ISSN 1674-8484 汽车安全与节能学报, 2010 年, 第 1 卷 第 3 期 09/13
CN 11-5904/U J Automotive Safety and Energy, 2010, Vol. 1 No. 3 219－228

Empirical Studies of EGR Enabled Diesel Low Temperature Combustion

Ming ZHENG, Xiaoye HAN, Graham T. READER

(Mechanical, Automotive & Materials Engineering, University of Windsor, Windsor, Ontario N9B 3P4, Canada)

Abstract: The use of exhaust gas recirculation (EGR) is an effective way of achieving low temperature combustion (LTC) in diesel engines thereby enabling lower levels of the in-cylinder oxides of nitrogen (NO_x) to be produced. In addition the fuel injection strategy used and the control of boost pressure are key aspects in attaining low NOx and soot emissions simultaneously. In the work reported in this paper, experiments were performed on an advanced testing engine platform which allows EGR, fuel injection timing and boost pressure to be precisely controlled and the influence of each parameter on the emissions to be studied independently. The results indicate that within the investigated LTC ranges, the ratio of EGR plays the most effective role in NO_x reduction; the injection pressure and boost have a more modest effect on NOx emissions in general. Nevertheless, the increased injection pressure lowers the soot emission across the EGR sweep and the augmented boost reduces the soot significantly from a high soot level. It was also observed that with the high levels of the EGR, both the carbon monoxide and unburned hydrocarbon emissions increase. The effect is attributed to the reduced oxygen concentration and the lowered flame temperature.

Key words: diesel engines; exhaust gas recirculation (EGR); boost pressure control; injection strategy; low temperature combustion (LTC); NO_x and soot emission

通过废气再循环实现柴油低温燃烧的实验研究

郑 明 , 韩晓野 , Graham T. Reader

(温莎大学 机械、汽车与材料工程系 , Windsor, Ontario N9B 3P4, Canada)

摘 要: 应用废气再循环（EGR）能够降低缸内氮氧化物（NO_x）生成，是实现柴油低温燃烧的一种有效方法。以同时降低 NO_x 和碳烟为目的，恰当的喷油策略和进气增压控制则是除 EGR 之外的两个关键因素。该文的实验是在先进的发动机实验平台上完成的，该实验平台可以精确并单独控制这三项参数，以单独研究每一个参数对发动机排放的影响。实验结果表明：在本研究的低温燃烧范围内，应用 EGR 是降低 NO_x 排放的最有效手段；然而，喷油压力和进气压力对 NO_x 仅有轻微影响。另一方面，在不同 EGR 条件下，可以通过提升喷油压力来减少碳烟排放；针对高碳烟情况，提升进气压力可以有效降低碳烟峰值。但是，随 EGR 率的增加，由于氧气含量减少和火焰温度降低，导致较高的碳氢和一氧化碳排放。

关键词: 柴油机；废气再循环（EGR）；低温燃烧（LTC）；碳烟增压控制；喷油策略；NO_x 和碳烟排放

中图分类号: X 701

INTRODUCTION

The use of diesel low temperature combustion (LTC) is aimed at reducing the occurrence of high combustion temperatures that prevail in conventional diffusion dominated diesel combustion and are the precursor for NOx production. In general, the homogeneous charge compression ignition (HCCI) is an effective approach to achieve LTC, and the use of high levels of EGR is another. In an HCCI system, the

收稿日期: 2010-08-26
作者简介: Ming ZHENG（郑明）：E-mail: mzheng@uwindsor.ca ；Phone: +1 (519) 253-3000 ext 2636; Fax: +1 (519) 973-7007;

combustion phasing is controlled mainly by the chemical kinetics rather than the injection timing, as the fuel is injected very early during the compression stroke in order to produce a homogeneous cylinder charge[1]. The mixture undergoes a much longer physical and chemical preparation than that in the conventional diesel cycles prior to combustion. The lack of direct control on combustion phasing is one of the major difficulties for HCCI systems. However, the combustion phasing is closely related to the levels of the EGR.

Two primary effects brought in by EGR are the oxygen dilution and the heat capacity increase of the cylinder charge[4]. When the fresh air intake is partially replaced by an EGR stream, the oxygen concentration of the cylinder charge reduces. Moreover, the combustion products, including carbon dioxide (CO_2) and water (H_2O), are re-circulated back to the cylinder. These gases have heat capacity higher than normal fresh air, resulting in decreased temperatures after compression and during combustion. The reduced oxygen concentration and flame temperature, therefore, suppress the in-cylinder NO_x formation.

Previous studies indicated that it was possible to achieve low NO_x and soot simultaneously when the flame temperature was below approximate 1 650 K[5-6]. An MK combustion mode had been reported by Nissan to successfully attain premixed LTC. The required mixing was obtained by the use of EGR and retarding the injection timing[7]. The re-circulated exhaust gas reduces the in-cylinder temperatures, dilutes the cylinder charge, and thereby prolongs the ignition delay and offers a longer mixing duration for the injected fuel with the air[8-10]. The duration of the ignition delay can be extended by 50% with EGR compared to that of zero EGR in presence[11].

Although EGR enabled LTC allowed drastically reduced NO_x emissions to be achieved, the high levels of carbon monoxide (CO) and unburned hydrocarbons (HC) production remained a challenge. The homogenized fuel charge is in direct contact with the combustion chamber surfaces and the ability to burn such crevice or quenched fuel is further deteriorated by the diluted cylinder charge and the lowered flame temperature. The high CO and HC emissions contain a considerable amount of the fuel energy, and thus the engine fuel economy is also diminished[11]. Thus to augment EGR, boosted intake pressure is commonly employed to make extra oxygen available and so complete the combustion. In addition, the increased air to fuel ratio helps soot reduction[12-22].

Previous investigations on the load applicability of the EGR enabled LTC are limited. When the engine load is progressively raised, the desirable low temperature combustion is more difficult to achieve. As the total amount of the fueling increases, the percentages of the premixed fuel decline within the given ignition delay period, whereas the diffusion combustion starts to spread and the combustion characteristics shift towards those of conventional diesel engine cycles. The non-homogeneity attributed to the diffusion burning cause an air to fuel ratio gradient in the cylinder charge mixture. The local flame temperature may increase wherever a stoichiometric air to fuel ratio exists.

Higher levels of EGR are generally employed to further prolong the ignition delay and suppress the combustion temperatures and hence obtain better mixing and the NO_x reduction. Additionally increased boost is employed to compensate for the diluted and depleted oxygen in the cylinder charge. However, with this strategy the peak cylinder pressure becomes a concern. The compression pressure (before the combustion occurs) can reach 16 MPa due to the high boost and compression ratio, such as a 300 kPa absolute boost with an 18.2 compression ratio. The combustion peak pressure can be expected to be even higher. The majority of modern production engines are designed to withstand peak cylinder pressures of up to 18~20 MPa. Therefore, when the engine loads increase under LTC cycles, the accompanying higher peak cylinder pressure are close to the engine's strength limits and could be exceeded causing structural damage and even failure.

To investigate these challenges of LTC diesel operation, a series of experiments have been conducted using an advanced engine testing platform developed at the University of Windsor. This platform has been designed and instrumented so that precise control of the boost pressure, degree of EGR and fuel injection parameters can be readily achieved. In this way it has been possible to study the independent influence of each parameter on the diesel engine emissions, including NO_x, soot, CO and THC. The experiments reported in this paper were performed at engine loads of up to 0.8 MPa IMEP (indicated mean effective pressure).

EXPERIMENT SETUP

A modern common rail diesel engine (Ford Puma) and a single cylinder test engine are integrated to the testing systems in the dynamometer cells of the Clean Diesel Research Centre at University of Windsor (UW). The specifications of each engine are listed in Table 1 and Table 2.

Table 1 Ford Test Engine Specifications

Engine Type	4 Cylinder, 4 Stroke Ford DuraTorq"Puma"
Displacement	1 998 cm^3
Bore x Stroke	86 mm × 86 mm
Connecting Rod	144
Compression Ratio	18.2 : 1
Combustion System	Direct Injection
Maximum Cylinder Pressure	18.0 MPa
Injection System	Common-rail (up to p_{Rail} ≈ 160 MPa)

Table 2 Single Cylinder Test Engine Specifications

Engine Type	Single Cylinder, 4 Stroke
Displacement	0.767 cm3
Bore x Stroke	96 mm × 106 mm
Compression Ratio	16.3：1
Combustion System	Direct Injection
Maximum Cylinder Pressure	20.0 MPa
Injection System	Common-rail (up to p_{Rail} ≈ 180 MPa)

Only one engine runs for each experiment on this testing platform, and the other engine is decoupled from the system. The Ford Puma has been modified to operate on a“ 1 + 3 ” configuration. With this arrangement a separated single cylinder is instrumented for the LTC research, and the remaining 3 cylinders are operated in conventional diesel cycle modes. This enables overall engine performance to be stabilized, for instance, the speed. A simplified schematic of the system setup is shown in Figure 1. In the figure, the Ford Puma is in use while the single cylinder research engine is decoupled. Both natural aspirated and boosted intake are available in this setup. The dry and clean compressed air is introduced to simulate the intake boost, and the pressure level is rigorously and precisely controlled. The exhaust backpressure management is achieved by a pressure regulator that restrains the exhaust out flow rate and builds up the backpressure. The intake and exhaust flow systems are independent of each other. An air mass flow meter is installed upstream of the intake surge tank, and the cooled EGR flow is directed to the downstream of the tank. The engine coolant is normally used to cool the EGR, and an additional cooling loop for alternative fluids, for instance, the city water, is also available for more effective cooling. The EGR flow rate is managed by a combination of the EGR valve and the exhaust backpressure. The EGR valve position is commanded through CAN bus communication with a LabVIEW ™ interface, and the pressure difference between the exhaust and intake can be fine tuned to precisely control the EGR ratio. The pressure of the research cylinder is acquired through the pressure transducers and a Kistler ™ 5010B charge amplifier is shared by both the engines. Encoders with 0.1 degree crank angle (CA) resolution are utilized to accurately obtain the engine position and provide the sampling clock for the pressure recording. The pressure of each data point is an average of 200 continuously recorded cycles, subsequently calculating the heat release rate (HRR), the crank angle of 50% of the total fuel burned (CA50), and the accumulated heat release.

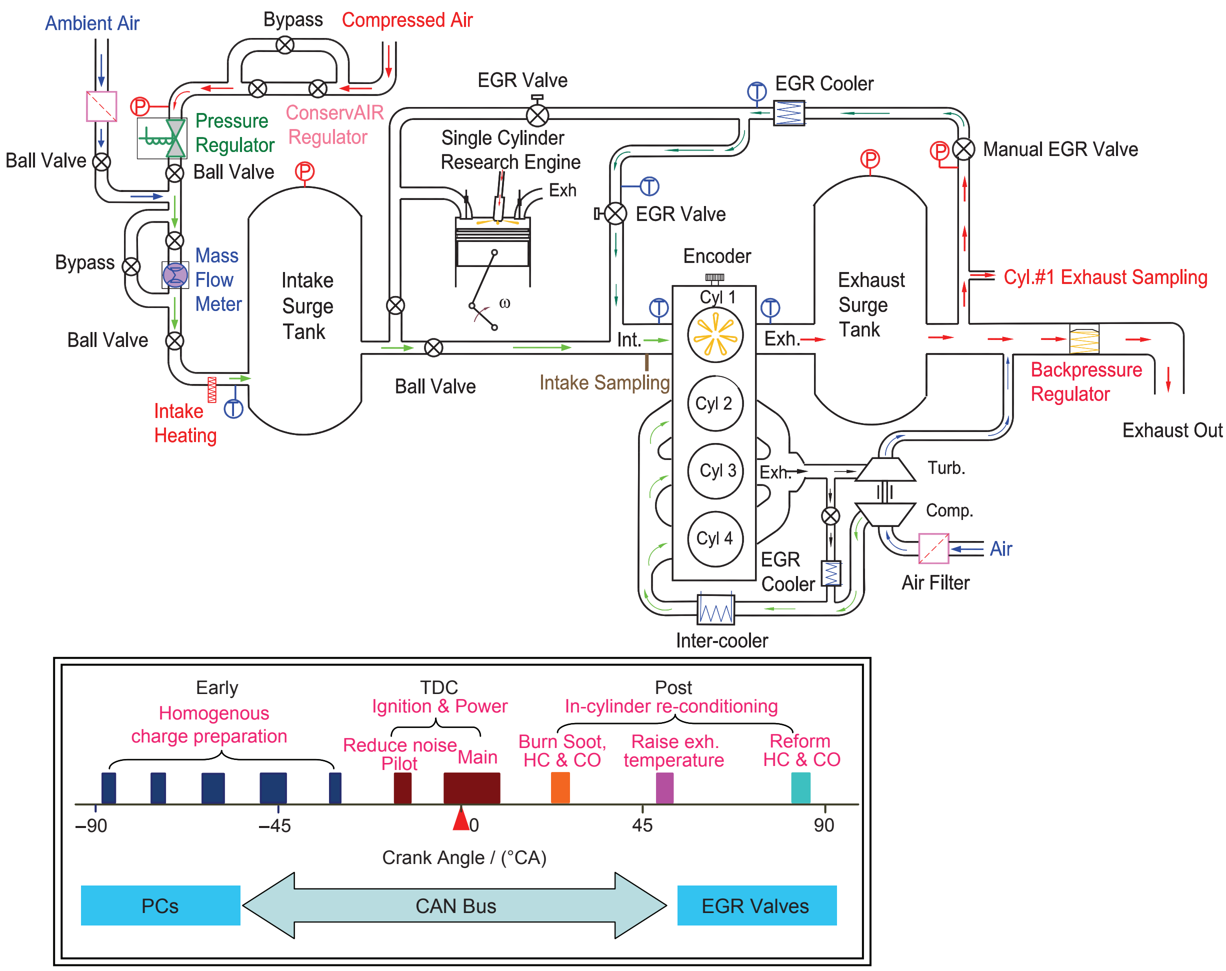

Figure 1 Schematic of Test Setup at University of Windsor

Other advanced facilities are employed to guarantee the controllability and repeatability of the test parameters. The temperatures of the engine coolant and oil are precisely controlled through the coolant and lubricant conditioning units. Additional heating on the intake surge tank can be used to further control the intake temperature. A DC dynamometer is coupled to the single cylinder research engine to measure the engine power/torque output and stabilize the engine speed, while an eddy current dynamometer is connected to the Ford Puma. The UW operating system also allows direct regulation of the volume control valve (VCV) and the pressure control valve (PCV) on the high pressure fuel pump, rather than solely relying on the engine control unit (ECU) [24]. The EFS ™ IPoD Piezo injector drivers are instrumented to energize the injectors. The injection pressure and scheduling are precisely controlled via a set of embedded real-time (RT) controllers and the field programmable gate array (FPGA) devices, and the control interface consists of two personal computers (PC) running the in-house written LabVIEW programs. Therefore, the UW custom-built system controls the injection independently, and allows the geometry resolved injection timing but the time resolved duration. Other LabVIEW programs have also been developed by the authors 'research teams to acquire, synchronize and record the data, to calculate the engine IMEP and HRR on the fly, and to control the various actuators, such as the EGR valve.

The soot is measured by an AVL 415S smoke meter. The intake and exhaust gaseous emissions, including NO_x, THC, CO, CO_2, and O_2, are measured using a dual-bank analyzer system.

RESULTS AND DISCUSSION

Previously reported work in the authors 'Clean Diesel Research Centre has described in detail the typical techniques which have been used to achieve EGR enabled diesel LTC (Figure 2) [11]. To aid understanding of the new work reported here a brief summary of these techniques is now provided. In operation, the EGR is progressively increased and the conventional high temperature combustion (HTC) is observed until the soot emission rises to its peak value at particular EGR ratio. The combustion emissions are characterized by the classical NO_x-soot trade-off. The term "Slope 1" is referred to this conventional trade-off in HTC, and is defined here as the ascending curve of the soot emission with the increasing EGR. When increased EGR levels continue to be applied, the levels of soot and NO_x production decrease simultaneously. In particular, the soot emission rapidly reduces to an ultra-low level while the CO and THC rise sharply within a fairly narrow window of the EGR. In this manner EGR enabled diesel LTC is achieved albeit over a narrow operating range. The term "Slope 2" is therefore defined by this segment of the emission curves, and it represents the combustion in LTC cycles.

Using the technique described a low load (IMEP = 280 kPa) LTC was achieved and a typical result set is illustrated as Figure 2. It should be noted that relatively old technologies were used in these experiments, such as the fixed start of injection (SOI, Start Of Injection), the low injection pressure (~20.0 MPa), and the non-boosted intake. It was determined that superior test results could be obtained, if a better control system could be developed which could, for instance, allow the flexible injection timing control to maintain CA50 (Crank Angle of 50% Heat Released).

Thus, the experimental platform has been further improved to enable investigations of the feasibility of EGR enabled diesel LTC cycles at load levels up to 800 kPa IMEP, and at the same time study the influence of the boost and injection during these cycles on the engine combustion and emission performances.

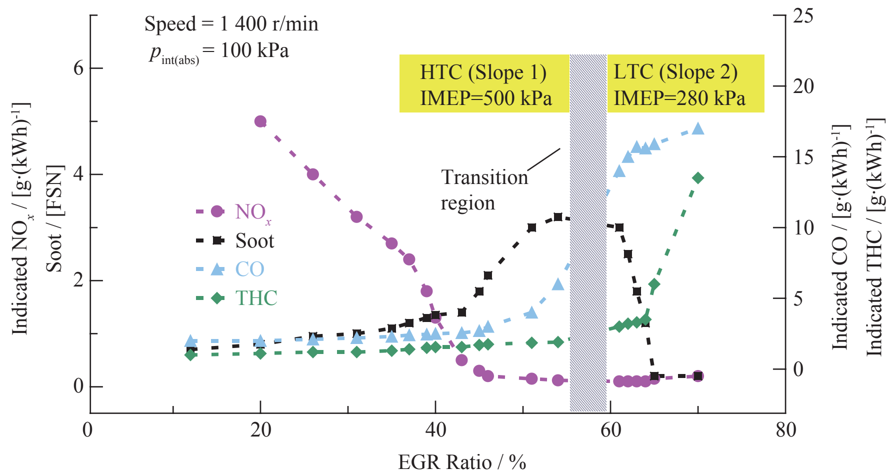

Figure 2 Typical EGR Enabled Diesel LTC [11] (EGR Sweep at fixed SOI~17~BDTC)

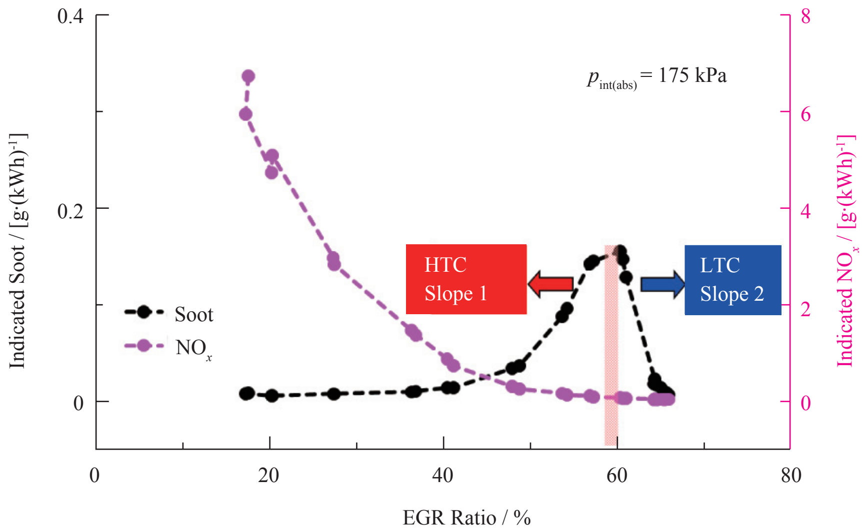

Figure 3 Soot and NO_x Emissions of EGR Sweep

EGR ENABLED DIESEL LTC AT EXPANDED LOADS

In this new work the same experiment procedures as those previously described and manifest from the data given as Figure 2 were repeated on the Ford Puma, but the level of particular experimental parameters was increased. Higher levels of the intake and injection pressure were applied, respectively 175 kPa absolute and 150 MPa. The CA50 was kept at 6 degrees after top dead center (TDC) by adjusting the SOI, although the injection duration was not changed. The common engine operating conditions for Figure 3 to 11 are listed in Table 3.

Table 3 Common Engine Operating Conditions for Figure 3 to Figure 11

Engine Speed	1 500 r/min
p_{inj}	150 MPa for Figure 3 to Figure 8
CA50	–6º BTDC except Figures 7 & 10 @ –5º~–6º BTDC
IMEP	800 kPa

The soot and NO_x emissions obtained as illustrated on Figure 3 show that the results are consistence with previously published data [24-28]. The NO_x emission declines monotonically as the EGR gradually rises, while the soot experiences the slope 1 and then slope 2. The engine runs in LTC cycles stably, and the load is raised to 800 kPa IMEP (Indicated Mean Effective Pressure) with the improved operating control.

The LTC emission trade-off can be observed, namely" NO_x & soot versus CO & THC ". It can be seen that the results are different from the conventional trade-off as the CO and THC increase rapidly after the engine enters LTC cycle mode (Figure 4), whereas the NO_x and soot simultaneously decrease (Figure 3). When the EGR is increased, the CO begins to increase significantly and earlier than the THC levels, and before the engine reaches the LTC regime. This effect is considered to the result of incomplete oxidization caused by the reduced oxygen concentration. The rapid rise of the THC emission level is indicative of the low combustion temperatures which do not enable the fuel to be burned thoroughly. The result is that the combustion efficiency of the engine is diminished.

BOOST & INJECTION PRESSURE EFFECT ON LTC ENABLING

Three sets of results for these effects are presented in Figure 5 which represents the NO_x emission levels for varying degrees under boost and injection pressure. The results indicate that the injection pressure level has noticeable influence at the higher levels of the NO_x where the degree of EGR is very low. Notwithstanding the injection pressure effect, it is clear that NOx reduction is more dependent on the EGR rather than the boost and injection pressure.

The effects of the boost and injection pressure on the other three important emissions (soot, CO and THC) were studied individually. In Figure 6, the soot emission results for the diesel LTC cycles achieved by progressively increasing EGR for two levels of the boost pressure, 145 and 175 kPa absolute are shown. The results show that the augmented boost did not help significantly when the soot emissions were low, regardless of whether the engine was running under the HTC or LTC cycle mode. However, the peak value of the soot emission did decline in the higher boost case, even at a higher EGR ratio and lower intake oxygen concentration. A considerable improvement was observed during the transition from the HTC to LTC regimes.

Figure 7 shows the pressure and HRR traces for the tested points of the peak soot emissions. The patterns of the pressure and HRR are similar for these two points; nonetheless, the

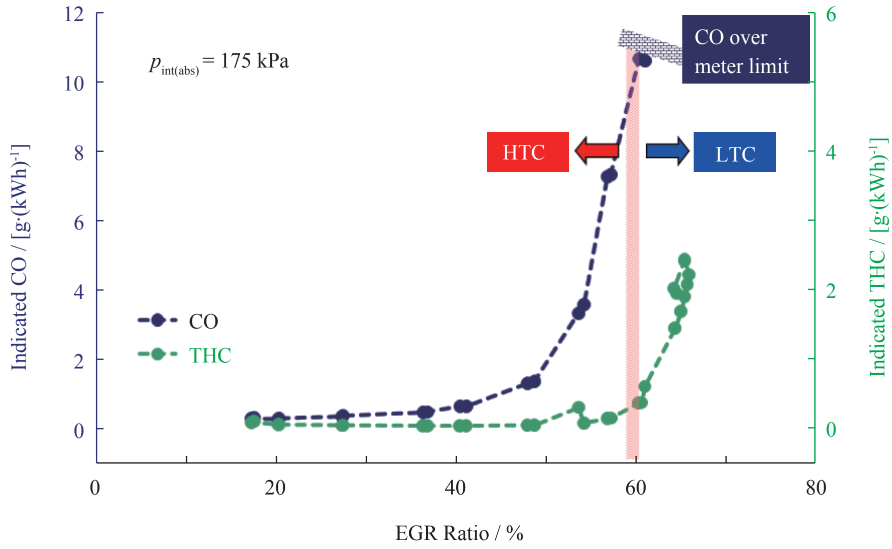

Figure 4 High HC & CO in LTC Cycles

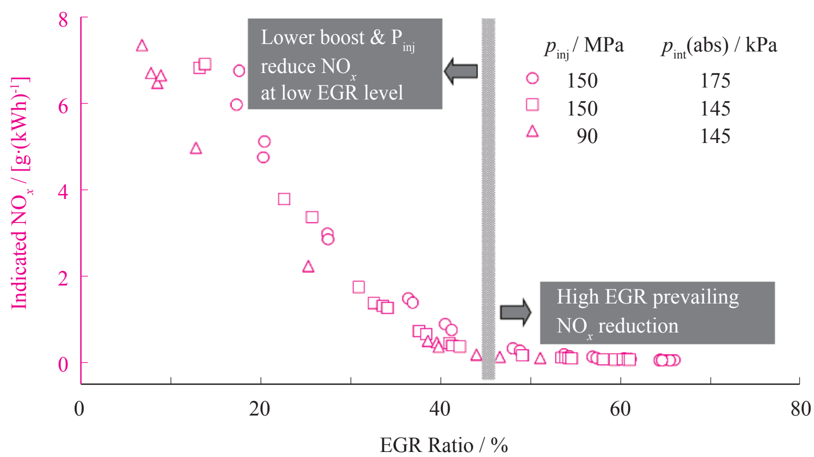

Figure 5 NO_x Emission at Different Levels of Boost and Injection Pressure

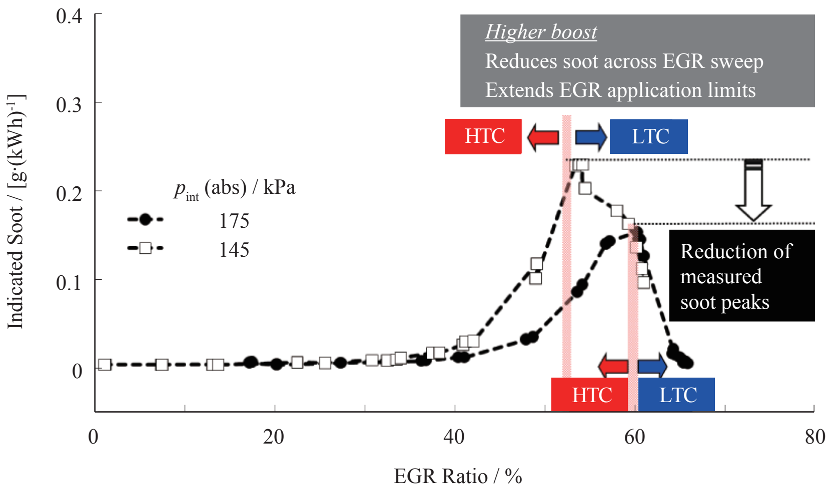

Figure 6 Soot Emission at Different Levels of Boost

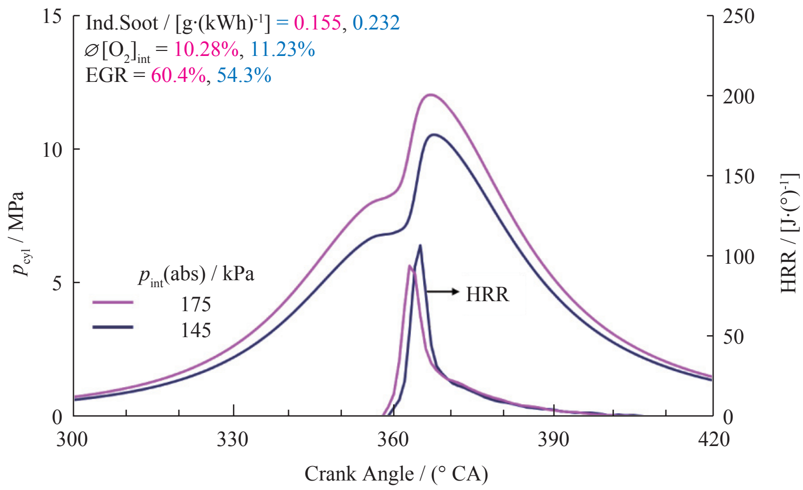

Figure 7 Pressure and HRR at Peak Soot Emissions

magnitude of the in-cylinder pressure was amplified by the higher boost, which resulted in a higher density of the cylinder charge and provided an extra amount of oxygen even at the lower oxygen concentration. This additional oxygen is considered to promote a leaner mixture and assist the soot oxidization process.

The elevated intake pressure was also beneficial for the CO and THC emissions profiles. As shown on Figure 8, the CO and THC increased as the degree of EGR was gradually increased. However the level of further EGR was restricted to prevent the engine efficiency from being unacceptably reduced due to the energy penalty drained by the CO and THC. It was abundantly clear from the data obtained that the high levels of the CO and THC emissions were shifted towards the direction of the higher EGR ratio. Therefore, there is no doubt that increasing the level of the intake pressure boost can extend the EGR application limits for diesel LTC mode operations.

The EGR sweeping experiments were performed at three levels of the injection pressure, 60, 90, and 150 MPa. In terms of the soot emission, a significant improvement was found when the higher injection pressure was applied. The empirical results shown in Figure 9 demonstrate that the LTC mode cycles were achieved with 150 MPa injection pressure when other engine conditions were kept the same. Conversely, the high soot emissions, in the cases of the lower injection pressure, preclude the use of increased degrees of EGR necessary to achieve the LTC mode operation. There is a strong likelihood if higher degrees of EGR were used that the engine could have been damaged by the excessive smoke prior to the establishment of LTC mode combustion. Therefore, the augmented injection pressure facilitates EGR enabled diesel LTC on account of its reducing soot emissions and extending EGR application limits. The lowered soot emission peak, in particular, makes the LTC operation feasible.

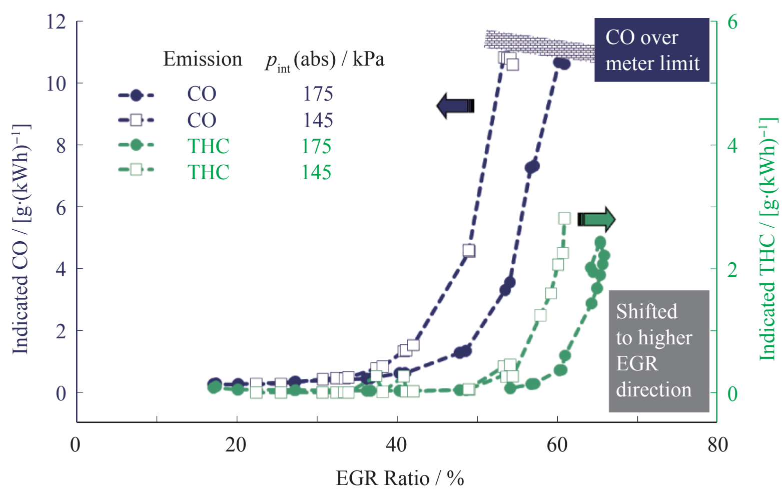

Figure 8 CO and THC Emissions at Different Boost Levels

A clearer appreciation of the effects of high injection pressures on the engine operation can be gained by considering the measured pressure and heat release rate (HRR) traces given as Figure 10 obtained with approximately 40% of EGR.

It can be seen that a larger proportion of premixed burning was present when the higher injection pressure was employed. This effect is considered to be the result of the enhanced spray penetration and atomization, since a much larger contact area would have become available between the fuel and the cylinder charge; thus offering a better environment for the premixing.

Furthermore, it is generally believed that the soot formation mainly occurs during diffusion burning. Consequently, it could be argued that the higher injection pressure reduces the soot emission, because it causes part of the total fuel charge to undergo premixed burning rather than the diffusion.

In addition, the elevated injection pressure was found to reduce the CO and THC emissions (Figure 11). The effect was similar to that of the higher boost pressure. The improved combustion efficiency gained from the decreased CO and THC emissions also contributes to the recovery of the engine thermal efficiency.

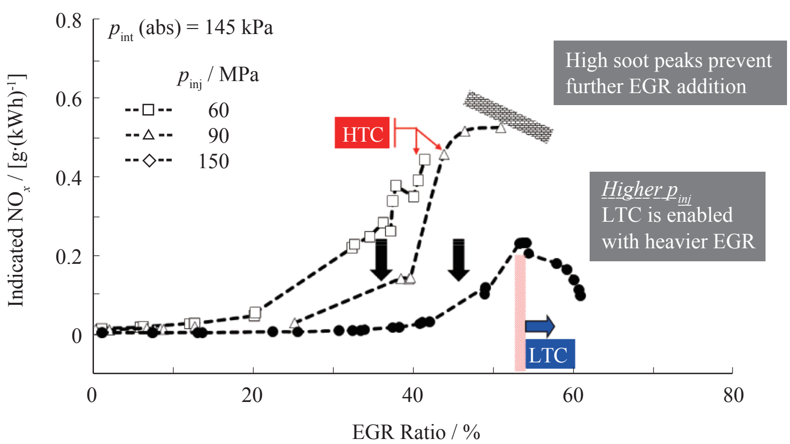

Figure 9 Soot Emissions at Different Injection Pressure Levels

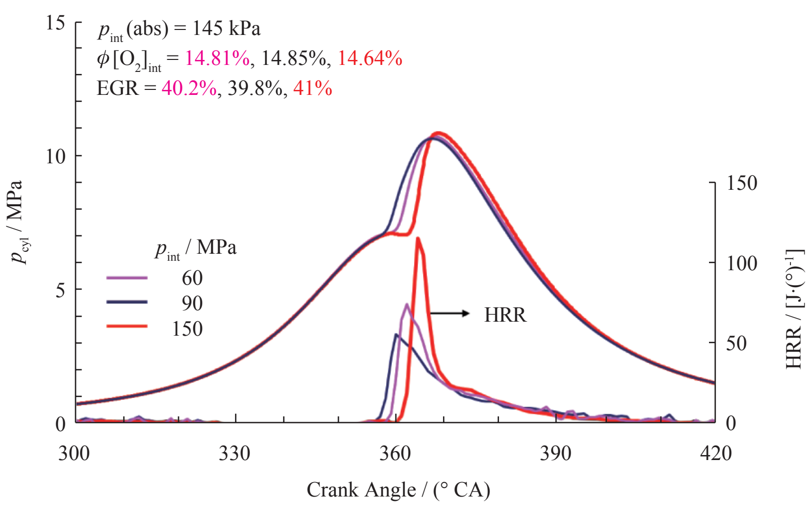

Figure 10 Pressure and HRR Traces at Different Injection Pressure Levels

CONCLUSIONS

Extensive bench mark engine tests for evaluating the effects of boost and injection pressure under the EGR enabled diesel LTC cycles have been carried out. The main findings of this experimental program can be summarized as follows:

1) An engine load of 800 kPa IMEP was achieved for an EGR enabled diesel LTC, with the precise control of the boost and injection pressure.

2) EGR was the most effective technique for lowering the cylinder temperature, and in turn, reducing NO_x emissions,

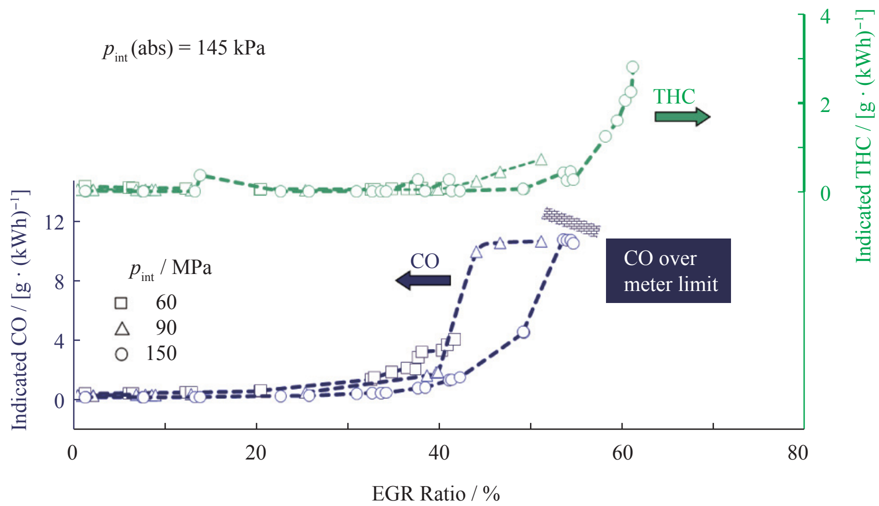

Figure 11 CO and THC Emissions at Different Levels of Injection Pressure

because of the mixture dilution effect and higher heat capacity.

3) Boost and injection pressure were less effective on NO_x emission reduction, and had little measureable effect at low levels of EGR.

4) Increases in either of the two parameters, boost and injector pressure, was found to improve the soot, CO and THC emissions and hence allowed the limits of the EGR enabled LTC mode cycles operation of the diesel engine to be extended.

ACKNOWLEDGMENTS

The research at the Clean Diesel Engine Centre Laboratory is sponsored by the Canada Research Chair program, NSERC, CFI, OIT, AUTO21, the University of Windsor, Ford Motor Company and other OEMs.

REFERENCES

[1] Asad U, Zheng M, Han X, Reader G T, Wang M. Fuel injection strategies to improve emissions and efficiency of high compression ratio diesel engines [J]. SAE Trans Journal of Engines, 2008, **17** (3): 1220-1233. Paper 2008-01-2472.

[2] Zhao F, Asumus T, Assanis D, et al. Homogeneous Charge Compression Ignition (HCCI) Engines [M]. SAE International, Key Research and Development Issues SP-94, 2003, ISBN: 978-0-7680-1123-4.

[3] Nishizawa I, Sugihara T, Sato N, Iijima T, Yoshida T. Full-load HCCI operation with variable valve actuation system in a heavy-duty diesel engine [R]. SAE Paper, 2007-01-0215.

[4] Zheng M, Reader G T, Hawley J G. Diesel engine exhaust gas recirculation: A review on advanced and novel concepts [J]. Energy Conversion and Management, 2004, **45**(6):883-900.

[5] Alriksson M, Rente T, Denbratt I. Low Soot, Low NOx in a heavy duty diesel using high levels of EGR [R]. SAE Paper, 2005-01-3836.

[6] Akihama K, Takatori Y, Inagaki K, Sasaki S, Dean A M. Mechanism of the smokeless rich diesel combustion by reducing temperature [R]. SAE Paper 2001-01-0655.

[7] Kimura S, Aoki O, Ogawa H, Muranaka S. Nissan Motor Co., Ltd. Yoshiteru Enomoto Musashi Institute of Technology. New combustion concept for ultra-clean and high-efficiency small DI diesel engines [R]. SAE Paper, 1999-01-3681.

[8] Kimura S, Aoki O, Ogawa H, Muranaka S, Enomoto Y. New combustion concept for ultra-clean and high-efficiency small DI diesel engines [R]. SAE Paper, 1999-01-3681.

[9] Kimura S, Ogawa H, Matusi M, Enomoto Y. An experimental analysis of low temperature and premixed combustion for simultaneous reduction of NO_x and Particulate emissions in direct injection diesel engines [J]. Int J Engine Research, 2002, **3**(4): 249-259.

[10] Kimura S, Aoki O, Kitahara Y, Aiyoshizawa E. Ultra-clean combustion technology combining a low-temperature and premixed combustion concept for meeting future emission standards [R]. SAE Paper, 2001-01-0200.

[11] Asad U, Zheng M. Efficacy of EGR and boost in single-injection enabled low temperature combustion [R]. SAE Paper, 2009-01-1126, 2009.

[12] Idicheria C A, Pickett L M, Soot formation in diesel combustion under high-EGR conditions [R]. SAE Paper 2005-01-3834.

[13] Pickett L M, Siebers D L. Non-Sooting, Low flame temperature mixing-controlled DI diesel combustion [R]. SAE Paper, 2004-01-1399.

[14] Helmantel A, Denbratt I. HCCI operation of a passenger car common-rail DI diesel engine with early injection of conventional diesel fuel [R]. SAE Paper 2004-01-0935.

[15] Zheng M, Reader G T, Kumar R, Mulenga C, Asad U, Tan

Y, Wang M. Adaptive control to improve low temperature diesel engine combustion [C]// 12th Diesel Engine-Efficiency and Emission Reduction Conference (DEER), 2006.

[16] Olsson J O, Tunestal P, Johansson B. Boosting for high load HCCI [R]. SAE Paper, 2004-01-0940.

[17] Kodama Y, Nishizawa I, Sugihara T, Sato N, Iijima T, Yoshida T. Full-load HCCI operation with variable valve actuation system in a heavy-duty diesel engine [R]. SAE Paper, 2007-01-0215.

[18] Ogawa H, Miyamoto N, Shimizu H, Kido S. Characteristics of diesel combustion in low oxygen mixtures with ultra-high EGR [R]. SAE Paper, 2006-01-1147.

[19] Asad U, Zheng M. EGR oxidation and catalytic fuel reforming for diesel engines [R]. SAE Paper, ICES 2008-1684.

[20] Han X, Asad U, Kumar R, Mulenga M C, Banerjee S, Wang M, Reader G T, Zheng M. Empirical studies of the diesel low temperature combustion on a modern diesel engine [C]// Combustion Institute/Canadian Section, 2007 Spring Technical Meeting, 2007.

[21] Heywood J B. Internal combustion engine fundamentals [M]. 1988, New York: McGraw-Hill.

[22] Benson R S, Whitehouse N D. Internal combustion engines [M]. 1979, Oxford: Pergamon Press.

[23] Kook S, Bae C, Miles P C, Choi D , Pickett L M. The influence of charge dilution and injection timing on low-temperature diesel combustion and emissions [R]. SAE Paper, 2005-01-3837.

[24] Zheng M, Tan Y, Mulenga M C, Wang M. Thermal efficiency analyses of diesel low temperature combustion cycles [J]. SAE Trans Journal of Fuel & Lubricants, 2007, **116**(3): 1292-1302. SAE 2007-01-4019.

[25] Zheng M, Asad U, Reader G T, Tan Y, Wang M. Energy efficiency improvements for a diesel engine in low temperature combustion [J]. Intl J Energy Research, 2009, **33**: 8-28.

[26] Asad U. Advanced diagnostics, control and testing of diesel low temperature combustion [D]. Windsor: University of Windsor, 2009.

[27] Asad U, Zheng M. fast heat release characterization of a diesel engine [J]. Intl J Thermal Sciences, 2008，**47**(12): 1688-1700.

[28] Zheng M, Reader G T. Energy efficiency analyses of active flow aftertreatment systems for lean burn internal combustion engines [J]. Energy Conversion and Management, 2004, **45**(15/16): 2473-2493.

NOMENCLATURE

BTDC	Before Top Dead Centre
CA50	Crank Angle of 50% Heat Released
DI	Direct Injection
EGR	Exhaust Gas Recirculation
HCCI	Homogeneous Charge Compression Ignition
HTC	High Temperature Combustion
HRR	Heat Release Rate
IMEP	Indicated Mean Effective Pressure
LTC	Low Temperature Combustion
PM	Particulate Matter
SOI	Start Of Injection
TDC	Top Dead Centre
p_{inj}	Pressure of Injection
p_{int}	Pressure of Intake
T_{mean}	Mean Cylinder Temperature