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A Study on the Effects of EGR and VNT on the Intake and Exhaust Pressure Waves in a High-Pressure Common-Rail Diesel Engine

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ABSTRACT

The transient pressure waves in the intake and exhaust systems directly affect the intake and exhaust processes of diesel engines, thus further affecting the combustion process and the performance of diesel engines. The variation rules of the intake and exhaust pressure waves at different engine speeds and loads in a high-pressure common-rail diesel engine were studied. Then, the effects of EGR rate and VNT nozzle opening on the intake and exhaust pressure waves were systematically studied by bench test and one-dimensional simulation analysis. The results show that at 2000 r·min-1 full-load, when the EGR rate increases from 0 to 10%, the average intake pressure and the average exhaust pressure both decrease. The fluctuation waveforms of the intake pressure and the exhaust pressure change significantly. The fluctuation intensity of the intake pressure decreases by 58.6%, and the fluctuation intensity of the exhaust pressure increases by 77.2%. As the EGR rate increases from 10% to 30%, the average intake pressure and the average exhaust pressure both decrease. The fluctuation waveforms are basically unchanged. The increasing magnitudes of the intake and exhaust pressure fluctuation intensities are 16.6% and 20.5%, respectively. As the VNT nozzle opening increases, the average intake pressure and the average exhaust pressure both decrease. The corresponding phases of the intake pressure wave crest and trough are delayed. The fluctuation waveforms of the intake and exhaust pressure are basically unchanged, and the fluctuation intensities do not change significantly.

Keywords: High-pressure common-rail diesel engine; Intake pressure wave; Exhaust pressure wave; EGR; VNT.

NOMENCLATURE

N	number of calculating data in an operation cycle	P_{mean}	average pressure in the inlet manifolds
η_i	calculating data	$\Delta\rho$	fluctuation intensity
η_{mean}	average turbine efficiency	δ_P	root-mean-square of pressure fluctuation
P_i	calculating data	δ_t	root-mean-square of turbine efficiency
		$\Delta\eta$	fluctuation intensity of turbine efficiency

1 INTRODUCTION

The transient pressure fluctuation of intake and exhaust systems directly impact the intake and exhaust processes of diesel engines, and then influence the combustion process and other performance of diesel engines (Xinghai *et al.* 2007, Huijie *et al*. 2016, Jinke *et al*. 2013, Wei *et al*. 2008). For multi-cylinder supercharged diesel engines, the intermittent exhaust process of each cylinder will result in complex pressure propagation and reflection phenomenon when several exhaust manifolds are connected to one manifold. The pressure waves directly affect the energy utilization ratio and back-pressure of exhaust gas, then influence emission of exhaust gas and inflate efficiency. And intense fluctuation may even cause back flow of gas and result in decrease of combustion efficiency in the cylinder, worse economy, reduction of turbine efficiency as well as the excessive exhaust temperature (Changwei *et al*. 2006, Jun *et al*. 2011). The strong fluctuation of pressure waves in inlet and exhaust manifolds will result in the significant fluctuation of pressure waves in cylinder. The effect of pressure waves propagating in inlet and exhaust manifold will further influence the thermodynamic and flow process of air in the manifolds, cylinder and turbocharger. At last combustion process, fuel economy ansd emission performance will be influenced (Wuqiang *et al*. 2011).

EGR (Exhaust Gas Recirculation) is an effective way to reduce NO_X (Nitrogen Oxide) emissions from diesel engines (Yang *et al*. 2016). Because of the increasingly stringent emission regulations, have made exploring sustainable and economic technologies a pressing need. The available range of EGR rate need to be broaden continuously (Qiwei *et al*. 2016), but for conventional turbocharged intercooler diesel engines, there are many intractable challenges including deviation between intake and exhaust (intake pressure is higher than exhaust pressure), delayed response of EGR and unfulfilled EGR rate (Langridge *et al*. 2002, Pischinger *et al*. 2006). VNT (Variable Nozzle Turbo) technology is an ideal solution to solve the problem of deviation between intake and exhaust in turbocharged diesel engines by adjusting the opening of nozzle ring according to demand of air at various conditions.(Wijetunge *et al*. 2004, Arnold *et al*. 2002, Wahlström *et al*. 2010) At present, research on the effect of EGR and VNT on diesel engines mainly focuses on combustion process, performance and emission of engines (Zamboni 2018, Tianling *et al*. 2006, Jimin *et al*. 2016, Wenbin *et al*. 2016, Yongzhong *et al*. 2018). At present other studies on pressure waves in the intake and exhaust system mainly focus on the effect of different engine conditions as well as the system structure parameters of intake and exhaust systems. (Xinghai *et al*. 2007, Huijie *et al*. 2016, Jinke *et al*. 2013, Wei *et al*. 2008, Jun *et al*. 2011). Besides, the evolution and development trend of pressure wave propagating in exhaust manifolds on both turbocharger and two-stage turbocharger was investigated. And the pressure waves propagating in exhaust manifolds played a significant role on torque and emission of the engines (Chiara *et al*. 2011). However, no clear conclusions reached on the effect of EGR rate and VNT angle on pressure waves propagating in the inlet and exhaust manifolds.

When EGR and VNT technologies are applied, the intake system and the exhaust system of diesel engines will generate varying degrees of intervention, which will affect the intake and exhaust pressure waves, and then affect the combustion and emission performance of diesel engines. Powerful fluctuation of pressure waves in the inlet and exhaust channel of turbocharger plays a significant role on the decrease of turbine efficiency (Xuewen *et al*. 2012). Moreover, it is easier to cause fatigue damage of turbine blade with the stress of exhaust pressure fluctuation. Thus, bench test and one-dimensional simulation analysis were coupled to explore the influence of various EGR rate and opening of VNT angle on diesel engines, which will provide a theoretical basis for improving the intake and exhaust pressure waves as well as the working performance of diesel engines.

2 TSETING EQUIPMENT AND EXPERIMEN METHOD

2.1 Testing Equipment

A four-cylinder turbocharged high-pressure common-rail diesel engine was used for bench test, and the major technique parameters were shown in Table 1. The main testing equipment includes AVL power dynamometer, AVL measurement system, cooling water thermostatic system, fuel thermostatic device, oil thermostatic device, electronic controlled calibration system, in-cylinder pressure collection system and analysis software, Kistler's transient intake and exhaust pressure sensor and its charge amplifier, sensor cooling device, etc. Installation positions of the intake and exhaust pressure sensors are shown in Fig. 1 and Fig. 2.

Table 1 Basic parameters of diesel engine

Items	Parameters
cylinder number	4
bore	80 mm
stroke	92 mm
compression ratio	18.5
rate power speed	4000 $r·min^{-1}$
displacement	1.85 L
supercharging mode	exhaust turbocharging

2.2 Experiment Method

Bench test was used to investigate the variation rules of the intake and exhaust transient pressure waves at different engine speeds and loads. Simultaneously the pressure signal in cylinder at different conditions was collected to provide basic test data for the verification of the one-dimensional simulation model. One-dimensional simulation analysis was used to analyze the influence of different EGR rate and VNT nozzle ring opening on the pressure fluctuation of the diesel engine. The testing speeds were 1000 $r·min^{-1}$, 1400 $r·min^{-1}$, 1800 $r·min^{-1}$, 2000 $r·min^{-1}$, 2400 $r·min^{-1}$, 2800 $r·min^{-1}$, 3200 $r·min^{-1}$ and 3600 $r·min^{-1}$. The testing loads were 25%, 50%, 75% and 100% at different speeds. The local atmospheric pressure was 80kPa.

And the specific designs of experiment were presented in Table 2, while the simulation arrangement was presented in Table 3 and Table 4.

1 STUDY ON FLUCTUATION RULES OF THE INTAKE AND EXHAUST PRESSURE UNDER DIFFERENT CONDITIONS

The intake and exhaust transient pressure fluctuation at full load conditions as the speed vary from 1000 r/min to 3600 r/min is shown in Fig.3 and Fig. 4 respectively.

Fig. 1. Intake pressure sensor.

Fig. 2. Exhaust pressure sensor.

From Fig.3 it can be observed that the average intake pressure increases gradually as the speed of engine increases. Furthermore, the intake pressure wave increases as the speed increases. Figure 4 represents the tendency that the corresponding crank phases of exhaust pressure crest are delayed, and the amplitude of exhaust pressure wave crest and trough increase. When the pressure wave is propagating in the exhaust manifold with the same structure of exhaust system, the increased speed of engine will lead to the increased calculation angle of crank during the same time. Considering the absolute time required for pressure wave to travel to the same location is essentially unchanged, there is the phenomenon that the corresponding phrases of the pressure wave crest are delayed.

Table 2 Design of experiment

Operating mode	Speed	Load	VNT angle
1	1000r/min	100%	Automatic control
2	1400 r/min	100%	Automatic control
3	1800r/min	100%	Automatic control
4	2000 r/min	25%	Automatic control
5	2000 r/min	50%	Automatic control
6	2000 r/min	75%	Automatic control
7	2000 r/min	100%	Automatic control
8	2400 r/min	100%	Automatic control
9	2800 r/min	100%	Automatic control
10	3200 r/min	100%	Automatic control
11	3600 r/min	25%	Automatic control
12	3600 r/min	50%	Automatic control
13	3600 r/min	75%	Automatic control
14	3600 r/min	100%	Automatic control
15	2000 r/min	100%	20%
16	2000 r/min	100%	25%
17	2000 r/min	100%	30%
18	2000 r/min	100%	35%

Table 3 To investigate the effect of EGR rate variation on intake and exhaust pressure wave

Operating mode	Speed	VNT angle	EGR rate
Full load condition	2000 r/min	0	0%
			10%
			20%
			30%

Table 4 To investigate the effect of VNT angle variation on intake and exhaust pressure wave

Operating mode	Speed	VNT angle	EGR rate
Full load condition	2000 r/min	20%	0%
		25%	
		30%	
		35%	

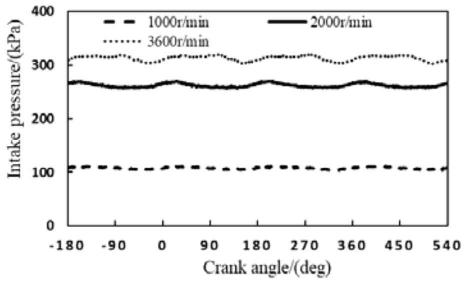

Fig. 3. Variation of transient intake pressure with different crank angle at different speeds full-load.

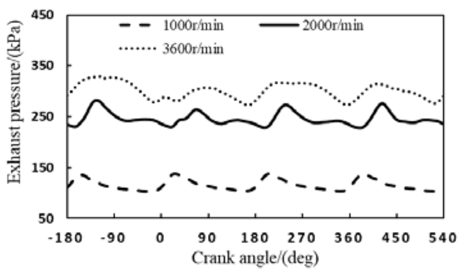

Fig. 4. Variation of transient exhaust pressure with different crank angle at different speeds full-load.

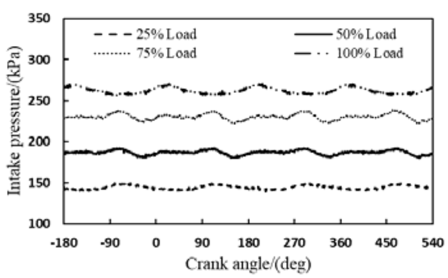

Fig. 5. Variation of transient intake pressure with the variation of crank angle at different loads of 2000 r·min^{-1}.

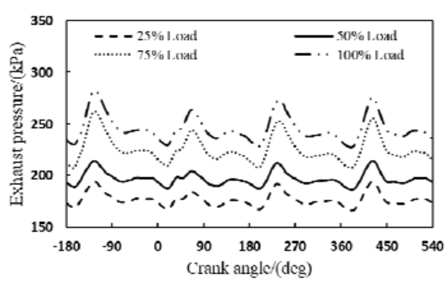

Fig. 6. Variation of transient exhaust pressure with the variation of crank angle at different loads of 2000 r·min^{-1}.

Figures 5 and 6 represent the transient intake and exhaust pressure waves.

Figures 5 and 6 depict that the changing tendency of intake and exhaust pressure fluctuation waveforms are basically consistent with the change of crank angle. The crest and trough of intake and exhaust pressure waves increase with the increased load. This is mainly because that the increased load brings on higher fuel injection quantity and higher heat released amount on fuel combustion process. When the heat efficiency changes rarely, the exhaust energy increases and then exhaust pressure increases.

2 ONE-DIMENSIONAL SIMULATION MODELING

The influence of different EGR rate and VNT nozzle opening on the intake and exhaust pressure waves is investigated by one-dimensional overall performance model combined with the experiment research. The GT-Power software is used.

Fig.7 depicts the one-dimensional model of the diesel engine, Fig.8 ~ Fig.10 depict the comparison between experiment results at 2000 r·min^{-1} full-load and the results of simulation.

As shown in Table 5, the comparison between experiment and simulation results including cylinder pressure, intake pressure and exhaust pressure indicates that the simulation data is in good agreement with the experiment data. Moreover, the errors are less than 5%, which suggests that the model can be used to calculate and analyze the change of intake and exhaust pressure waves.

Table 5 The comparison between the simulated and experimental data

Parameter	Experime-ntal data	Simulat-ed data	Error
In-cylinder pressure(MPa)	16.75	15.96	0.0472
Intake pressure(kPa)	261.85	251.89	0.0380
Exhaust pressure(kPa)	233.74	222.23	0.0492

3 ANALYSIS OF INTAKE PRESSURE WAVE

The parameters including maximum and minimum pressure wave, root-mean-square of pressure fluctuation δ_P and fluctuation intensity $\Delta\rho$ are adopted to estimate the intake pressure waves. The specific calculation methods are as follows:

$$\delta_P = \sqrt{\frac{\sum_{i=1}^{N}\left(P_i - P_{mean}\right)^2}{N}} \quad (1)$$

$$\Delta\rho = \frac{\delta_P}{P_{\text{mean}}} \quad (2)$$

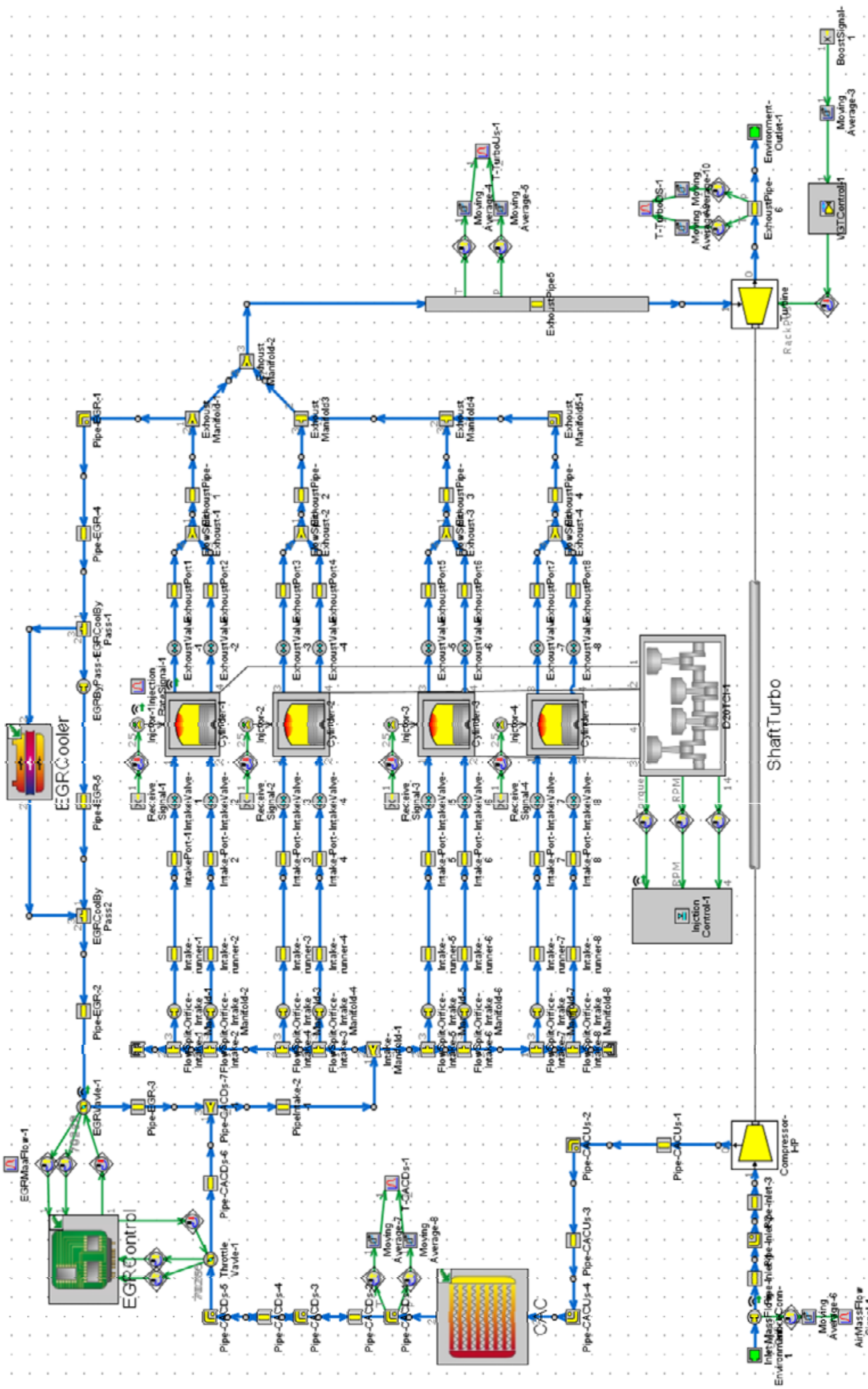

Fig. 7. One-dimensional model of the diesel engine.

There, P_{mean} —Average pressure in the inlet manifolds, MPa N —Number of calculating data in an operation cycle

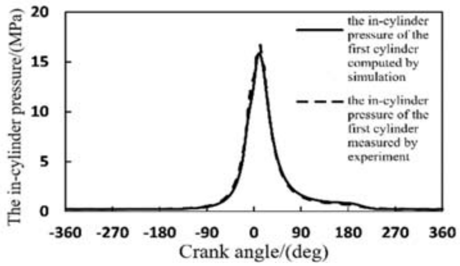

Fig. 8. Variation of the first cylinder pressure with different crank angle at 2000 r·min^{-1} full-load.

3.1 Effect of EGR Rate on the Intake Pressure Wave

The flowing part is based on simulation results conducted and validated above. Figure 11 represents the pressure waveforms on the inlet of intake manifold at 2000 r·min^{-1} full-load with different EGR rate (0%、10%、20%、30%).

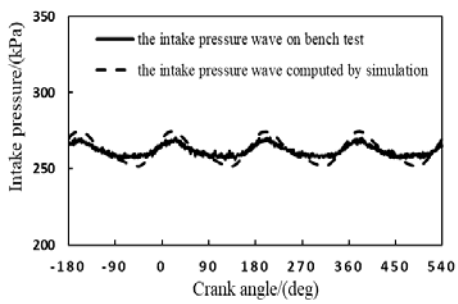

Fig. 9. Variation of the transient intake pressure with different crank angle at 2000 r·min^{-1} full-load.

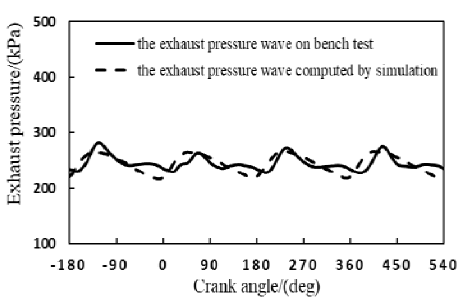

Fig. 10. Variation of the transient exhaust pressure with different crank angle at 2000 r·min^{-1} full-load.

The fluctuation of the pressure waves on the inlet of the intake manifold significantly decrease with the opening of the EGR valve (EGR rate increase from 0 to 10%). The intake pressure waveforms change significantly, and the average intake pressure also decreases. The main reason is that, after opening the EGR valve, part of the exhaust gas is involved into the EGR system and the exhaust flow utilized by the turbocharger decreases, resulting in the decrease of available energy for the turbine. Then lead to the decrease of boost pressure, intake flow as well as the intake pressure. After opening the EGR valve, as the EGR rate increases from 10% to 30% the fluctuation of intake pressure waves on the inlet of the intake manifold are basically consistent. The waveforms are basically unchanged, while the amplitude of wave crest and trough decrease.

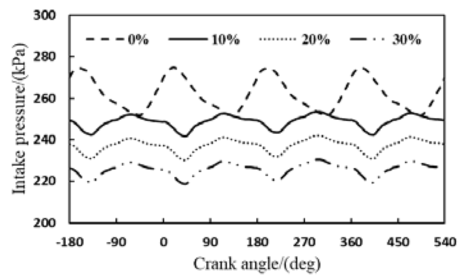

Fig. 11. Variation of the transient intake pressure with the variation of crank angle under different EGR rate at 2000 r·min^{-1} full-load.

Figure 12 portrays the fluctuation intensity variation of intake pressure with different EGR rate. After opening the EGR valve (EGR rate increase from 0 to 10%), part of the exhaust gas gets into the intake-side. At this time, the fluctuation intensity of the intake pressure on inlet of intake manifold decreases from 0.029 to 0.012, with the reduction by 58.6%. The fluctuation intensity of the intake pressure increases from 0.012 to 0.014 as EGR rate increase from 10% to 30%, with the increase by 16.6%. It is clear that when the EGR valve is just opened, the intake pressure waveforms are obviously influenced and there is a significant reduction in the fluctuation intensity of intake pressure. Whereas as the EGR rate continues to increase, the average intake pressure changes a lot while the intake pressure waveforms are basically unchanged and the variation of intake pressure wave intensity are not significant. The reason is that, with the opening of EGR valve, part of the exhaust flow is derived into the intake-side. With the decrease of the available energy in the exhaust gas, the turbine efficiency decreases and the fluctuation intensity decreases as well.

3.2 The Effect of VNT Nozzle Opening on the Intake Pressure Wave

The flowing part is based on simulation results conducted above. Figure 13 represents the intake pressure curves on the inlet of intake manifold with various VNT nozzle opening (20%、25%、30%、35%) at 2000 r·min-1 full-load.

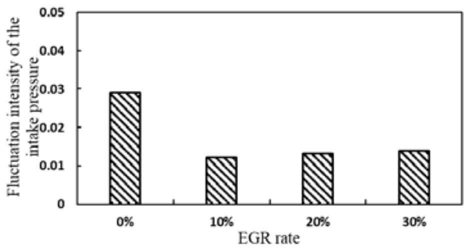

Fig. 12. Variation of the fluctuation intensity of intake pressure with the variation of crank angle under different EGR rate at 2000 r·min^{-1} full-load.

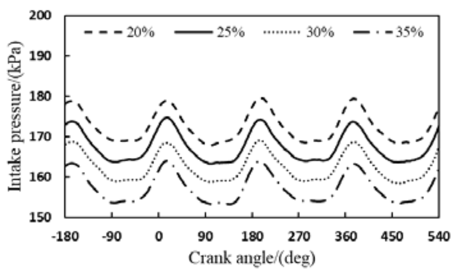

Fig. 13. Variation of the transient intake pressure with the variation of crank angle with different VNT nozzle opening at 2000 r·min^{-1} full-load.

From the picture it can be seen that with the increase of the VNT angle, the fluctuation of the intake pressure waves on the inlet of the intake manifold change rarely. Likewise, the pressure waveforms are basically unchanged, while the average fluctuation of the intake pressure decreases. And there is a tendency that the corresponding phases of wave crest and trough are delayed. The main reason is that, at the same speed full-load, the speed of turbine decreases as the VNT valve opening increases, driving the impeller speed of coaxial compressor decreases and then the intake flow as well as the intake pressure decrease. As the VNT angle decrease, the phenomenon of gas accumulation in the intake tube is more significant, resulting in a faster increase of the intake pressure and higher intake pressure crest at the same time. On the contrary, as the VNT angle increase, the gas accumulation is gradually fading, which result in the decreased slop of pressure wave growth. Because the effect of VNT angle on falling edge of pressure wave is not significant, the corresponding phrases of wave crest and trough are delayed.

Figure 14 represents the variation of root-mean-square of the intake pressure fluctuation intensity as VNT angle changes. At the same speed full-load condition, the fluctuation intensity of the intake pressure wave increases from 0.019 to 0.02 by 5.2% with the increase of VNT nozzle opening, it can be seen that the fluctuation intensity changes rarely. Thus, the VNT opening has obvious influence on the average intake pressure while has little impact on the fluctuation intensity and waveforms of the intake pressure.

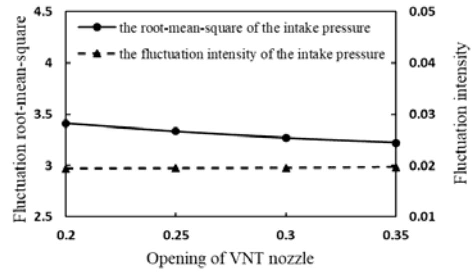

Fig. 14. Variation of root-mean-square and fluctuation intensity of the intake pressure with different VNT nozzle opening at 2000 r·min^{-1} full-load.

4 ANALYSES OF EXHAUST PRESSURE WAVE

4.1 The Effect of EGR Rate of the Exhaust Pressure Wave

The flowing part is based on simulation results conducted and validated above. *Figure*15 portrays the exhaust pressure waves on the inlet of the turbine with different EGR rate (0%、10%、20%、30%) at 2000 r·min^{-1} full-load.

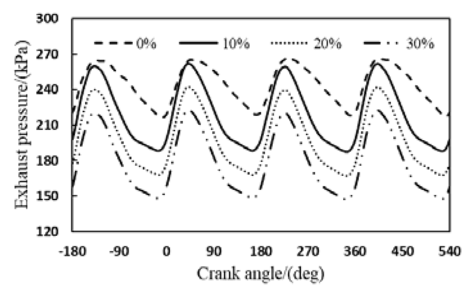

Fig. 15. Variation of the transient exhaust pressure with the variation of crank angle under different EGR rate at 2000 r·min^{-1} full-load.

The fluctuation of exhaust pressure waves on the inlet of the turbine increases markedly with the opening of EGR valve (EGR rate increase from 0 to 10%). It is evident that the waveforms of exhaust pressure changes notably, and the average fluctuation of intake and exhaust pressure descends significantly. This is because, after the opening of the EGR valve, part of the exhaust gets into the EGR system, resulting in decrease of exhaust flow required for the turbocharger, which lead to the decrease of exhaust pressure. When the EGR rate increases from 10% to 30%, the fluctuation of exhaust pressure wave rarely changes, while the wave crest and trough gradually decrease.

Figure 16 depicts the variation of fluctuation intensity of exhaust pressure. After opening the EGR valve (EGR rate increase from 0 to 10%), part of the exhaust gas is introduced into the intake side, mixing with the fresh air to get into the intake manifold. With this valve opening, the fluctuation intensity of exhaust pressure on the inlet of the turbine increases from 0.066 to 0.117 by 77.2%, whereas, as the EGR rate increases from 10% to 30%, the fluctuation intensity increases from 0.117 to 0.141 by 20.5%. This indicates that, the fluctuation intensity of exhaust pressure increases significantly when the EGR valve is just opened. With the larger EGR rate, the average exhaust pressure declines obviously, while the waveforms of exhaust pressure are basically unchanged and the fluctuation intensities do not change significantly.

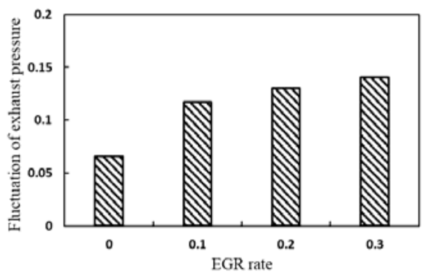

Fig. 16. Variation of the fluctuation intensity of exhaust pressure with different EGR rate at 2000 r·min^{-1} full-load.

4.2 The Effect of VNT Nozzle Opening on Fluctuation of the Exhaust Pressure Wave

The flowing part is based on simulation results conducted above. Figure 17 depicts the exhaust pressure curves on the inlet of turbine with different VNT nozzle opening at 2000 r·min^{-1} full-load.

With larger VNT nozzle opening, the fluctuation of the waveforms of exhaust pressure on the inlet of turbine rarely change. The waveforms basically stay unchanged and corresponding phrases variation of the wave crest as well as trough are not distinct. The main reason is that, the actual internal area of turbine increases as the VNT nozzle opening increase, resulting in decrease of the exhaust pressure on the inlet of the turbine.

Figure18. represents the change of root-mean-square and the fluctuation intensity of the exhaust pressure with different VNT nozzle angle. From the simulation test values, it is clear that the fluctuation intensity of the exhaust pressure on the inlet of the turbine increases from 0.116 to 0.118 by 1.7%, which is just a small change. The conclusion is that, VNT nozzle opening draws an obvious influence on the average exhaust pressure, while the influence on the waveforms and fluctuation intensity of exhaust pressure are weak.

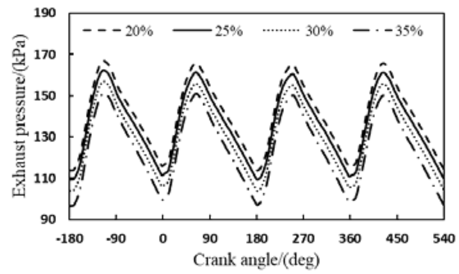

Fig. 17. Variation of the transient exhaust pressure with different crank angle and VNT nozzle opening at 2000 r·min^{-1} full-load.

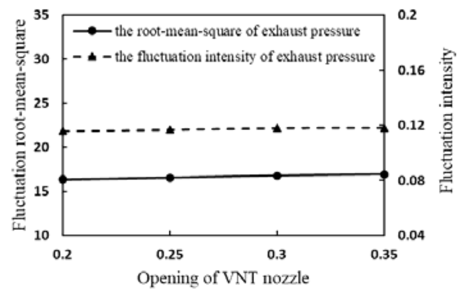

Fig. 18. Variation of the root-mean-square and fluctuation intensity of exhaust pressure with different VNT nozzle opening at 2000 r·min^{-1} full-load.

5 THE CALCULATION RESULTS OF TURBINE EFFICIENCY

In this part, the turbine efficiency and fluctuation intensity of turbine efficiency are adopted to investigate the effect of EGR rate and VNT angle on turbocharger (Huijie *et al*.2016). The calculation methods are as follows:

$$\delta_t = \sqrt{\frac{\sum_{i=1}^{N}\left(\eta_i - \eta_{mean}\right)^2}{N}} \tag{3}$$

$$\Delta\eta = \frac{\delta_t}{\eta_{mean}} \tag{4}$$

There, δ_t —Root-mean-square of turbine efficiency

$\Delta\eta$ —Fluctuation intensity of turbine efficiency

η_{mean} —Average turbine efficiency

5.1 The Effect of Exhaust Pressure on Turbine Efficiency

Figure19 indicates the effect of exhaust pressure wave on turbine efficiency at 2000 r·min^{-1} full-load. It can be observer that with the same crank angle, the crest and trough of both exhaust pressure wave and turbine efficiency are at the same phrase. The reason is that the turbocharger is directly derived by the energy of exhaust pressure.

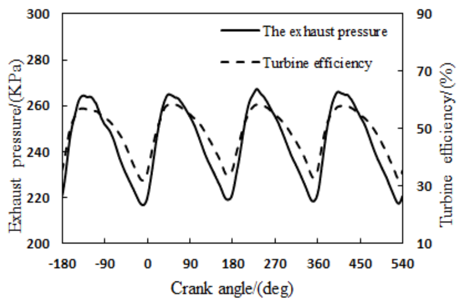

Fig. 19. Variation of the exhaust pressure wave and turbine efficiency with different crank angle.

5.2 The Effect of Turbine Efficiency on Intake Pressure Wave

Figure 20 presents The effect of turbine efficiency on the intake pressure waves. It can be observed that at the operating condition of 2000 r·min^{-1} full-load, when the turbine efficiency reaches the crest value, the intake pressure wave reaches the crest value after 143 crank angle. As the turbine efficiency reaches the trough value, the intake pressure wave reaches the trough value after 138 crank angle. The mainly is due to the reason that the turbocharger drives the compressor, causing a delayed effect on the pressure wave.

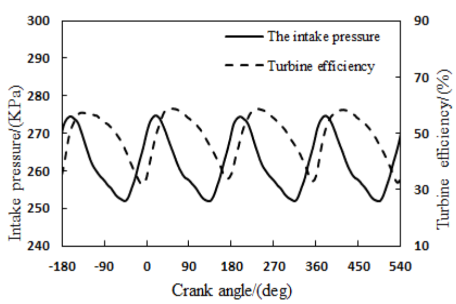

Fig. 20. Variation of intake pressure wave and turbine efficiency with different crank angle.

5.3 The Effect of the EGR Rate on Turbine Efficiency

Figure21 indicates the effect of EGR rate on the turbine efficiency at the operating condition of 2000 r·min^{-1} full-load. It shows that, as the EGR rate increases, both the maximum and minimum values of turbine efficiency decrease. The fluctuation waveforms and the average value of turbine efficiency decrease significantly. Because with the opening of the EGR valve, part of the exhaust gas is derived into the intake system to take part in the another combustion process. Therefore, the loss of exhaust gas energy results in the decreased turbine efficiency.

Figure 22 shows the effect of EGR rate on the fluctuation intensity of turbine efficiency at the operating condition of 2000 r·min^{-1} full-load. It can be observed that with the increase of EGR rate the fluctuation intensity of turbine efficiency decrease significantly. As the EGR rate increases by 10%, the fluctuation intensity decreases from 0.17 to 0.09. Hence, it can be concluded that the influence of EGR valve opening on fluctuation intensity of turbine efficiency is remarkable.

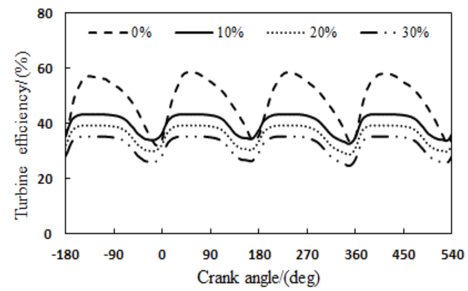

Fig. 21. The effect of EGR rate on turbine efficiency.

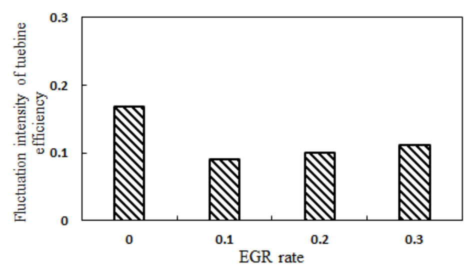

Fig. 22. The effect of EGR rate on fluctuation intensity of turbine efficiency.

5.4 The Effect of VNT Angle on Turbine Efficiency

The variation of turbine efficiency with the increase of the VNT angle is shown in Fig.23. It shows that the fluctuation waveforms of turbine efficiency are basically unchanged and the average turbine efficiency decrease as the VNT angle increase. The main reason is due to the increase of VNT angle, the cross section of turbocharger decreases, causing the decrease of exhaust pressure on the inlet of turbocharger.

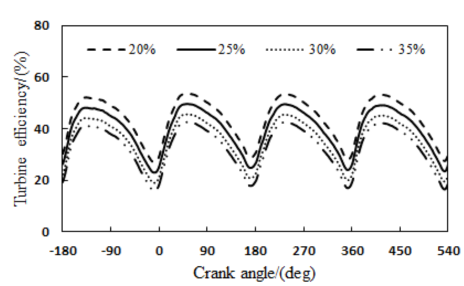

Fig. 23. The effect of VNT angle on fluctuation intensity of turbine efficiency.

From Fig.24 it can be concluded that as the VNT angle increases, the fluctuation intensity of turbine efficiency is basically unchanged, which just increases from 0.19 to 0.22.

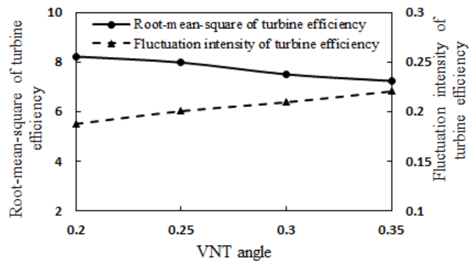

Fig. 24. The effect of VNT angle on fluctuation intensity of turbine efficiency.

6 CONCLUSION

This study investigates the effects of EGR rate and VNT angle on the intake and exhaust pressure waves by one-dimensional simulation analysis and experiment. Some major points can be summarized as follow:

(1) At full-load conditions, the average intake pressure increases as the speed of the diesel engine increases. The fluctuation of the intake pressure increases likewise. The corresponding phases of the exhaust pressure wave crest are delayed, and the amplitude of wave crest and trough increases. With respect to the conditions of same speed-different load, the fluctuation waveforms of intake and exhaust pressure are rarely changed; at the larger load, the wave crest and trough of the intake and exhaust pressure waveforms increase.

(2) At 2000 $r \cdot min^{-1}$ full-load, the average intake pressure and the average exhaust pressure decrease as the EGR rate increases from 0 to 10%. At the same condition, the fluctuation of intake and exhaust pressure change significantly. The fluctuation intensity of intake pressure by 58.6% and fluctuation intensity of the exhaust pressure decreases by 77.2%. As the VNT nozzle opening increases from 10% to 30%, the average intake pressure and the average exhaust pressure decrease, and the corresponding phases of the intake pressure wave crest and trough are delayed. The fluctuation waveforms of the intake and exhaust pressure are basically unchanged, and the fluctuation intensity do not change significantly.

(3) At 2000 $r \cdot min^{-1}$ full-load, the average intake pressure and the average exhaust pressure decrease as the VNT nozzle opening increase from 20% to 35%. The corresponding phrases of the intake pressure wave crest and trough are delayed. The waveforms of the intake pressure and exhaust pressure are basically constant. The fluctuation intensity of the intake pressure and the exhaust pressure respectively increase by 5.2% and 1.7%.

(4) At the operating condition of 2000 $r \cdot min^{-1}$ full-load, with the increase of EGR rate, both the average turbine efficiency and the fluctuation intensity of turbine efficiency decrease. And as the VNT angle increases, the average turbine efficiency decreases while the fluctuation intensity of turbine efficiency is basically unchanged.

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