IOP Conference Series: Earth and Environmental Science

PAPER • OPEN ACCESS

Study on Diesel Engine Characteristics under Large Transient EGR

To cite this article: Huasheng Cui *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **300** 032042

Study on Diesel Engine Characteristics under Large Transient EGR

Huasheng Cui [1], Zhenfeng Zhao [1, *], Zhao Geng[1] and Yuhang Liu [2]

[1]Beijijng Institute of Technology, Beijing, China
[2]Beijijng Institute of Space Launch Technology, Beijing, China

*Corresponding author e-mail: zhzhf@bit.edu.cn

Abstract. Modern diesel engines tend to employ up to 50-70% exhaust gas recirculation (EGR) together with high intake pressure and injection strategies to enable low temperature combustion (LTC) cycles for reducing NOx and soot emissions simultaneously. Obviously, the combustion conditions and exhaust emissions are sensitive at such high EGR rate. And any slight fluctuation in the EGR quantity will bring unintended deviations from the desired engine performance, thus LTC mode is only limited at partial engine operation points. So the engine has to switch combustion mode frequently between compression ignition (CI) and LTC region within a few engine cycles in real application, which may result in combustion cyclic variations and even misfire, especially during transient operation. In order to investigate effect of heavy EGR transient process on engine combustion cycles, the experimental work was carried out on a four-cylinder VM common-rail turbocharged diesel engine. The results show that the oxygen concentration in the intake charge almost maintains at steady level at EGR steady conditions, while the exhaust oxygen concentration is affected by exhaust values opening/exhaust values closing (EVO/EVC), and result in intra-cycle fluctuation, which will approximately bring 2% calculation error bandwidth for EGR ratio. From 37% to 55% EGR ratio, the EGR gas is mainly driven by the pressure ratio of intake and exhaust duct, and it will experience a long accumulating process to reach a new equilibrium. And the inordinate delayed injection timing will promote in-cylinder cycle-to-cycle variation and even misfire, especially during transition from CI to LTC region.

1. Introduction

In order to meet the current and future stringent diesel emission legislation, advanced combustion modes which can reduce nitrogen oxide (NOx) and soot emissions simultaneously have been widely studied, such as homogeneous charge compression ignition (HCCI), premixed charge compression ignition (PCCI)and low temperature combustion (LTC) [1-3]. Many approaches including heavy exhaust gas recirculation (EGR), variable valve actuation (VVA) and multiple-injection strategies were demonstrated to realize advanced combustion modes [4-7]. So far, however, they are only applicable in low speed and partial load, which result in diesel engine combustion mode switching from advanced combustion modes to conventional compression ignition (CI) frequently to satisfy emission requirements and drivability in real application. To achieve stable operations, it's essential for ECU to control in-cylinder conditions exactly, especially during transient process.

EGR, as a practical method, is always employed to maintain low combustion flame temperature and reduce NOx emissions in diesel engine attributable to its three generally defined effects, namely dilution effect, thermal effect and chemical effect [8-13]. Moreover, low soot emission can also be achieved with high level of EGR rate, as soot formation is restricted by low combustion flame temperature. Based on the use of heavy EGR in conjunction with injection strategies, LTC mode is capable to obtain a dramatic demotion in NOx, soot emissions and hold a higher thermal efficiency at the same time. Extensive studies, both theoretical and empirical, were carried out to investigate the influence of EGR on the diesel combustion and emissions aspect. Lee et al. [4] reported the simulated physical models and numerical methods in KIVA-CMC to analyze the characteristics of different models of LTC by ultra-high EGR and modulated kinetics (MK) in a CI engine. Aithal [14] developed a zero-dimensional model which is accomplished through numerical simulation of the energy equation to assess the impact of EGR on diesel combustion parameters under steady-state conditions. Anand et al. [15] utilized multi-component surrogate models to quantify fuel and EGR effects under LTC mode and CI mode. Zhao et al. [11] explored a detailed chemical kinetics simulation model to analyze the EGR influence on HCCI combustion. Ogawa et al. [16] examined characteristics of diesel combustion in low-oxygen condition mixtures with ultra-high EGR and discussed the potentiality to expand operation range of smokeless and efficient combustion. Bae et al. [17] conducted a comparative research between LTC mode and CI mode to investigate the effects of air-fuel mixing quality on the performances, for instance, in-cylinder pressure, heat release rate (HRR), combustion phase parameters, exhaust emissions, as well as flame image. Andwari et al. [18] carried out a detailed experiment to study the influence of extend EGR, inner EGR and fuel octane number utilization on the cyclic variability and combustion phasing characteristics of the controlled auto-ignition combustion. Spessa et al. [19] established a real-time zero-dimensional diagnostic combustion model to calculate in-cylinder flame temperature, HRR and NOx emission in diesel engine under steady state and transient conditions.

Commonly, modern diesel engines tend to employ up to 50-70% EGR together with high intake pressure and injection strategies to enable LTC cycles. The combustion process and exhaust emissions are obviously sensitive at such high EGR rate. And any slight fluctuation in the EGR quantity will bring unintended deviations from the desired engine performance characteristics [13], for which LTC mode is only limited at partial engine operation points. So the engine has to switch combustion mode frequently between CI and LTC region within a few engine cycles in real application [5, 20-22], which may result in combustion cyclic variations or misfire, especially during transient operation. One of the current trends is to coordinate EGR valve with intake throttle, based on static look-up tables, to implement wide-ranging EGR requirements in high pressure EGR air-path system [23-26]. Nevertheless, there is a practical need to track the EGR transport process in air-path system so as to correct the use of EGR quantity and maintain stable combustion.

The focus of this work is to investigate the effect of heavy EGR transient process on engine combustion cycles. The EGR ratio is defined according to the oxygen concentrations of intake and exhaust ducts. First of all, the trace of intra-cycle oxygen concentration is plotted at steady state, and the calculation error of EGR ratio is analyzed based on oxygen concentration. Following, to study the transient EGR behavior on combustion cycles, an experiment is carried out to trace the combustion cycles characteristics from CI to LTC region. The EGR transient process from 37% to 55% EGR ratio is presented cycle-to-cycle, and the development of in-cylinder, HRR, ignition delay, and CA50 are discussed in the work. At last, the effect of injection timing on combustion performance is explored.

2. Experimental setup

2.1. *Experimental engine and apparatus*

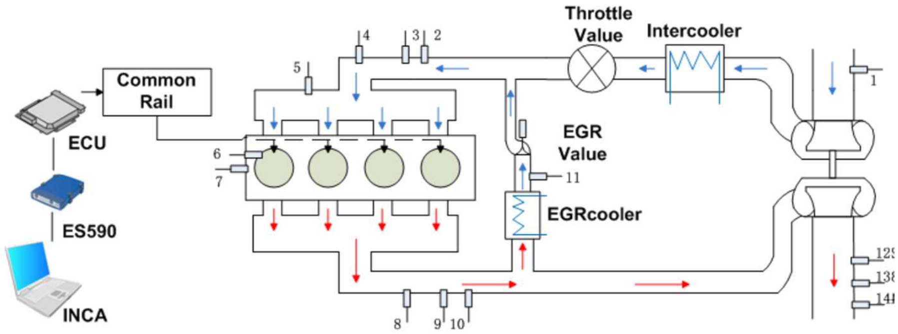
The experimental work was carried out on a four-cylinder VM common-rail turbocharged diesel engine. The specifications of the test engine are listed in Table 1. The air system of original diesel engine was upgraded by modifying a high pressure intercooler EGR system and inserting an electronic throttle control system (ETCS) in intake manifold. The high pressure EGR system connects intake manifold and exhaust manifold directly, and the exhaust gas is re-circulated and mixed with fresh air after intake throttle valve. What's more, the intake throttle valve is used to depress the intake manifold pressure for increasing the pressure difference across EGR valve to acquire large amounts of exhaust gas at low speed and partial load. Fig. 1 illustrates the layout of the test bench structure.

Table 1. Experimental engine specifications

Engine type	VMR 425DOHC
Bore × stroke	92 mm × 94 mm
Displacement volume	2.499 L
Compression ratio	17.5:1
Intake valve open (IVO)	344.4oCA ATDC
Intake valve close (IVC)	-115.6oCA ATDC
Exhaust valve open (EVO)	114oCA ATDC
Exhaust valve close (EVC)	-328oCA ATDC
Rate power	105kW@4000r/min
Max. torque	320Nm@2000r/min
Injection system	Bosch common rail
Injector	6 ×φ 0.14mm, 145o

The diesel engine was coupled to an eddy current dynamometer, and engine coolant, intake intercooler and fuel temperatures were controlled at constant valves. A Bosch ETK-Bypass ECU was applied for accomplishing real-time fuel injection, calibration, and monitoring parameters with INCA. The EGR valve and intake throttle were precisely dominated by a self-developed air-path aided control system (AACS) based on MC9S12XDP512. The overall EGR rate was monitored by EGR5230 through sampling O2 concentration sensors (Bosch LSU 4.2) and pressures directly in the intake and exhaust manifold of the diesel engine. NOx concentration in the exhaust gas was gauged using a smart NOx sensor (SNS) manufactured by Continental AG, while soot concentration was estimated based on the measured results of an AVL 415S smoke meter [27]. A Kistler 6056A cylinder pressure transducer was mounted through the glow-plug access-hole and connected to the DEWETRON 5000 combustion analysis system. Furthermore, in-cylinder pressure data were logged at 0.2 degree crank angle (CA) and 100 consecutive combustion cycles at steady-state conditions for calculating combustion parameters such as HRR, cumulative heat release, start crank angle of combustion, crank angle of 50% heat release (CA50), indicated mean effective pressure (IMEP), etc. The main control and acquisition system structure is described in Fig. 2. During some air-path transient operations, like EGR valve or intake throttle step- change, there is a necessary demand to track and record the cycle-to-cycle transition of combustion characteristics in time. So the self-developed AACS sample the crank angle of the diesel engine and process it through X-Gate, following, it generates a signal to combustion analysis system in order to realize crank phase synchronization.

IOP Conf. Series: Earth and Environmental Science **300** (2019) 032042 doi:10.1088/1755-1315/300/3/032042



1-MAF Sensor, 2-EGR5230 Intake Pressure Sensor, 3-EGR5230 Oxygen Sensor, 4-Transient Intake Pressure Sensor, 5-Temperature and Pressure Sensor, 6-In-cylinder Pressure Sensor, 7-Encoder Sensor, 8-Transient Exhaust Pressure Sensor, 9-EGR5230 Exhaust Pressure Sensor, 10-EGR5230 Oxygen Sensor, 11-Teperature Sensor, 12-Temperature Sensor, 13-NOx Sensor, 14-Smoke Meter

Figure 1. Schematic of the test setup

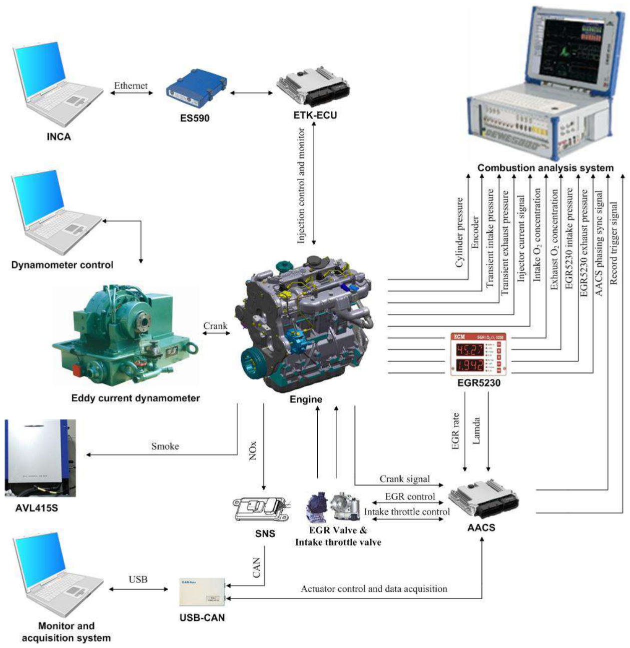


Figure 2. Schematic of the control and acquisition system

2.2. *Experimental conditions*

In this study, the coolant temperature was set at 358K, and the fuel temperature was held constant at 308K. Meanwhile, the intake cooler temperature of intake manifold was controlled at 303K. The engine tests were performed at a fixed engine speed of 1500rpm. A single-injection strategy was used with injection pressure of 750 bar and injection quantity of 15mg for each cycle. The EGR value was kept at full opening during the experiment, then, the EGR ratio was achieved about 37% and the engine operated at CI combustion region. The intake throttle was controlled to execute a step change to increase the pressure difference between intake manifold and exhaust pipe in order to drive enough EGR gas through the EGR value to enable LTC cycle. Moreover, the injection timing retarded from -14 deg CA to -7 deg CA after top dead center (ATDC) for investigating the effect of injection timing on combustion cycle characteristics in LTC mode.

2.3. EGR

In the research work, the oxygen concentrations of the intake and exhaust streams were utilized to quantify the amount of external EGR in engine test cells, and the accuracy of the results have been found to be reliable over a wide range of engine operation conditions [13]. The EGR ratio is defined as follows:

$$\mathrm{EGR_v} \approx \frac{[\mathrm{O_2}]_{\mathrm{amb}} - [\mathrm{O_2}]_{\mathrm{int}}}{[\mathrm{O_2}]_{\mathrm{amb}} - [\mathrm{O_2}]_{\mathrm{exh}}} \tag{1}$$

Where EGR_v is the volume rate of the EGR, $[O2]_{amb}$ is the ambient oxygen concentration which is calculated by ambient temperature and humidity, $[O2]_{int}$ is the intake oxygen concentration, and $[O2]_{exh}$ is the exhaust oxygen concentration.

The oxygen concentrations were measured by wideband universal exhaust gas oxygen (UEGO) sensor (Bosch LSU 4.2), and the output value of the UEGO sensor was corrected through the intake/exhaust pressure to make up the deviation of the sensor signal which was caused by a change of the intake/exhaust gas pressure [28].

The mixture fraction of the fresh air and EGR gas is vital for engine combustion and emission characteristics, especially when engine switch from CI to LTC region, which may cause cycle-to-cycle variation and even misfire. The EGR gas flow rate through the EGR value is modeled by the standard orifice flow equation, and it can be approximately described as:

$$\dot{m}_{EGR} = \begin{cases} C_d A_{EGR\mathrm{Re}f} \dfrac{p_u}{\sqrt{RT_d}} \sqrt{\dfrac{2\gamma}{\gamma-1}\left[\left(\dfrac{p_d}{p_u}\right)^{\frac{2}{\gamma}} - \left(\dfrac{p_d}{p_u}\right)^{\frac{\gamma+1}{\gamma}}\right]} & \dfrac{p_d}{p_u} > \left(\dfrac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \\ C_d A_{EGR\mathrm{Re}f} \dfrac{p_u}{\sqrt{RT_d}} \left[\gamma^{1/2}\left(\dfrac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}\right] & \dfrac{p_d}{p_u} < \left(\dfrac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \end{cases} \tag{2}$$

Where $\dot{m}_{EGR}$ is the EGR gas flow rate, C_d is the flow coefficient of the EGR value as a function of the value opening position, A_{EGRRef} is total opening reference area of the EGR value, γ is the specific heat ratio, p_u is the upstream exhaust gas pressure, p_d is the downstream exhaust gas pressure, R is the gas constant, and T_d is the exhaust gas temperature after EGR cooler. T_d is calculated from the definition of the cooler effectiveness as follows:

$$Td = (1-\varepsilon_{EGR})T_u + \varepsilon_{EGR} T_{cool} \tag{3}$$

Where T_u is the exhaust gas temperature, T_{cool} is the EGR coolant temperature, ε_{EGR} is the EGR cooler efficiency.

2.4. Heat release rate calculation

The apparent heat release rate is calculated using the first law of thermodynamics from measured cylinder pressure trace [29] as expressed in Eq. (4).

$$\frac{dQ}{d\theta} = \frac{\gamma}{\gamma-1} p \frac{dV}{d\theta} + \frac{1}{\gamma-1} V \frac{dp}{d\theta} \tag{4}$$

Where Q is apparent heat release, γ is the specific heat ratio, V is the volume of cylinder, p is the cylinder pressure, and θ is crank angle position. The timing of the start of combustion (SOC) is determined according to the steepest ascent point of the heat release rate curve. Then the ignition delay is decided as the different between the start of injection (SOI) and SOC.

3. Results and Discussion

3.1. Intra-cycle oxygen concentration

Fig. 3 illustrates the cycle values of intake and exhaust oxygen concentrations at 37% EGR ratio under steady state conditions. The fuel delivery timing was set at -11°CA ATDC. It can be seen that the oxygen concentration in the intake charge almost maintains at steady level at each EGR condition. While the exhaust oxygen concentration is affected by exhaust values opening/closing (EVO/EVC), and result in intra-cycle fluctuation. The similar phenomenon is observed at other EGR conditions. The difference of peak to valley value in the exhaust oxygen concentration will approximately bring 2% calculation error bandwidth for EGR ratio. So the medium value of exhaust oxygen concentration is taken for EGR ratio calculation in the following work.

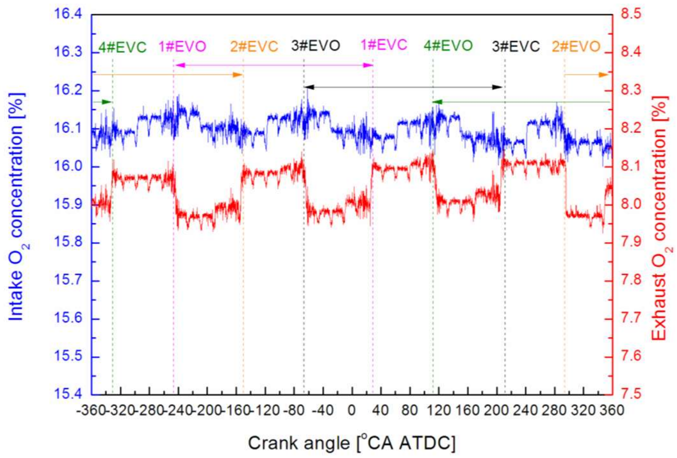


Figure 3. Intra-cycle values of intake and exhaust oxygen concentration at 37% EGR ratio

3.2. Intra-cycle oxygen concentration

During EGR transient operation, the change of recycled exhaust oxygen to the intake charge affects the in-cylinder combustion state and result in the fluctuation of oxygen in the exhaust during the next engine cycle. The process last until the oxygen concentration between intake and exhaust achieve equilibrium. To investigate the effect of heavy EGR transient condition for engine combustion cycle, the engine test was performed at 1500 rpm. A single-injection strategy was taken with injection pressure of 750 bar and injection quantity of 15mg for each cycle. The fuel injection timing was -11° CA ATDC. And the intake throttle value was controlled to make a step change from 15% to 5% opening position so as to drive the EGR ratio from about 37% to 55%. Fig. 4 plots the EGR transient process from CI (30th cycle) to LTC (70th cycle) engine cycles. The EGR transient process consists mainly of two parts: the value execution process and the EGR accumulating process. The experimental results show that the EGR ratio and exhaust oxygen concentration don't alter significantly at the stage of value closing process due to the stable gas pressure ratio across the EGR value, as shown in Fig. 5. And during the EGR accumulating process, the EGR ratio varies slowly, and it comes to stabilize after about 25 engine cycles (~2s) under fixed fuel injection parameters condition. It's a long delay time compared to fuel adjusting. The EGR gas is driven by the pressure difference between intake and exhaust duct, and it experiences a long gas transport and accumulating process before in-cylinder combustion state come to a new equilibrium. The effect of engine load on EGR accumulating process time will be studied in the later work. Additionally, the amount of heavy EGR diminish exhaust stream to turbocharger, so intake boosting is weakened, intake charge is decreased, and engine load is limited. Therefore it's necessary to adjust boost pressure in order to avoid unstable combustion and maintain the engine load.

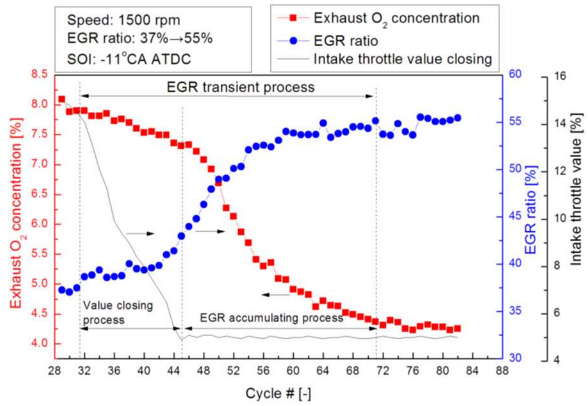


Figure 4. EGR transient process from CI to LTC engine cycles

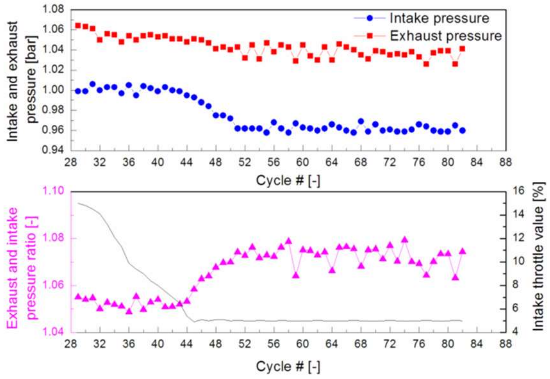


Figure 5. Intake and exhaust pressure across the EGR value

Fig. 6 and Fig. 7 give the effect of transient EGR process on combustion characteristics. As shown in Fig.6, with the promotion of EGR ratio from 37% (30th cycle) to 55% (70th cycle), the peak value of in-cylinder pressure and heat release trace drop cycle by cycle due to the higher heat capacity of the diluent intake charge as well as slower reaction rates during the premixed combustion. And as the increasing EGR proportion in intake charge, the specific heat ratio of intake charge gradually decrease, which lead to the demotion of the in-cylinder pressure at adiabatic compression process. Meanwhile, it should be note that the heat release trace emerge a slight fluctuation at near TDC crank angle (enlarge zone) with the development of transient EGR process. It presumes that this phenomenon is mainly affected by the low temperature cold fire action. Fig. 7 provides the development of ignition delay period and CA50. From CI to LTC region, the crank angle period of ignition delay prolong over 100% from 6.8°CA to 14.2°CA, thus it allows more time to achieve a more homogeneous mixture. As we know, NOx emission will directly be affected by EGR. And soot emissions are a completion between soot formation and oxidation process. In CI combustion region, soot emissions are found to increase with the promotion of EGR ratio. While the use of heavy EGR (over 50%) will limit in-cylinder combustion temperature level at which the soot formation is restrained. Because of the extended ignition delay, more premixed in-cylinder condition, and low combustion temperature, LTC mode is achieved to reduce NOx and soot emissions simultaneously. The NOx and soot emissions are 10 ppm and 0.103 FSN at 55% EGR ratio, respectively.

However, CA50 generally follows the trends of ignition delay, and it's retarded from 3°CA ATDC to 10°CA ATDC at fixed injection condition, which cause the decline of indicated thermal efficiency.

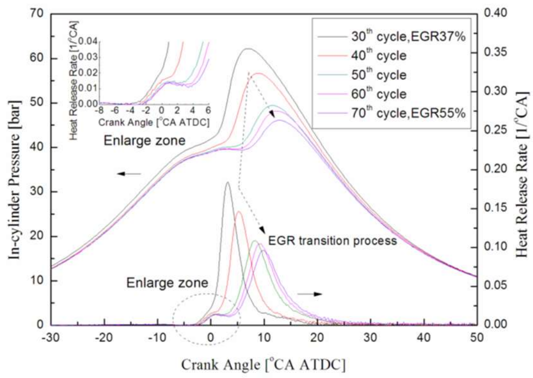


Figure 6. In-cylinder pressure and heat release profiles of transient EGR process

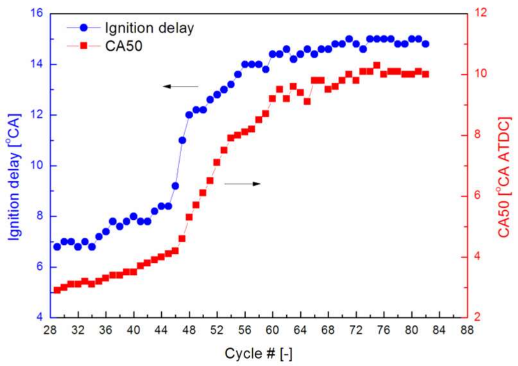


Figure 7. Ignition delay and CA50 of transient EGR process

3.3. Effect of SOI

Fig. 8 and Fig. 9 present the effect of SOI on combustion performance under 37% and 55% EGR ratio. The SOI was respectively set at -14°CA ATDC, -11°CA ATDC, -9°CA ATDC and -7°CA ATDC under a fixed EGR ratio. The experimental results show that the peak pressure as well as the peak value of heat release rate is increased by advancing the injection timing. The ignition delays are shortened by delaying the injection timing, which result in the absence of premixed combustion process. And the heat release extends into expansion process when the injection timing is too late. The inordinate delayed injection timing will cause the promotion of in-cylinder cycle-to-cycle variation and even misfire, especially when the engine switches from CI to LTC region, as shown in Fig. 10. Thus it's critical for the ECU to optimize the injection timing or combustion phase to keep combustion stable at different combustion region.

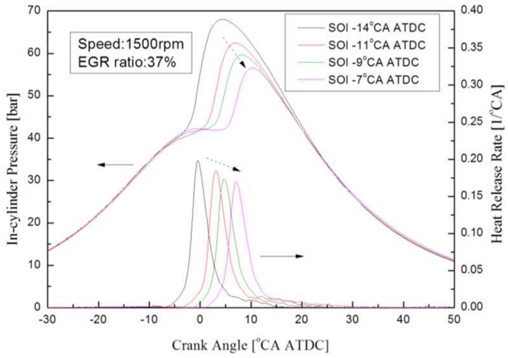


Figure 8. In-cylinder pressure and heat release profiles at 37% EGR ratio

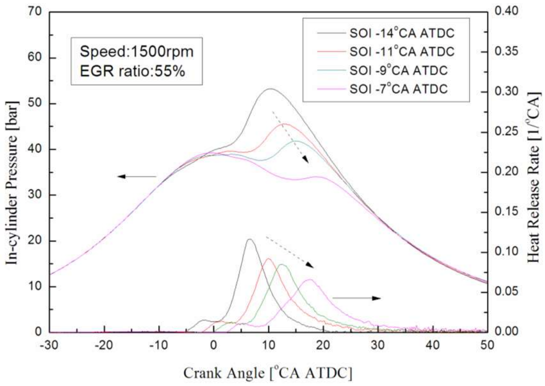


Figure 9. In-cylinder pressure and heat release profiles at 55% EGR ratio

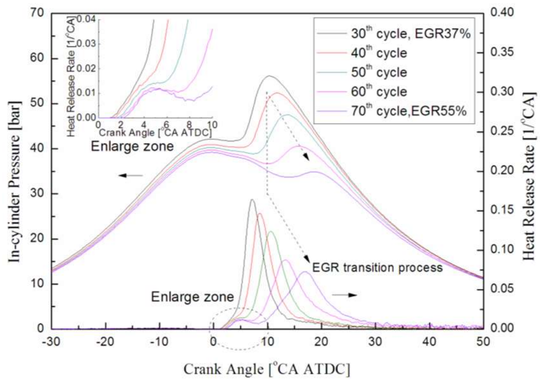


Figure 10. In-cylinder pressure and heat release profiles of transient EGR process at -7°CA ATDC injection timing

4. Conclusion

In this study, the effect of heavy EGR transient process on engine combustion cycles is investigated from CI to LTC region. The results are concluded as follows:

(1) At EGR steady conditions, the oxygen concentration in the intake charge almost maintains at steady level, but the exhaust oxygen concentration is affected by EVO/EVC, and result in intra-cycle fluctuation, which will approximately bring 2% calculation error bandwidth for EGR ratio.

(2) From 37% to 55% EGR ratio, the EGR gas is mainly driven by the pressure ratio of intake and exhaust duct, and it will experience a long accumulating process to reach a new equilibrium. With the promotion of EGR ratio, the specific heat ratio of intake charge gradually decreases, which causes the

demotion of the in-cylinder pressure at adiabatic compression process. The ignition delay period prolongs 100%, thus it allows more time to achieve a more homogeneous mixture, and CA50 retards from 3°CA ATDC to 10°CA ATDC at fixed injection condition.

(3) The inordinate delayed injection timing will promote in-cylinder cycle-to-cycle variation and even misfire, especially during transition from CI to LTC region.

Acknowledgements

The authors gratefully acknowledge the financial support by the foundation research funds of Ministry of Industry and Information Technology of the People’s Republic of China.

References

[1] R.H. Thring, Homogeneous-charge Compression-ignition (HCCI) Engines, 1989. SAE Paper 892068.
[2] K. Robert, T. Eiji, K. Nobuyuki, Y. Sumito, Effects of spray impingement, injection parameters, and EGR on the combustion and emission characteristics of a PCCI diesel engine, Appl. Therm. Eng. 37(2012)165-175.
[3] S. Kook, C. Bae, The influence of charge dilution and injection timing on low-temperature diesel combustion and emissions, 2005. SAE Paper 2005-01-3837.
[4] Y. Lee, K.Y. Huh, Analysis of different modes of low temperature combustion by ultra-high EGR and modulated kinetics in a heavy duty diesel engine, Appl. Therm. Eng. 70(2014)776-787.
[5] Q. Fang, J. Fang, J. Zhuang, Influences of pilot injection and exhaust gas recirculation (EGR) on combustion and emissions in a HCCI-DI combustion engine, Appl. Therm. Eng. 48(2012)97-104.
[6] L. Kocher, K. Stricker, D. Alstine, E. Koeberlein, Oxygen fraction estimation for diesel engines utilizing variable intake valve actuation, 2012. Proceedings of the 2012 American control conference, 4963-4968.
[7] O. William, Z. Phil, E. Raul, Development of a fuel injection strategy for diesel LTC, 2008. SAE Paper 2008-01-0057.
[8] N. Ladommatos, S.M. Abdelhalim, H. Zhao, Z. Hu, The dilution, chemical, and thermal effects of exhaust gas recirculation on diesel engine emissions —Part 1: Effect of Reducing Inlet Charge Oxygen, 1996. SAE Paper 961165.
[9] N. Ladommatos, S.M. Abdelhalim, H. Zhao, Z. Hu, The dilution, chemical, and thermal effects of exhaust gas recirculation on diesel engine emissions —Part 4: Effect of carbon dioxide and water vapor, 1997. SAE Paper 971660.
[10] N. Ladommatos, S.M. Abdelhalim, H. Zhao, Z. Hu, Effects o EGR on heat release in diesel combustion, 1998. SAE Paper 980184.
[11] H. Zhao, H. Xie, Z. Peng, Effect of recycled burned gases on homogeneous charge compression ignition combustion, Combustion Science and Technology 177(2005)1863-1882.
[12] A. Maiboom, X. Tauzia, J.F. Hetet, Experimental study of various effects of exhaust gas recirculation (EGR) on combustion and emissions of an automotive direct injection diesel engine, Energy 33(2008)22-34.
[13] U. Asad, M. Zheng, Exhaust gas recirculation for advanced diesel combustion cycles, Applied Energy, 123 (2014)242-252.
[14] S.M. Aithal, Impact of EGR fraction on diesel engine performance considering heat loss and temperature-dependent properties of the working fluid, Int. J Energy Res. 33(2009)415-430.
[15] K. Anand, R.D. Reitz, E. Kurtz, W. Willems, Modeling Fuel and EGR Effects under Conventional and Low Temperautre Combustion Conditions, Energy Fuels 27(2013)7827-7842.
[16] H. Ogawa, T. Li, N. Miyamoto, Characteristics of low temperature and low oxygen diesel combustion with ultra-high exhaust gas recirculation, Int. J Energy Res. 8(2007)365-378.
[17] S. Han, J. Kim, C. Bae, Effect of mixing quality on characteristics of conventional and low temperature diesel combustion, Applied Energy 119(2014)454-466.

[18] A.M. Andwari, A.A. Zziz, M.F.M. Said, Z.A. Latiff, An experimental study on the influence of EGR rate and fuel octane number on the combustion characteristics of a CAI two-stroke cycle engine, Appl. Therm. Eng. 71(2014)248-258.
[19] R. Finesso, E. Spessa, A real time zero-dimensional diagnostic model for the calculation of in-cylinder temperatures, HRR and nitrogen oxides in diesel engines, Energy Conversion and Management 79(2014)498-510.
[20] C. Fang, F. Yang, M. Ouyang, G. G, Combustion mode switching control in a HCCI diesel engine, Applied Energy 110(2013)190-200.
[21] A.P. Carlucci, D. Laforgia, S. Motz, R. Saracino, S.P. Wenzel, Advanced closed loop combustion control of a LTC diesel engine based on in-cylinder pressure signals, Energy Conversion and Management 77(2014)193-207.
[22] L. Shi, W. Hu, K. Deng, Effects of fuel compensation in transitional cycles on the smoothness of combustion mode switching in a diesel engine, Fuel Processing Technology 118(2014)55-63.
[23] L.E. Kocher, C.M. Hall, K. Stricker, D. Fain, Robust oxygen fraction estimation for conventional and premixed charge compression ignition engines with variable valve actuation, Control Engineering Parctice, 29(2014)187-200.
[24] D. Alberer, L. Re, Fast oxygen based transient diesel engine operation, 2009. SAE Paper 2009-01-0622.
[25] S. Nakayama, T. Fukuma, A. Matsunaga, T. Miyake, A dynamic combustion control method based on charge oxygen concentration for diesel engines, 2003. SAE Paper 2003-01-3181.
[26] H. Yokomura, S. kouketsu, S. kotooka, Y. Akao, Transient EGR control for a turbocharged heavy duty diesel engine, 2004. SAE Paper 2004-01-0120.
[27] J. Arregle, V. Bermudez, J.R. Serrano, E. Fuentes, Procedure for engine transient cycle emissions testing in real time, Experimental Thermal and Fluid Science 30(2006)485-496.
[28] BOSCH R. Planar wideband lambda sensor-LSU 4.2. In: Bosch RG, editor: 2003.
[29] J.B. Heywood, Internal combustion engine fundamental, New York: McGraw Hill Press, 1998.