

**TEST RESULT**

*With the same fuel delivery and start of injection (Case A)*

Figures 2, 3, and 4 are the test results for Case A, with the same fuel delivery and start of injection for both cases. It can be confirmed that the increase of a boost pressure and charge air mass by closing nozzle vanes of the VGT is very effective for improving combustion efficiency. Exhaust smoke decreases and BSFC is improved by about 3 ~ 10 %, at a low engine speed region of 1000 ~ 1500 rpm. With the VGT, it is possible to raise the boost pressure in 1000 ~ 1500 rpm to the optimum value of 132 ~ 194 kPa absolute, which almost doubles the boost pressure of a wastegated turbocharger. It is also possible to raise the boost pressure beyond this level, but there is no benefit because torque decreases due to an excessive increase in the engine back pressure. For VGT, since the engine back pressure could rise doubled or tripled, the turbine efficiency would become lower for the case of a higher boost pressure, even at low engine speeds. However, the deterioration of the engine performance due to the higher back pressure is not so big as to override the improvement in the thermal efficiency from the higher boost pressure and the combustion improvement which results from the higher charging efficiency. The increase in a charge air mass is very efficient to improve the combustion quality. The richer the air fuel ratio is with the wastegated turbocharger, the more effective the application of VGT is to improve the combustion quality at low engine speeds.

In a medium engine speed range beyond 2000 rpm, the boost pressure is set to the same level with the case of the wastegated turbocharger used. Thus, the exhaust smoke and air-fuel ratio are almost the same. However, the turbine inlet pressure of the VGT is reduced by 15 ~ 23 % for the same boost pressure. This is more efficient than using a wastegated turbine with a large flow range. As a result of this reduction, the fuel consumption is improved by 2 ~ 3 %.
At high engine speeds, there is an obvious benefit in fuel consumption by using the VGT, compared with the wastegated turbocharger. It can be seen that the back pressure is reduced for the VGT by about 32 kPa at 4000 rpm, the benefit of which shows up as the power increase of 4 %. Furthermore, even with the same boost pressure, using the VGT increases the charge air mass by 3 %, and the exhaust smoke is reduced by the corresponding amount. This results from the lower back pressure and more efficient gas exchange process, as explained before. Because of the lower engine back pressure and higher turbine efficiency, the temperature of the exhaust gas at the turbine inlet is also lower with VGT than that with a wastegated turbocharger.

Within the same boundary conditions (Case B) Figures 5, 6, and 7 are the result of the test in which the maximum potential of full load performance can be seen with the boundary conditions of the smoke limit of 2.5 FSN, the cylinder pressure limit of 150 bar, and the limit of turbine inlet temperature of 760 °C. It can be observed that the effect of the VGT on the torque at low engine speeds is conspicuous. At 1500 rpm, by higher boosting with VGT, the full load torque can be enhanced by about 31 %. The BMEP level at this point reaches 18.5 bar. The engine speed where the advantage of using VGT is most evident is at 1200 rpm. At this speed, the torque increase of 44 % is observed. Since the increase of pumping loss for higher boosting is negligible compared with the benefits from the increase of an indicated work, the
fuel consumption stays either at the same level or is reduced.

At medium engine speeds, the torque enhancement is possible, but as can be seen at the speed of 2000 or 2500 rpm, the torque gain is not so prominent as in the case of low engine speeds. Since the cylinder pressure is mostly the main parameter that limits the full load performance in this speed range, the increase of the boost pressure is not so much effective as in the case of low engine speeds. The higher the boost pressure is, the later injection timing must be used, which may result in the deterioration of fuel consumption and the increase of a turbine inlet pressure, which could offset the positive effect of the VGT. However, for the case of the present study, the improvement in fuel consumption could be seen, even with the retarded fuel injection timing for the case of using the VGT. The benefit of increased air mass, which is the outcome of higher boost pressure and lower engine back pressure, is more prevailing than the negative effect of the injection timing retardation. With the VGT, the maximum BMEP of 18.6 bar could be achievable. However, even with the wastegated turbocharger, 17.8 bar was realized. Because the limits of the maximum cylinder pressure and gas temperature at the turbine inlet precede the exhaust smoke limit, the more fuel delivery for more torque than this level is not possible in medium engine speeds, despite the lower exhaust smoke number far below 2.5 FSN.

At high engine speeds, the benefit of the VGT, to say,
pressure is evident. At the rated speed of 4000 rpm, power can be enhanced by about 7.9 % with the same combustion system. The sizes of the VGT turbine volute and wheel are bigger than those of the wastegated turbocharger. This means that VGT turbine is designed for larger flow range than the wastegated turbocharger. As can be seen in Fig. 7, the turbine works more efficiently over a wide speed range. On the contrary, because a wastegated turbine is usually designed for the use at smaller flow range in order to achieve a good power boosting at low engine speed and a better transient behavior, the turbine efficiency at the larger flow range with wastegating cannot help becoming worse. Even with the richer air-fuel ratio, the VGT yields the same exhaust smoke level as that of the wastegated turbocharger because of the reduction of an internal exhaust gas recirculation.

RESULTS AND DISCUSSION

With the use of the VGT, it is possible to increase the charge air mass by about 10 ~ 20 % at a low speed range. As a result of this, the exhaust smoke is reduced and the fuel consumption is improved with the same fuel delivery and start timing of injection. At low speed, over 40 % of additional torque increase can be observed within the same exhaust smoke, the cylinder pressure, and the exhaust gas temperature limit, by adjusting the boost pressure and fuel delivery with the VGT. In the medium engine speed range, there is a marginal gain in the fuel consumption for the VGT, with the same fuel delivery. When the boost pressure and fuel delivery are increased, more torque could be achieved with the expense of the deterioration in fuel consumption. This is because the injection timing should be retarded not to exceed the maximum cylinder pressure limit. At high engine speed, with the same fuel delivery, the rated power can be enhanced by 3.5 %, mainly caused by the reduction of pumping loss. However, within the same boundary conditions, the power increase for the VGT could reach about 7.9 %.

CONCLUSION

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.

NOMENCLATURE

- $P_{\text{max}}$: maximum cylinder pressure, bar
- $P_{\text{rail}}$: common rail pressure, bar
- $FD$: fuel delivery, mg/str
- SOI & BOI_MAIN: start of injection
- SFC: brake specific fuel consumption, g/kWh
- $P_{B}$: boost pressure, kPa absolute
- $\eta_V$: volumetric efficiency, %
- $P_{\text{ex1}}$: turbine inlet pressure, kPa gauge
- $P_{\text{ex2}}$: turbine outlet pressure, kPa gauge
- $T_{\text{ex1}}$: turbine inlet temperature, °C
- $T_{\text{ex2}}$: turbine outlet temperature, °C
- BMEP: Brake Mean Effective Pressure, bar
- IMEP: Indicated Mean Effective Pressure

REFERENCES