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Numerical analysis of the fuel economy and dynamic performance of a GDI engine using EGR coupled high expansion ratio cycle

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Abstract. The energy conservation strategy with EGR dilution coupled high expansion ratio was discussed for improving the fuel economy of a 1.8 L turbocharged GDI engine. A 1-D simulation engine model coupled with LP-EGR system was modelled and verified by the bench test. The influence of different GCR and EGR rates on BSFC (Brake Specific Fuel Consumption) and torque was analysed based on the simulation calculations. Results show that the BSFC is reduced by much higher GCR design but the risk of combustion detonation is prone to rising. Then two detonation inhibition methods of LIVC (late intake valve closing) and EGR were compared. Results show that either delaying of LIVC angle from 15℃A to 55 ℃A or increasing of EGR rate from 0 to 15% can suppress the detonation, but the two methods will reduce power performance and fuel economy benefits of increasing GCR without other control parameters adjustments like ignition timing. Even not EGR coupled high expansion ratio cycle has better fuel economy performance than the original engine.

1. Introduction

The dramatic development of automobile industry has promoted the economic growth meanwhile it also brings a serious energy crisis and environmental pollution in China [1]. High expansion ratio cycle like Atkinson cycle and Miller cycle with higher GCR has been verified for better thermal efficiency in many study cases [2]. However, high expansion ratio cycles applied in high load will cause torque decreasing due to large LIVC angles [3]. The reduced power for high expansion ratio cycle engines can be compensated by the driven motor but it will be increasing cost [4]. The other compensation methods is using GDI technology coupled to turbocharged systems for engine downsizing that also has great advantages in improving power, economy and emissions, it has become an important development direction of the vehicle engines for automotive markets [5]. However turbocharged GDI engines are penalized by detonation high- probability than those of naturally aspirate engines [6]. There are four methods for the resistance of knocks: the low compression ratio design, the mixture enrichment, spark retard and the EGR application. Among those methods, EGR is a promoting way not only for suppressing engine knock but also for high efficiency and clean combustion. The potential has been shown in the latest study of energy conservation and emission reduction with EGR in gasoline engines [7]. The combined effects of EGR and high expansion cycle on engine performance need further investigation. Hence, A new approach for GDI fuel economy improvement with EGR dilution and high

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expansion cycle was expounded in this study. The effects of EGR, GCR (Geometric compression ratio) and LIVC on GDI engine fuel economy and power output were analyzed.

2. Engine Modelling and Calibration

A typical 1.8 L turbocharged GDI engine was adopted for this study. The geometry parameters of the engine components were directly measured and other specifications that are shown in table 1 were provided by the component manufacturer.

Table 1. Engine Specifications.

Engine parameters	Value
Displaced volume	1.8 L
Stroke	84.1 mm
Bore	82.5 mm
Connecting Rod	146 mm
Compression ratio	9.6
Power Max.(kW/rpm)	118/5000
Torque Max.(N.m/rpm)	250/2000
Number of Valves	4 (2 intake, 2exhaust)
Injection	GDI
Fuel	Gasoline #96 of Chinese Standard

As is shown in fig.1, the 1-D simulation engine model coupled with LP-EGR system was set up in the GT-Power software according to the main characteristics of the engine. The engine working condition of 2000 rpm with WOT (wide open throttle) was chose for this Study. The coding method of the 1-D simulation engine model has been expounded by the author before in another paper [8].

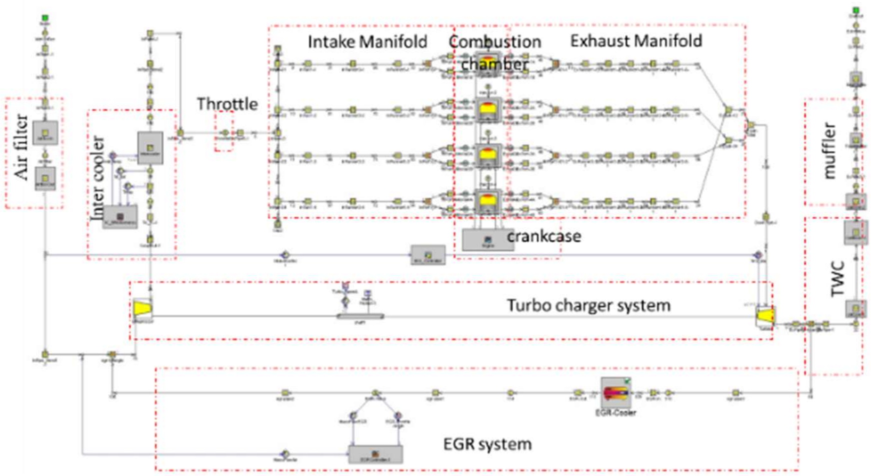

Figure 1. The 1-D engine model

The engine simulation model has been calibrated and verified by the bench test. The bench test rigs include electrical dynamometer system, fuel consumption measurement system, exhaust analyzer, engine ECU combined with ETAS ES690 equipment and combustion analyzer developed base on NI CompactRIO system. The schematic of bench test system layout was shown in fig.2. The temperatures of the combustion system components at WOT of 2000 rpm are shown in table 2. The other boundary parameters are shown in table 3.

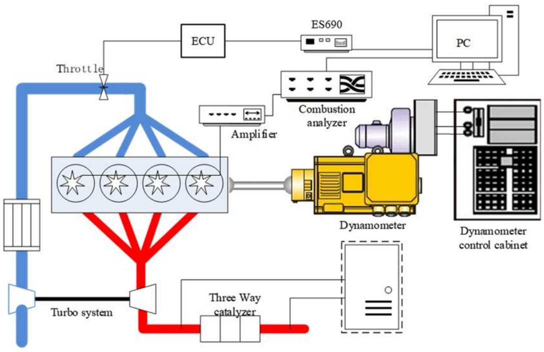

Figure 2. Bench test system layouts

Table 2. Temperature boundaries of Case @2000rpm WOT

Components	Temperature/K
Cylinder head	540
Piston	500
Cylinder	410
Intake port	320
Exhaust port	700

Table 3. Engine Specifications of Case @2000rpm WOT

Parameters	Value
AFR	14.7
IVO/° CA	15.7 BTDC
EVC/° CA	15 BBDC
Ignition timing/° CA	-4 BTDC
Air mass (g/s)	65
Intake air temperature/K	293 K

As the effects of EGR on the combustion process was studied at operating points of WOT @2000 rpm. The model was calibrated and verified by the cylinder pressure of engine tests. The comparisons of cylinder pressure data between simulation and test are shown in fig.3.The results indicated that the simulation values were close to the test values. The errors were in the acceptable range of the engineering simulation works, within 4% of the basic test value.

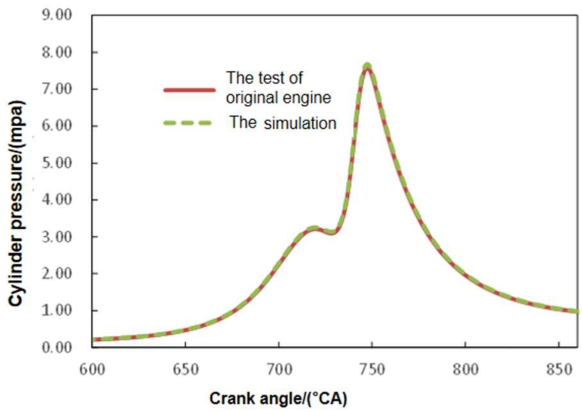

Figure 3. Cylinder pressure comparisons between test data and simulation data of WOT@2000rpm

3. Results discussion

3.1. Influence of Different EGR Rates and GCRs on Engine Performance

Theoretically, the thermal efficiency of the gasoline engine is increasing with the increase of the geometric compression ratio. According to the calculation of the actual physical structure of the original engine, the geometric compression ratio can be increased to 13 by combining the redesign of the top surface of engine piston and cutting cylinder height. In order to analyze the change law of EGR rates under different geometric compression ratios, four geometric compression ratios of 10, 11, 12 and 13 were designed and the cases of different EGR rates were simulated.

The simulation cases of different EGR rates for each GCR are shown in table 4. There are 6 cases for each GCR scheme. The boundary values such as valve timing, AFR, ignition timing were fixed to study the EGR effects without influences caused by other factors. As shown in fig.4, the torque output decreases as the EGR rate increases, which means EGR has a negative effect on Torque output performance. Fig.5 shows that the BSFC increases as the EGR rate increases. When other parameters remain unchanged, the increase of EGR rate leads to higher fuel consumption and lower torque. The introduction of EGR weakens the role of high geometric compression ratio in reducing BSFC.

Table 4. EGR simulation cases for each GCR

Case	EGR rates
Case 1	0%
Case 2	2.5%
Case 3	5%
Case 4	7.5%
Case 5	10%
Case 6	12.5%
Case7	15%

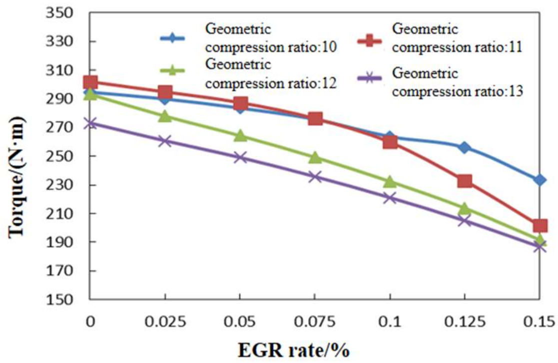

Figure 4. The torque output curves VS different EGR rates

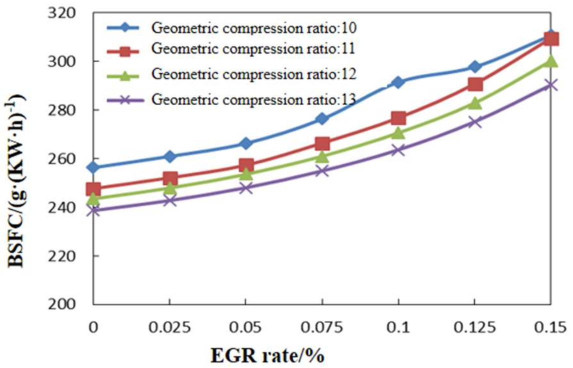

Figure 5. The BSFC curves VS different EGR rates

Fig.6 shows the change of thermal efficiency of different geometric compression ratios with EGR. When other parameters remain unchanged, the high geometric compression ratio realized by reducing the volume of the combustion chamber can improve the thermal efficiency of the gasoline engine. However, with the same geometric compression ratio, the thermal efficiency decreases with the increase of the EGR rate. Fig.7 shows the change of knock index of different geometric compression ratios with EGR. When EGR is zero, the larger the geometric compression ratio is, the higher the knock index is, the more likely the knock occurs and eventually leads to the decrease of power performance. With the increase of the EGR rate, the knock index gradually drops to 0 for suppressing the knock. The larger the geometric compression ratio is, the higher the EGR rate is required to suppress the knock. However, the suppression of the knock by EGR will increase the BSFC and reduce the dynamic performance.

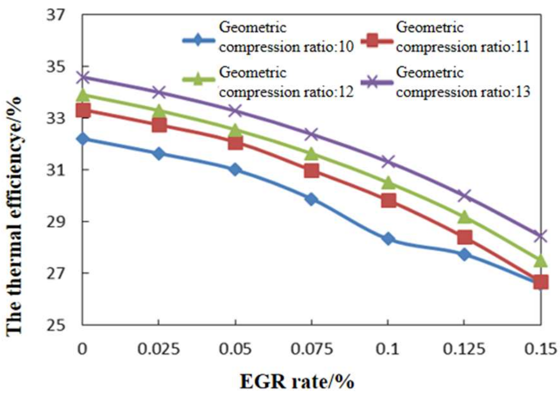

Figure 6. The thermal efficiency VS different EGR rates

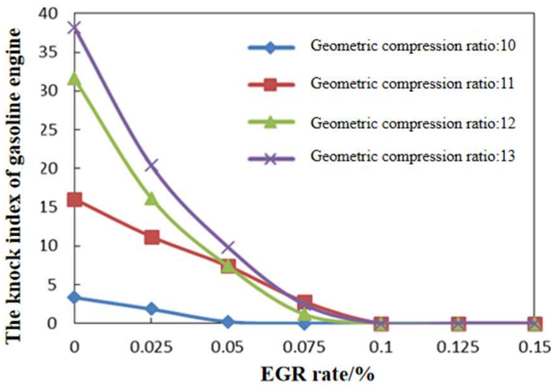

Figure 7. The thermal efficiency VS different EGR rates

The LIVC strategy is the traditional method for the high expansion ratio engine to reduce the effective compression ratios for the inhibition of the detonation. But this method also has problems with the decrease of fuel economy and power performance. Therefore, it is necessary to take further study for joint effects of EGR and LIVC on inhibition of detonation and improvement of the performance of gasoline engine. The scheme of geometric compression ratio 11 is selected for the further study in overall consideration of the effects of fuel economy, power performance and the detonation.

3.2. Influence of Engine Performance by Different EGR Rates and LIVC

In order to analyze the influence of EGR coupled LIVC on energy conservation and detonation of gasoline engine, 20 simulation cases were constructed for different LIVC and EGR rates under the full load condition of speed 2000 rpm. The corresponding LIVC is 15, 25, 35, 45, 55°CAn ABDC (After bottom dead center), and the EGR rate is 0, 5%, 10%, 15%.

The trends of the effect of LIVC and EGR on gasoline engine torque output are similar. As shown in fig.8, the influence curves of different EGR ratios on torque at a 15 ℃A LIVC are compared with the influence curves of different LIVC at 0% EGR ratio. The 0-15% EGR rate has the same effect scope with the 15-40 ℃A LIVC. The effect of LIVC on torque is more obvious. The LIVC and EGR play a similar role on fuel economy of gasoline engine. But EGR has a larger influence range on the BSFC of gasoline engine than LIVC. As shown in fig.9, the influence curve of different EGR ratios at a 15℃A on BSFC are compared with the influence curve of different LIVC at 0% EGR ratio on BSFC.

The results of KI calculation show that proper EGR ratio and LIVC angle can effectively reduce the detonation. The detonation distribution is shown in fig. 10. When the LIVC angle is bigger than 35℃A, the detonation can be suppressed without EGR.

Above all, the effects of LIVC and EGR on engine performance are similar. The EGR strategy coupled with LIVC can suppress the detonation after increasing the geometric compression ratio, but the increment of BSFC should be considered.

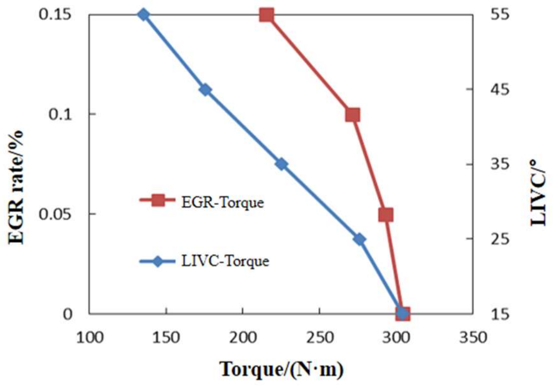

Figure 8. Influence of EGR and LIVC on Torque

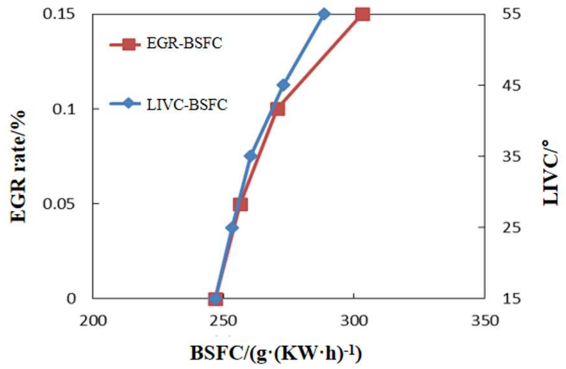

Figure 9. Influence of EGR and LIVC on BSFC

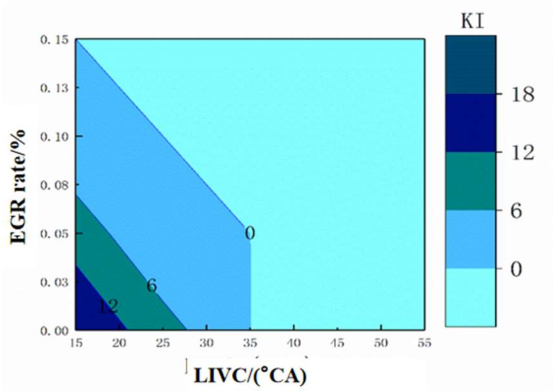

Figure 10. Influence of EGR and LIVC on Detonation

4. Conclusion

The energy conservation mechanism of EGR dilution coupled high expansion ratio thermodynamic cycle was investigated base on engine modeling and simulation. The simulation results of different geometric compression ratios show that the increase of the geometric compression ratio tends to improve fuel economy, but the gasoline engine has a trend to knock, which affects the dynamic performance. The effects of EGR and LIVC strategy on the performance of gasoline engines and inhibition of detonation were further analyzed. The detonation can be effectively suppressed by increasing EGR rate or LIVC without changing other control parameters, but the torque output and fuel economy are deteriorated with the EGR and LIVC increase. However, as the GCR is bigger than the original engine, the torque output and fuel economy can be improved.

In order to further improve the performance of gasoline engine, the multi-parameters such as throttle position, ignition timing and air fuel ratio should be optimized in next step study.

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