VNT and EGR Technologies for a Turbocharged Diesel Engine

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Abstract-In this study an experimental investigation was carried out on a turbocharger with variable nozzle turbine (VNT) and exhaust gas recirculation (EGR) system reducing emissions of a direct injection diesel engine. In the EGR system, the exhaust gas was tapped off before the turbine, cooled, and mixed with the intake air after the compressor. A positive pressure difference across the EGR circuit was set up by using a VNT turbocharger, a venturi pipe positioned in the intake manifold such as to provide extra suction power to the EGR gases. The emissions behavior and efficiency with the EGR system were tested in a number of engine working points. The results indicated that the engine could achieve a perfect performance in all speed range with applying of the turbocharger with VNT. The torque was improved greatly at any speed, especially at low speeds; The fuel consumption was improved too; The nitric oxides (NO_X) emissions was reduced by large scale by EGR system. With using VNT and venturi pipe, the EGR area and the maximum EGR rate could be enlarged, the NO_X emissions was reduced to lower level.

Keywords-Variable nozzle turbine; Turbocharger; Emissions, EGR

I. INTRODUCTION

The emissions legislation for diesel engine across the world has continuously sharpened. The primary target of this legislation has been the reduction of the emissions of nitric oxides (NO_X) and of particulate matter (PM) by these engines[1].

It is difficult to reduce NO_X and PM emissions simultaneously owing to NO_X /PM trade-offs. One useful NO_X reduction technique is exhaust gas recirculation (EGR) [2]. Research at TNO on EGR-technology for HD diesel engines has shown before that with appropriate hardware and a dedicated control strategy very low levels of NOx and PM emissions can be achieved while maintaining competitive fuel economy and transient behavior[3]. Other researches show that the NO_X emissions of the engine can be reduced by large scale without increasing in smoke or fuel consumption while maintaining an adequate excess air ratio[4-6]. EGR has already been used on naturally aspirated diesel engine for many years. While there are many difficulties for EGR technology applying on turbocharged engine. A larger EGR rate is needed in turbocharged diesel engine. While the pressure before turbine is lower than that of after compressor in many operating points. It would be an obstacle for the gas flow of high pressure routine EGR system circuit. In most cases there are solutions for setting up EGR in a HP (high pressure)-EGR circuit: either through modified valve timing (Miller-timing), through implementation of additional turbocharging equipment (a so-called EGR-pump) [7-9], or through application of turbocharger with variable nozzle turbine.

On the basis of this background, the purpose of this paper is to reduce emissions of a turbocharged diesel engine by VNT and EGR technologies. In this case the recirculated gas was taken from the upstream of the turbine to the downstream side of the compressor.

II. EXPERIMENTAL APPARATUS AND PROCEDURE

A. Experimental apparatus

In this paper, a number of innovations had been developed specifically to accomplish EGR system and deliver optimum performance. They included a new EGR valve, to regulate the recirculation of exhaust gases; an EGR cooler, to reduce the temperature of exhaust gas; a new variable nozzle turbine (Fig.1) , to provide the pressure necessary to drive the recirculated gases into the intake pipe; a venturi-pipe (Fig.2) , to combine inlet air and cooled exhaust gases prior to introduction into the cylinder.

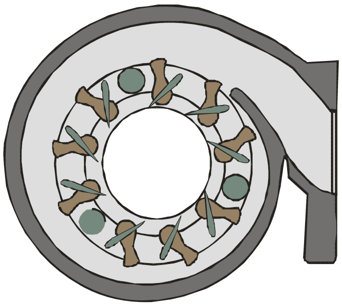


Fig.1 Schematic description of VNT

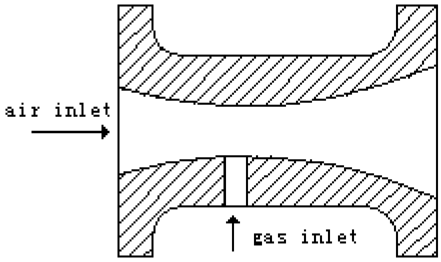


Fig. 2 Schematic description of venturi-pipe

The VNT turbocharger adjusts the gases cross section at the inlet of the turbine wheel in order to optimize turbine power with the required load. Instead of using one nozzle to accelerate the exhaust gases towards the turbine wheel, it has a ring of 9 variable vanes. As the vanes are rotated, they change the area of the nozzles that the exhaust must pass through.. An electric-liquid proportional valve was used to regulate the vanes position of the VNT. The smaller the nozzle area brings about the faster the gas velocity, the more turbine power, the more boost. At the other extreme the vanes can open fully when boost is not needed, with the resulting reduction in exhaust restriction.

Fig.2 shows a schematic description of the venturi pipe. The ventrui pipe was designed specially and it wouldn't affect the performance of the engine. The flow area reaches the minimum at the position of throat. The exhaust gases enter the throat and mix with the inlet air.

The engine is an inline 4-cylinder turbocharged direct injection diesel engine. The parameters of the engine are described in Table1. The base-line engine used a wastegate turbocharger with constant nozzle area.

The experimental apparatus are shown in Table 2. The torque of the engine is measured directly by the PECD 9400 dynamometer. The EGR rate and concentrations of NO_x are measured by a MEXA-7000EGR emission analyzer, and the smoke emissions are tested by a full-automated fqd-102A smoke meter.

Table 1 Engine specifications

Specification	Value
Type	DI TCI
Cylinder Numbe	4
Bore×Stroke	98x105 mm
Displacement	3.168 L
Compress ratio	18:1
Swirl ratio	2.2
Maximal torque/speed	265N.m/2000rpm
Rated Power	81.5kW /3400rpm
Turbocharger	TB28

Table 2 Test equipment of experiment

Equipment	Type
Test control instrument	EIM301D
dynamometer	PECD 9400
EGR analyzer	MEXA-7000EGR
Emission analyzer	MEXA-7000EGR
Digital smoke	FQD-102A
Air flow-meter	sensycon

B. Procedures

In this paper, a turbocharger with VNT was installed on the test engine instead of the conventional turbocharger. The optimal vanes position was decided in every operating point through experiment. EGR experiment was based on VNT system. The schematic description of experiment is shown in Fig.3.

Fig.4 shows the pressure before turbine and after compressor at full load operating points of the engine. As can be seen in Fig.4, the pressure after turbine is higher than that of before compressor between 1750rpm and 2750rpm, it means that EGR is impossible in these operating points. With applying of VNT and venturi-pipe, the pressure difference problem was solved.

The EGR rate was varied by controlling the opening degree of the EGR valve. The EGR rate was obtained from the measured CO_2 concentration [CO_2] at the inlet manifold, at the exhaust, and the ambient atmosphere[6,10].

$$EGR\% = \frac{CO_{2\text{int}} - CO_{2ambient}}{CO_{2ext} - CO_{2ambient}}$$

In this paper, the performance of the engine was optimized with using a turbocharger with VNT. The performance and emissions characteristics of the engine with the vanes position at full load of the engine were investigated. The larger the vanes position, the smaller the flow area of the turbine, more air enters the engine. The more the inlet air, the larger the boosting rate. Different EGR rates were gotten when the EGR valve was opened to different degree. The EGR rate can be varied for the EGR method the base turbocharger was replaced with a VNT turbocharger. Then the EGR rate was varied by changing the turbine nozzle area. The EGR effects on the performance and emissions characteristics had been investigated VNT and venturi-pipe system provided the suitable pressure gradient for EGR flow. How the VNT system affects the EGR system had been investigated.

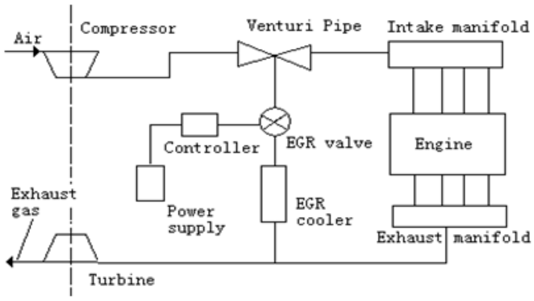


Fig.3 Schematic description of experiment

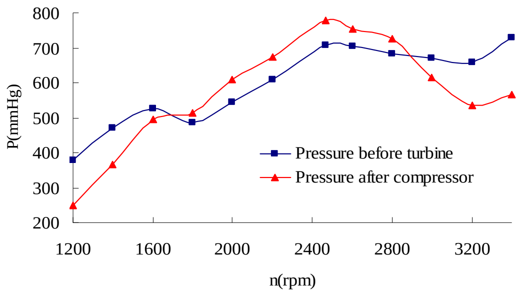


Fig.4 The pressure before turbine and after compressor at full load operating points of the engine

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. *Effects of VNT on the engine*

1). Comparison of VNT with conventional turbocharger

The performance and emissions of diesel engine equipped with conventional turbocharger were compared with that of engine equipped with VNT. Figs.(5-6) are the comparison of performance and emissions between VNT and conventional turbocharger(CT).

It is known from Fig.5 that the torques of engine equipped with VNT are larger than that of engine equipped with CT at all engine speed range. The increasing of torques is more obvious at low speeds. At the speed of 1200rpm, the torque of the engine with VNT at full load is 226Nm, which is 35Nm larger than that of the original engine. The torque is increased by 18.3% by using VNT. At the speed of 1400rpm, the torque is increased by 16.3% at full load point.

According to Fig.6, the BSFC at full load operating points of the engine with VNT is lower than that of engine with CT at all speed range. It is more obviously at high speeds. At the speed of 3400rpm, the BSFC of the engine with VNT is 247.9g/kWh. It is reduced by 4.1% than that of original engine, which is 258.5g/kWh.

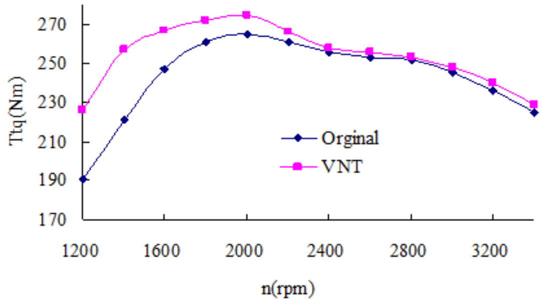


Fig. 5 Comparison of torque

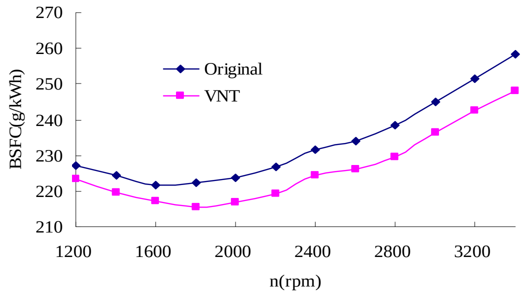
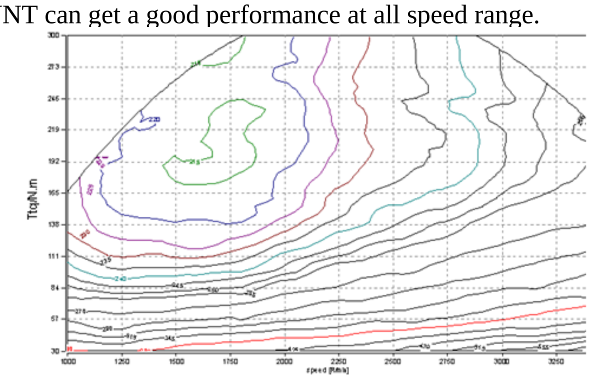


Fig.6 Comparison of BSFC

2). The performance of engine with VNT

Fig.7 shows comparison the general performance of the original engine with VNT engine, it can be found that the fuel consumption of VNT is lower than that of original engine. Take the fuel consumption contour line of 230 g/kWh as an example, the largest engine speed is 2300rpm in the original engine, it is improved to 2800rpm in VNT engine. It means that the engine can get better fuel consumption by using of VNT at medium and high speeds. The speed of lowest fuel consumption in original engine is lower than that of VNT engine. It is difficult to get good performance both at low speed and at high speed when matching wasted gate turbocharger. The engine with VNT can get a good performance at all speed range.



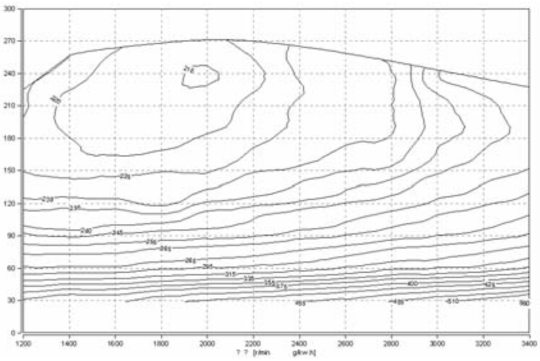
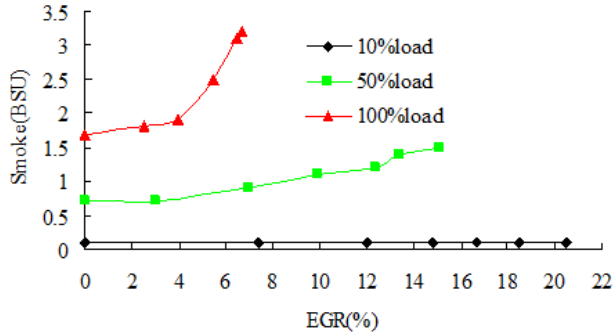


Fig.7 Comparison the general performance of the original engine with VNT engine



(b) Smoke

Fig. 8 Effects of EGR rate on NO_X emission and the smoke

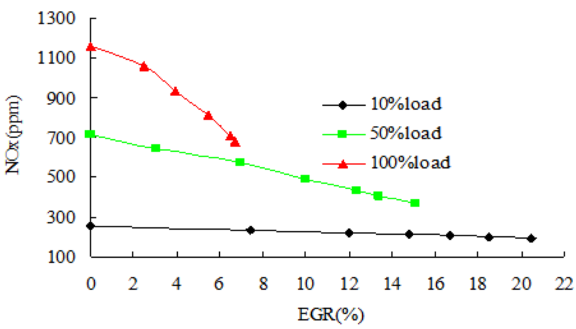
B. *Effects of EGR on the engine*

Effects of EGR rate and emissions of the engine were investigated. Different operating points had been tested. Take the speed of 2000rpm as an example, Fig.8 (a-b) are EGR rate on NO_X emissions and smoke respectively at different loads.

1). Effects of EGR rate on emissions of the engine

Figs.8(a) and (b) show the effects of EGR rate on NO_X and smoke of the engine at different loads. The EGR rate has greatly affected NO_X and smoke. At 10% load, the smoke is at a very low level. It keeps constant with increasing of EGR rate. While the EGR rate has greatly effects on NO_X emissions , it is reduced by 22.6%, from 350ppm to 271ppm. At this operating point, in order to achieve the best engine performance, the optimal EGR rate should be largest EGR rate. At 50% load, when the EGR rate is zero, the NO_X is 715ppm, but when the EGR rate arrives to 15.1%, the NO_X turns to 375ppm. In this case, the reduction rate is 47.6%. On the contrary, the smoke is increased from 0.7BSU to 1.5BSU. For choosing the optimal EGR rate, the trade-off relation between NO_X and smoke must be considered. At full load, NO_X is reduced more rapidly with the increasing of EGR rate, it is 1160ppm at zero EGR rate, and it reduces to 680ppm at the largest EGR rate, the largest EGR rate is only 6.7% at this operating point, the reduction of NO_X emissions is 41.4%. At the same time the smoke is increased from 1.7 BSU to 3.4 BSU.

(a)



(a) NO_X

2). Effects of Optimal EGR rate on the performance and emission of the engine

Fig.9(a-d) shows the comparison of performance and emissions of the engine between optimal EGR and without EGR at the speed of 2000rpm, the optimal rate of each load at the speed of 2000rpm are listed in table3.

Table 3 Optimal EGR rate

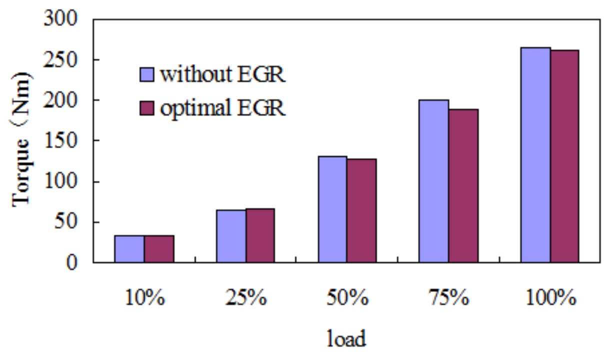
Load(%)	10	25	50	75	100
EGR(%)	20.5	18.3	10	7.2	2.4

As shown in this figure, the effect of EGR on the torque variation is not appeared when the load is lower than 50%, but if had a bad effect on the engine torque when the load is larger than 50%.

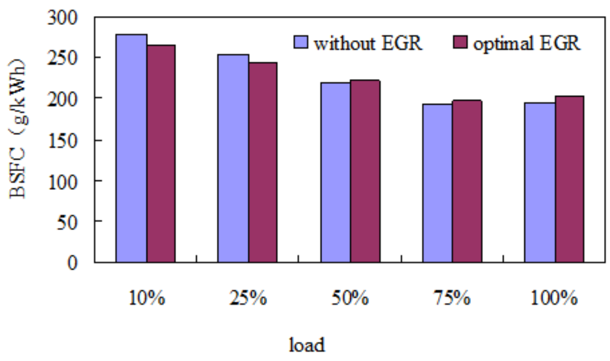
The fuel consumption is decreased slightly at low load, while it is increased at high load.

The reduction of NO_X emission is obviously at different loads.

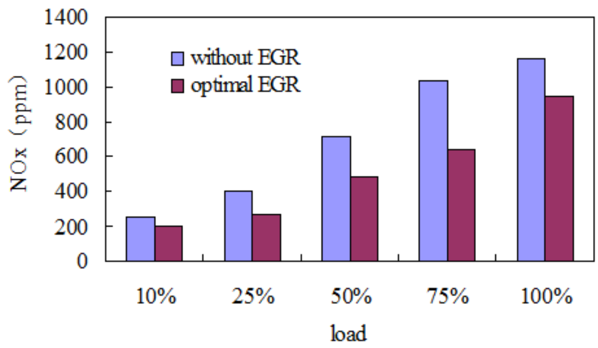
The smoke does not change at the low load, but it increases with the increase of engine load.



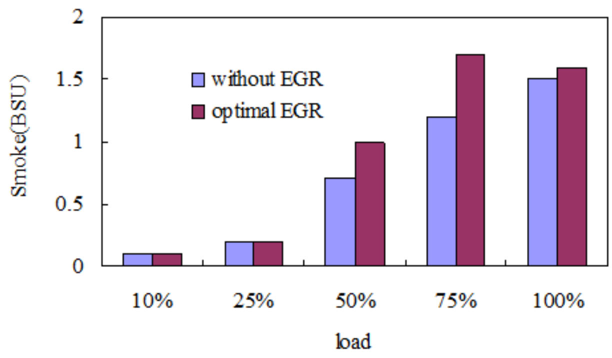
(a) Torque



(b) BSFC



(c) NOX



d) Smoke

Fig.9 (a～d) Comparison the performance and emissions of the engine between optimal EGR rate and without EGR at the speed of 2000rpm

C. Effects of VNT on EGR system

Fig.10 shows that the pressure before turbine is increased with the increasing of engine speed. The pressure almost keeps in linear relation with the speed in original engine. It is 125mmHg at the speed of 1200rpm, and it reaches 830mmHg at the speed of 3400rpm, which shows that the increasing of pressure is mainly affected by speed. For the engine matched with VNT, the pressure before turbine is mainly affected by the vanes position, the pressure curve keeps flat with the speed increasing, it is 506mmHg at the speed of 1200rpm, and it turns to 655mmHg at the speed of 3400rpm. the increasing is slightly. When the speed is larger than 2800rpm, the pressure of VNT is lower than that of CT. While the pressure before turbine of VNT is greatly higher than that of CT at low and medium speeds.

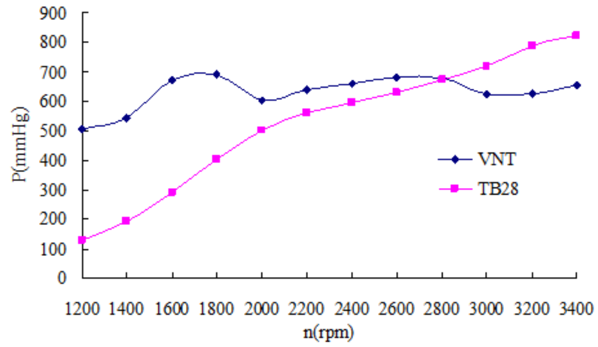


Fig.10 Comparison of pressure before-turbine between VNT and CT at full loads

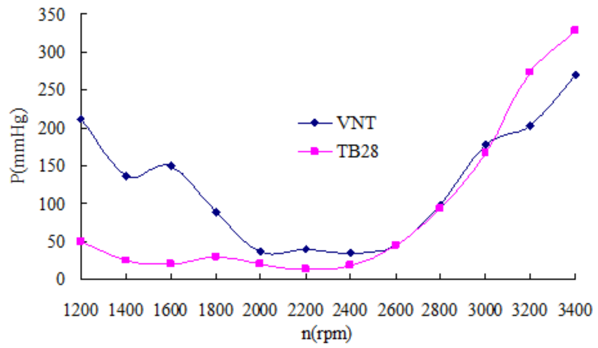
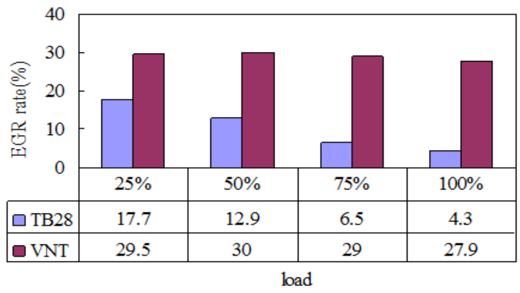


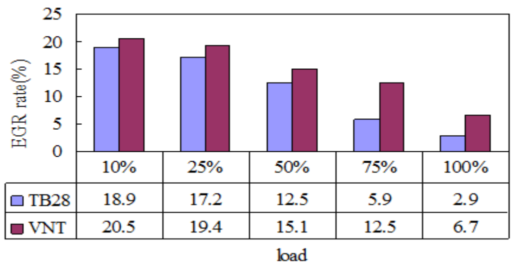
Fig.11 Comparison of pressure difference between VNT and CT at full loads

Fig.11 shows that the pressure difference between before-turbine and after-compressor is reduced with the increasing of speed. It reaches its minimum when the speed is between 2000rpm and 2400rpm. At the speed of 1200rpm, the pressure difference of VNT is 211mmHg; the pressure difference of CT is 50mmHg. The pressure difference in CT changes a little with the speed increasing when the speed is lower than 2400rpm. The pressure difference of VNT is less than that of CT when the speed is larger than 3000rpm. It is known that the pressures before turbine are always higher than that of throat of venturi-pipe in all speed range. EGR can be easily acquired with using of VNT and venturi-pipe.

It is shown in Fig.12 (a-b), at low speed, the maximum EGR rate of VNT is much larger than that of CT. The maximum EGR rate of CT is affected by load. The maximum EGR rate is 17.7% at 25% load; it is 4.3% at 100% load. The maximum EGR rate in VNT is little affected by load. The maximum EGR rate is about 29% at different loads. Although the pressure difference between EGR valve is small at low speed, it can be adjusted in the engine equipped with VNT. At the speed of 2000rpm, the EGR rate in VNT is still larger than that of TB28.



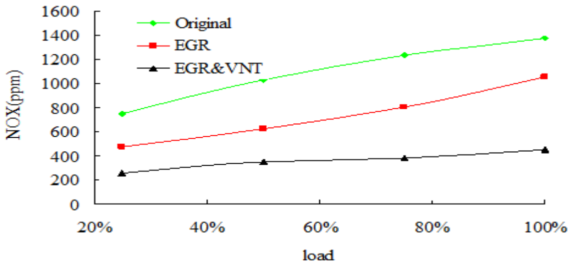
(a) Comparison of maximum EGR rate at 1200rpm



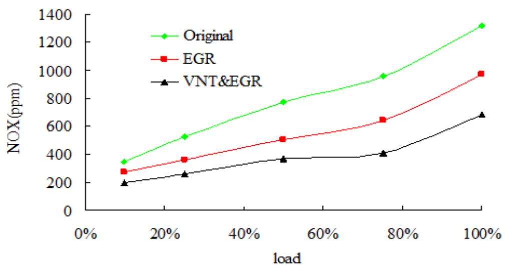
(b) Comparison of maximum EGR rate at 2000rpm

Fig.12 Comparison of maximal EGR rate between CT and VNT

Fig.13(a-b) shows the comparison of NO_X reduction by maximum EGR rate between CT and VNT. At the speed of 1200rpm, the NO_X of the original is 1375ppm at full load; it is reduced to 1051ppm when the EGR rate reaches the maximum 4.3% with applying of CT. For the engine matched with VNT, the maximum EGR rate at this operating point is increased to 27.9%, the NO_X emission is reduced to 456ppm, comparing with that of zero EGR, it has reduced 66.8%. Of course, EGR has a bad effect on the torque and BSFC and smoke of the engine. The EGR reduces NO_X emissions by the reduction of intake air. It shows the same trend as the engine at speed of 2000rpm.. It can be concluded that the NO_X emissions can be reduced to a lower level with the using of VNT.



(a) Comparison of NOx reduction at 1200rpm



(b) Comparison of NOx reduction at 2000rpm

Fig.13 Comparison of NO_X reduction by EGR between TB28 and VNT

IV. CONCLUSIONS

The following conclusions can be drawn from this study :

1) The engine performance is improved by using a turbocharger with variable nozzle turbine. The torques of the engine at low speeds were improved largely. The fuel consumptions were reduced dramatically .The smoke was reduced greatly for the increasing of inlet air.

2) EGR can reduce the NO_X emissions of the engine greatly while maintaining competitive fuel economy. The reduction of NO_X emission is larger at high load. While EGR has bad effects on BSFC and smoke of the engine at high load.

3) A suitable pressure gradient for EGR flow can be established using a turbocharger with variable nozzle turbine. The scope of EGR rate is extended; The NO_X emissions of the engine can be reduced to a lower level by EGR system based on VNT.

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