Research on the Effect of ETCI Based HCCI Technology in the Best Fuel Area

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Abstract: Exhaust check point injection compression ignition (ETCİ), the trapped promote internal thermal residues high temperature high pressure jet fuel mixture is one of the most effective methods to achieve homogeneous charge compression ignition (HCCI). This paper is based on the ETCİ combustion mode to study the effect of timing heating of the exhaust valve and the cooling effect of the pressure on the combustion process.. Results show that the best fuel economy can start injection of Ca BTDC at 1500r/min, the exhaust valve timing on combustion properties are strongly influenced by the 370, Shan'xi. Using the residual gas coefficient of the exhaust valve timing control, the combustion stage can be controlled indirectly by the intake temperature of the cylinder. In addition, constant pressure, inlet pressure increasing can increase the excess air coefficient decrease the mixture of average air temperature, which can also be control as the key parameters of the combustion phase in some areas. Therefore, the reasonable cooperation between the exhaust valve timing and the pressure pressure can effectively control the combustion process and emission minimization. At 1500r / min, 30 (calcium negative valve overlap (NVO) and 0.18 MPa pressure, the limit of low load and high load limit of HCCI combustion can be reached 0.27 MPa and 0.723 MPa, respectively.

Keywords: Diesel engine, HCCI, load extension, NVO, supercharging.

1. INTRODUCTION

It has been proved that homogeneous charge compression ignition (HCCI) has a great potential for reducing NOx and PM emissions while providing high thermal efficiency [1-3]. However, HCCI engines still encounter many difficulties such as it being easy to misfire at low loads and difficult to form a premixedhomogeneous charge, control the combustion phase, andoperate at high loads. [4-6]. Therefore, determining how to solve these technical problems has been the research focus in the practical application of HCCI engines [7, 8].

The negative valve overlap (NVO), which is achieved by the early closing of the exhaust valve and the late opening of the inlet valve, can be used to change the amount and temperature of the exhaust gas in the cylinder [9].

To date, most of the studies on the NVO have focused on gasoline engines. The combined effects of boosting, intake air temperature, trapped residual gas fraction, and dilution on the maximum pressure rise rate (MPRR) was investigated in a boosted single cylinder gasoline HCCI engine with combustion controlled by negative valve overlap [10]. Weall *et al.* enabled the lowest load point of 160 kPa indicated mean effective pressure (IMEP) using a valve deactivation strategy, making it more compatible for production-intent platforms [11]. Hunicz *et al.* achieved better performance of combustion using the NVO and split injection in a CAI gasoline engine [12, 13].

Because diesel fuel is more difficult to vaporize, the NVO can be applied to diesel HCCI engines [14]. The stronger turbulence intensity and higher temperature homogeneity with higher NVO improve fuel vaporization and air-fuel mixing.

However, only a few researchers have focused on the NVO technique on diesel engines. A three-dimensional simulation was applied to investigate the effects of negative valve overlap on the gas exchange processes and mixture and temperature distributions in a diesel HCCI engine with early in-cylinder injection [15]. The result indicated that enlarged NVO not only increased the in-cylinder temperature but also improved the temperature homogeneity.

A previous study demonstrated that the technique of exhaust top dead center injection compression ignition (ETCI) is one of the most effective methods to realize HCCI combustion [14]. This method uses high temperature residuals produced by NVO to help vaporize diesel fuel and promote mixing. A large amount of high temperature gas could reduce fuel wall wetting but cause an over advanced combustion phase and an over rapid burn rate, and the operation is limited at low loads.

In order to overcome the limitation of the operating range of the diesel HCCI, the air pressure method is increased.. Thus, a wider range of operation is achieved compared with the natural inspiratory condition because the relatively complete combustion occurs because more air is utilized under these conditions [16]. In addition, the increase in the intake pressure of hydrocarbons and carbon monoxide emissions due to higher oxygen rate. Han *et al.* The operating range of LTC is in performance and exhaust gas emissions.. The operating range of cryogenic diesel combustion increases with

the intake pressure and the higher injection pressure promotes the expansion. In addition, the exhaust gas emissions include hydrocarbon, carbon monoxide, soot emissions and natural air suction conditions compared to lower the low-temperature combustion.

In this study, the authors extended the load range of a diesel HCCI engine by combining the control strategy of variable exhaust valve timing with inlet boosting and researched the effects of NVO and supercharging on combustion performance, load range, and emissions.

2. EXPERIMENTAL SETUP

The experiment was performed on a naturally aspirated, single-cylinder 135 diesel engine. Table **1** lists the basic parameters of the engine. To achieve better injection strategies, a common-rail fuel injection system whose maximum injection pressure could be raised as high as 160 MPa was attached. In addition, the engine was equipped with a simulated supercharging system whose maximum boost pressure could reach 0.8 MPa and a VVT mechanism which could realize inlet and exhaust valve regulation by 40 °CA. As HCCI combustion is sensitive to the temperature of cooling water, the experiment controlled the lubricating oil temperature at 70±1°C and cooling water temperature at 80±1°C using an oil and water temperature control system.

Table 1.   Parameters of the test engine.

Engine base type	Direct-injection, single-cylinder
Cycle	4 stroke
Number of valves	4
Bore / mm	135
Stroke / mm	150
Displacement volume / cm3	2147
Compression ratio	14.8:1
Nozzle design	Φ0.20 mm×7holes,
Spray included angle	150 °
Boost control	External Simulated boosting
Valve timing	Variable (manually)

Fig. (**1**) presents a schematic of the experimental setup for the single cylinder diesel engine. The engine was coupled to a DC dynamometer, which could keep the engine operating at a set speed. The cylinder was fitted with a Kistler6125B piezoelectric pressure transducer and the output signals were amplified with a Kistler5011.AVLDiGas 4000 gas analyzer. In addition, an AVL439opacimeterwas used for the exhaust emission measurements.

Fig. (**2**) illustrates the simple structure of our VVT system. The valve timing was adjusted by changing the axial distance between bevel wheel1 and bevel wheel 2.The timing of the inlet and exhaust valves was set manually. As the distance was limited by the mechanism structure, the operation

range of valve timing varied from 0 to 40° CA. In the research, the exhaust valve timing was defined by the exhaust valve closure (EVC).

A simulated supercharging system was adopted in the research. The intake boost pressure was controlled by a valve before a surge tank, and the exhaust pressure was uncontrolled. Compressed air was produced by an air compressor which could provide at most 0.8 MPa (gauge) pressure. The inlet pressure could be adjusted from 0 to 0.3 MPa (gauge).

The fuel was injected into the cylinder in the NVO period. By closing the exhaust valve early and opening the inlet valve late, the residual gas in the cylinder heated the mixture to promote the vaporization of the diesel.

In the experiment, the engine speed was fixed at 1500r/min, and the common rail pressure was 80 MPa. For HCCI combustion, we first optimized the injection timing and then researched the effect of various levels of NVO and boost pressure on the load extension and emission characteristic of HCCI combustion under the fixed optimum injection timing. Because the exhaust pressure was not adjusted, we used the gross indicated mean effective pressure ($IMEP_g$) as the comparison parameter for the engine load to eliminate the effect of simulated supercharging on the pumping power.

Considering $IMEP_g$,ISFC and emissions, 370 ºCA BTDC was confirmed as the optimal start of injection timing for HCCI in the following experiments.

3. EXPERIMENTALRESULTS AND DISCUSSION

3.1. Effects of EVC and Supercharging on Internal Exhaust Gas Recycling (IEGR) and Tivc

The engine speed was maintained at 1500 r/min, the fuel injection pressure was maintained at 80 MPa, the injection fuel quantity per-cycle was maintained at 0.0585 g, and IVO was maintained at 380 ° CA ATDC. The boost pressure was adjusted in steps of 0.02 MPa.

3.1.1. Effects of EVC and Supercharging on IEGR

Fig. (**3**) shows the effects of EVC and boost pressure(gauge) on the residual gas fraction (RGF) and the excess air ratio α. When the boost pressure was maintained at 0 MPa and EVC varied from 350 ° CA ATDC to 330 ° CA ATDC, the RGF increased from 5.88% to 13.27%. EVC had a significant effect on the RGF. Increasing the boost pressure caused the in-cylinder fresh charge to increase rapidly; however, the exhaust back pressure was kept constant, and the total mass of residuals did not change distinctly; thus, the RGF was slightly reduced. When EVC was maintained at 330 ° CA ATDC and the boost pressure was adjusted from 0 MPa to 0.08 MPa, the RGF decreased from 13.27% to 10.89%. Thus, it could be observed that EVC had a greater effect on the RGF than the boost pressure.

The injection fuel quantity was kept constant, and the excess air ratio α was mainly determined by the amount of in-cylinder fresh charge. When EVC was maintained at 350 ° CA ATDC, α was the largest at a constant boost pressure. By advancing EVC from 350 ° CA ATDC to 330 ° CA ATDC, α gradually decreased from 3.081 to 2.461 when the boost
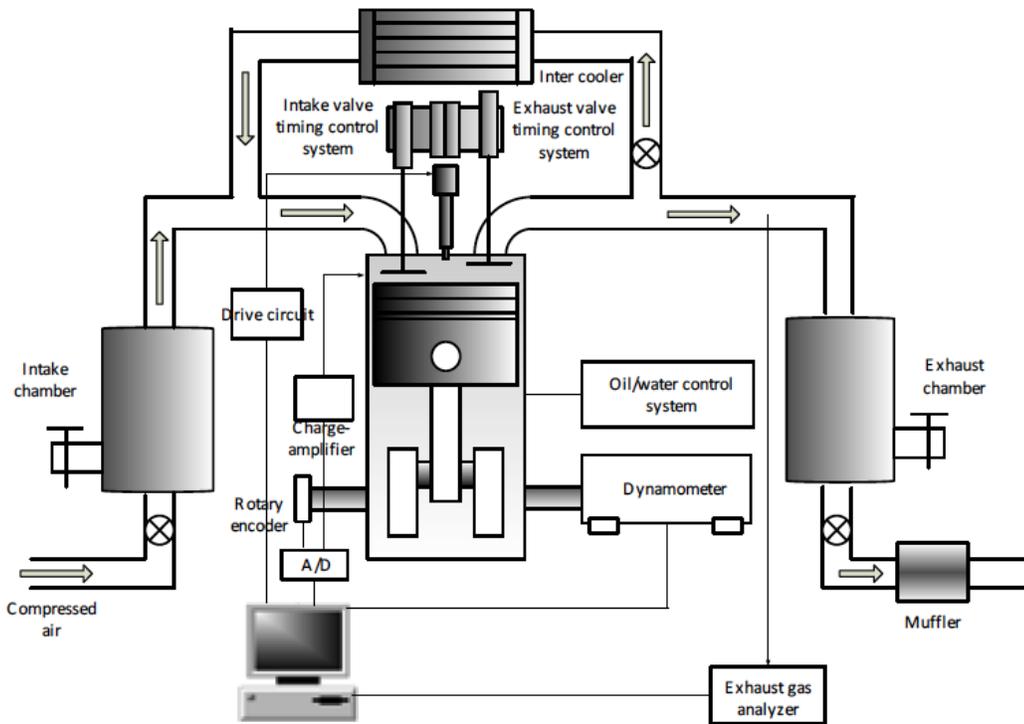
Fig. (1). Schematic diagram of the test system.
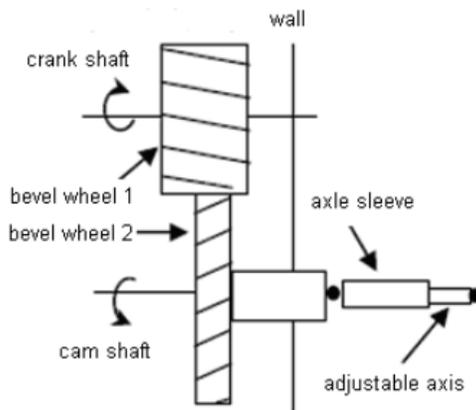
Fig. (2). VVT system.
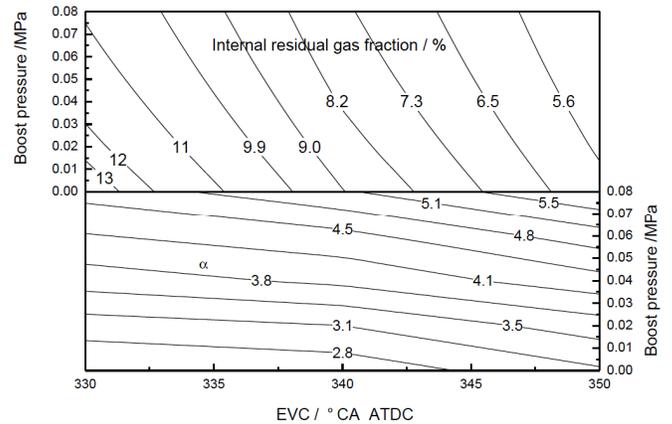
Fig. (3). Effects of EVC and boost pressure (gauge) on IEGR.

pressure was 0 MPa because the amount of trapped residuals increased when the fresh charge amount decreased. A higher boost pressure increased the density of intake air and the total mass of charge in the cylinder. There was a wide variation of α over the range of boost pressure. α reached the maximum value of 5.814 at the highest boost pressure. The effect of the boost pressure on α is larger than that of EVC on α.

3.1.2. Effects of EVC and Supercharging on Tivc

T_{ivc}(the mean intake temperature at the IVC moment) is one of the most important factors for HCCI combustion characteristics. Because of the existence of NVO, internal residuals were trapped in the cylinder. High temperature residuals heated cool fresh charge, and the volume efficiency decreased. As EVC advanced, the amount of residual gases increased. More residual gases heated more fresh charge, and

the mean temperature of mixing charge increased. Supercharging caused more fresh charge to enter the cylinder. However, EVC was kept constant and the amount of residuals varied little; thus, the percent of cool charge increased, and T_{ivc} declined.

Fig. **(4)** illustrates the effects of EVC and boost pressure(gauge) on T_{ivc}. T_{ivc} is mainly controlled by EVCtiming; however, the boost pressure also has a smaller effect on this parameter. Especially at advanced EVC, the temperature of residuals is higher than retarded EVC, and the cooling effect of boosting is more distinct. When EVC was at 350 ° CA ATDC, there was little difference in the temperature between the internal residuals and the fresh charge; thus, increasing the boost pressure almost had no effect on the mean temperature of the mixtures.
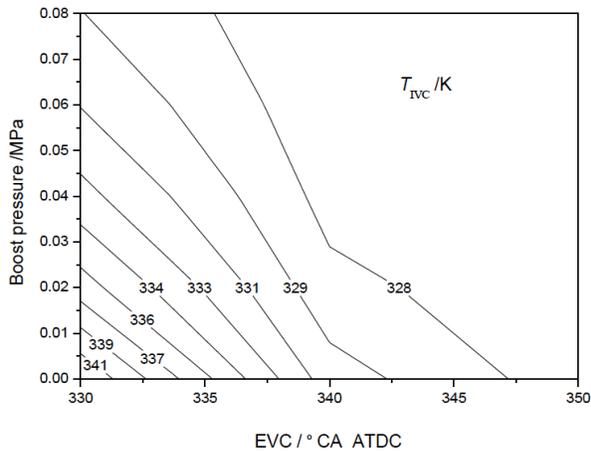
Fig. (4). Effects of EVC and boost pressure (gauge) on T_{ivc}.

3.2. Effects of EVC and Supercharging on the Combustion Parameters

3.2.1. Effect of Supercharging on the Combustion Pressure and Heat Release Rate

Compared with the boost pressure, EVC has a more distinct effect on the combustion phase. As observed in Fig. (**5**),

retarding EVC can retard the start of combustion and decrease the heat release rate at different boost pressures because EVC determines the amount of internal residuals, which affects T_{ivc} and α.

More importantly, over retarded EVC can only trap a few high-temperature residuals, which cannot supply enough thermal energy to vaporize diesel fuel. As Fig. (**5**) illustrates, the peak cylinder pressure at EVC=350 ° CA ATDC is much lower than that at EVC=330 ° CA ATDC at different boost pressures because of the sharp increase in fuel wall wetting.

3.2.2. Effect of EVC on the Combustion Pressure and Heat Release Rate

Fig. (**6**) plots the cylinder pressure and heat release rate as a function of the boost pressure(gauge) for three different EVC conditions. The cylinder pressure rapidly increased with the increase in boost pressure due to the increase in fresh charge. The combustion phase was retarded, and the heat release rate clearly decreased due to the effect of boosting on the excess air ratio and mean intake air temperature. A higher excess air ratio makes the mixture leaner, and the increasing cool charge decreases the mean temperature of the mixture, which both have the advantages of retarding the start of combustion and reducing the peak of the heat release rate.

a) boost pressure = 0 MPa

b) boost pressure = 0.04 MPa

c) boost pressure = 0.08 MPa
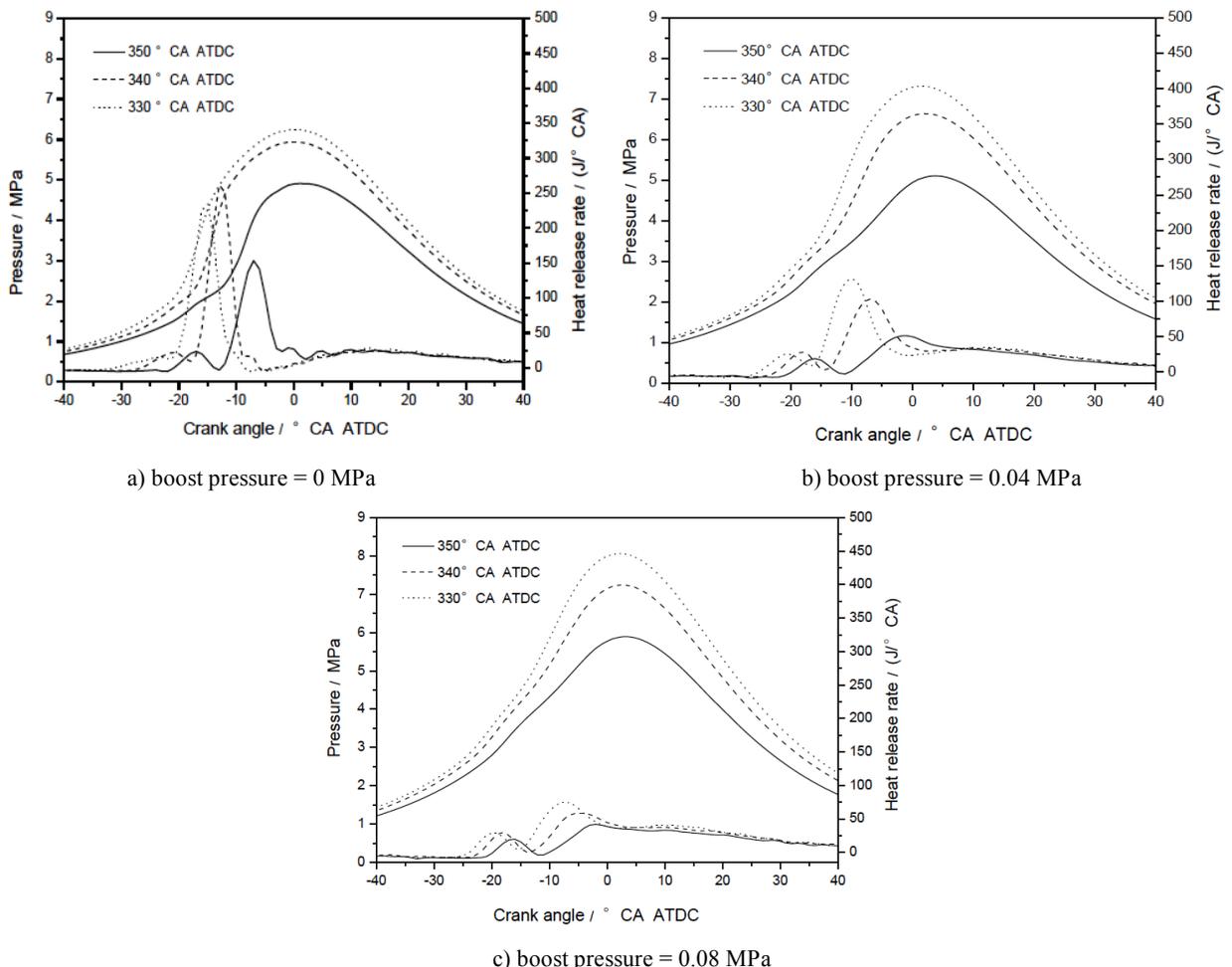
Fig. (5). Effects of EVC on cylinder pressure and heat release rate at various boost pressures (gauge).

a) EVC=350°CA ATDC

b) EVC=340°CA ATDC

c) EVC=330°CA ATDC
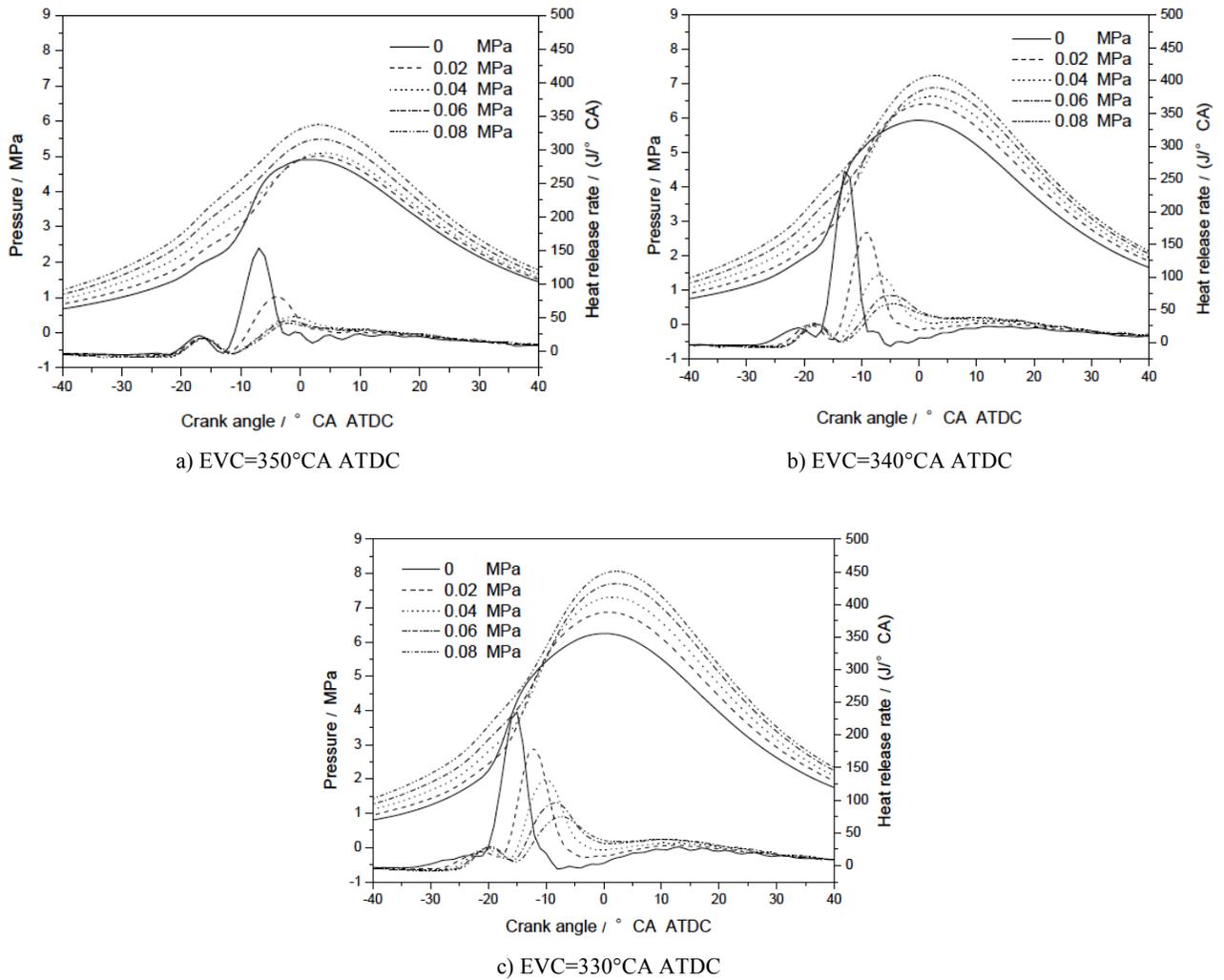
Fig. (6). Effects of boost pressure (gauge) on cylinder pressure and heat release rate at various EVCs.

By changing the engine exhaust valve timing, a manageable quantity of internal residuals can be trapped in the cylinder. By tuning the quantity of residuals, the ignition delay and heat release rate of HCCI combustion can be adjusted. The main effect of residual gas on the HCCI combustion phase is thermal, which can advance the start of combustion.

3.2.3. Effects of EVC and Supercharging on IMEPg and SOC

Fig. (7) shows the effects of exhaust valve timing and boost pressure (gauge) on $IMEP_g$ and the start of combustion (SOC) (defined as the crank angle degree of cumulative HRR reaching 5%). It can be observed that $IMEP_g$ of the EVC at 350 ° CA ATDC decreased as the boost pressure increased, and $IMEP_g$ both of EVC at 340 ° CA ATDC and 330 ° CA ATDC increased at first and then decreased. Overall, $IMEP_g$ of the EVC at 350 ° CA ATDC was lower than that of EVC at 340 ° CA and 330 ° CA ATDC because the low RGF at EVC of 350 ° CA ATDC resulted in a low cylinder pressure. In addition, the fuel injected in the NVO period could not evaporate rapidly; thus, a large amount of fuel impingement occurred. The impingement resulted in a sharp decrease in the combustion efficiency. Increasing the boost pressure delayed the combustion phase and increased the combustion pressure but

also decreased the combustion temperature. If the boost pressure was larger than the pressure corresponding to the maximum $IMEP_g$, $IMEP_g$ decreased as the boost pressure increased and decreased as the boost pressure decreased. Advancing EVC resulted in a more advanced combustion phase and was harmful for extending the engine load.
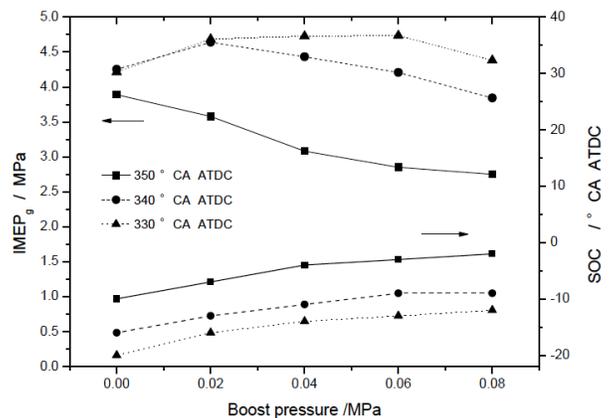
Fig. (7). Effects of EVC and boost pressure (gauge) on $IMEP_g$ and SOC.

3.2.4. Effects of NVO and Supercharging on the Maximum Pressure Rising Rate

Fig. (**8**) shows the effects of NVO and supercharging on the maximum pressure rising rate. The results indicated that the maximum pressure rising rate increased gradually as EVC advanced and decreased gradually as the boost pressure increased. Because advancing the EVC degree advanced the combustion phase such that more fuel was combusted in a short time, the result was an increase in the maximum pressure rising rate. However, the increase in the boost pressure diluted the mixture such that the combustion became smooth and the peak of HRR decreased, which was beneficial for decreasing the maximum pressure rising rate.
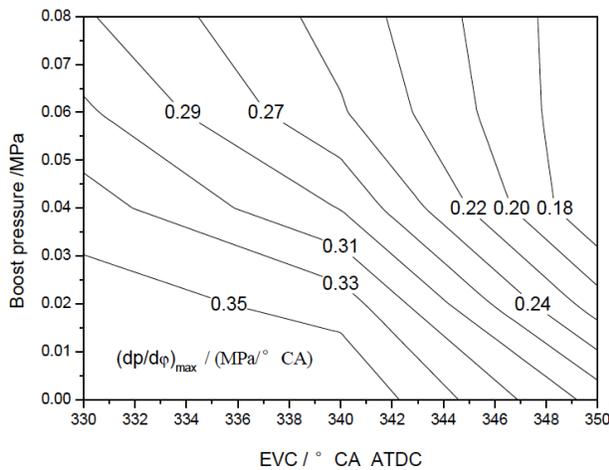
Fig. (8). Effects of EVC and boost pressure (gauge) on $dp/d\varphi_{max}$.

3.3. Research on Load Extension of HCCI Combustion

3.3.1. Effect of NVO Duration on Load and Emissions of HCCI Combustion

The high exhaust temperature produced by internal EGR can promote fuel evaporation and reduce fuel impingement; in addition, more internal EGR can also advance the start of combustion and lead to a higher cylinder pressure and pressure rising rate. Increasing the NVO duration caused more residuals to remain in the cylinder and enhanced the internal EGR. Therefore, in the research, the authors selected three different NVO durations of 20 ° CA, 30 ° CA and 40 ° CA to study the effects of NVO duration on internal EGR.

Fig. (**9**) (a) demonstrates how IMEP$_g$ and ISFC are affected by the excess air ratio. The excess air ratio decreased from 3.32 to 2.82, and IMEP$_g$ increased from 0.324 MPa to 0.428 MPa when NVO was 20 ° CA. ISFC reached a minimum value of 223.3 g/kWh when the excess air ratio was 2.82. Continuing to decrease the excess air ratio by increasing the fuel injection quantity after the minimum value caused the load to begin to decrease; the load range was approximately 0.104 MPa. At a high load, a low internal EGR rate was not sufficient to evaporate all the injected fuel, and further increasing the fuel injection quantity caused an increase in fuel impingement and a decrease in the combustion rate. When the NVO was 30 ° CA, the decrease in excess air ratio caused IMEP$_g$ to increase gradually from 0.287 MPa to 0.445 MPa. Meanwhile the load range changed by 0.158

MPa, which represented an increase of 0.054 MPa compared with 20 ° CA NVO. The ISFC decreased to the minimum value of 205.8 g/kWh and then began to increase slightly as the excess air ratio decreased. When the NVO was 40 ° CA, more internal EGR helped evaporate more fuel, and promoted fuel and air mixing. Meanwhile IMEP$_g$ could reach the maximum value of 0.484 MPa. In comparison, the smallest load range occurred at 20 ° CA NVO, the lowest low limit of the load range occurred at 30 ° CA NVO and the highest high limit of the load range occurred at 40 ° CA NVO. However, as observed from 40 ° CA NVO, the NOx emission would increase sharply. Therefore, a gap of load remained between the HCCI combustion mode achieved using internal EGR and the traditional compression ignition mode, and the load range needs to be further extended using supercharging.
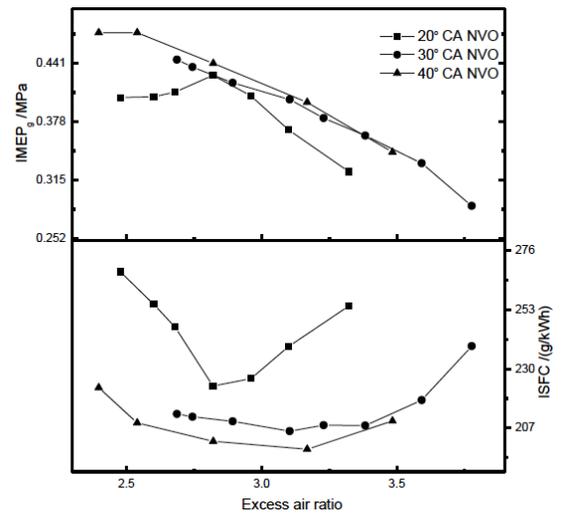
Fig. (9). (a) Effect of α on IMEP$_g$ and ISFC of HCCI Combustion at Various NVOs.
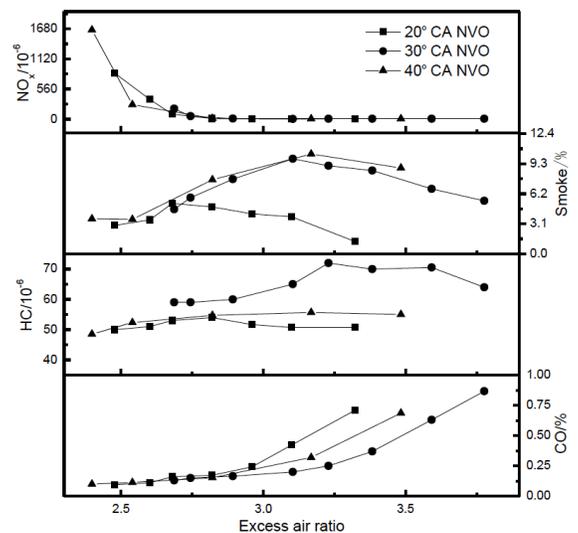
Fig. (9). (b) Effect of α on emissions of HCCI combustion for various NVOs.

Fig. (**9**) (b) shows the effect of the excess air ratio on emissions of HCCI combustion at various NVOs. The excess

air ratio apparently affects the NOx emission of HCCI combustion because increasing the excess air ratio decreases the combustion temperature, which directly affects NOx generation. In the range that the excess air ratio changed from 2.5 to 2.8, the NOx emission decreased sharply; however, there was no obvious change of NOx emission after the excess air ratio exceeded 2.8, and the NOx emission value was less than 20×10^{-6}. When the excess air ratio was large, there was less fuel impingement and fuel and air mixing was sufficient; thus, the smoke emission was low. As the fuel injection per cycle increased, the excess air ratio decreased, and there was more fuel impingement; thus, the smoke emission was high. However, when we continued to increase the fuel injection, the increase of the combustion temperature benefitted the oxidation of smoke to reduce the smoke emission. Therefore, the change of smoke emission exhibited a trend that it increased at first and then decreased. There was no obvious change trend for HC emission; however, we observe that the HC emission at 30 ° CA NVO was higher overall than that at 20 ° CA and 40 ° CA NVO. The CO emission increased with increasing excess air ratio because too low of a combustion temperature limited the further oxidation of CO.

3.3.2. Effect of Boost Pressure on Load and Emission of HCCI Combustion

To further extend the load range of a diesel HCCI engine, the authors researched the effect of supercharging on the load and emissions by selecting three different intake pressures, 0.13 MPa, 0.16 MPa and 0.18 MPa, at 30 ° CA NVO. Fig. (**10a**) shows the effect of the excess air ratio on the load and emissions at various boost pressures. At the boost pressure of 0.13 MPa, the low limit and high limit of load were 0.469 MPa and 0.601 MPa, respectively, both of which increased compared with the values without supercharging. When the boost pressure increased to 0.16 MPa, there was an obvious improvement in the load range. As the low load limit decreased to 0.378 MPa and the high load limit increased to 0.675 MPa, the load range was as high as 0.297 MPa. Upon further increasing the boost pressure to 0.18 MPa, the low load limit further decreased to 0.27 MPa and the high load limit further increased to 0.723 MPa; the load range was as high as 0.453 MPa.

Fig. (**10b**) presents the emission results at various boost pressures. When the excess air ratio exceeded 3, there was no obvious change in NOx emissions, and the value was less than 20×10^{-6}. The trend of smoke emissions continued to increase at first and then decreased as the excess air ratio decreased. However, with a continuous increase in the excess air ratio, the mixture was gradually diluted, the combustion temperature decreased and the combustion deteriorated; thus, both the HC and CO emissions increased.

3.3.3. The Limit of Load Extension of HCCI

The load extension of HCCI combustion is mainly limited by the maximum combustion pressure, maximum pressure rising rate and cycle-to-cycle variation of $IMEP_g$. The low load limit is determined by cycle-to-cycle variations of the load (COV of $IMEP_g$ less than 8%); the high load limit is determined by the maximum combustion pressure Pmax (less than 15 MPa) and the maximum pressure rising rate $(dp/d\varphi)_{max}$ (less than 0.6 MPa/ ° CA).
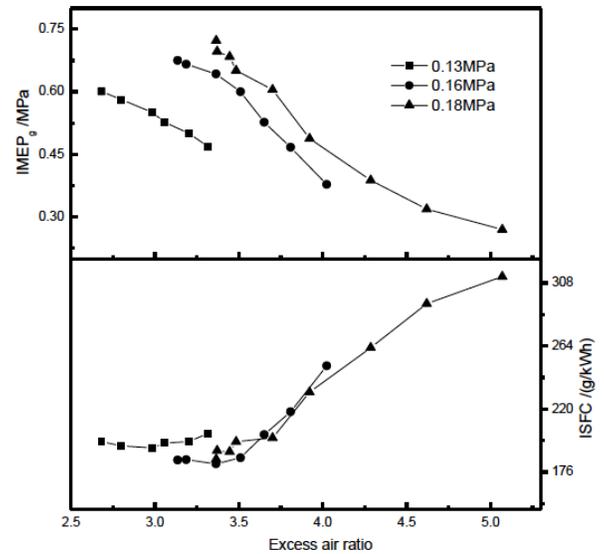
Fig. (10). (a) Effect of α on $IMEP_g$ and ISFC of HCCI combustion at various boost pressures.
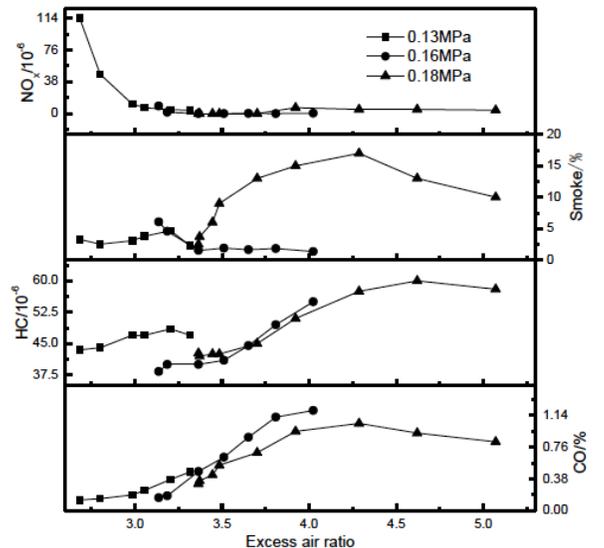
Fig. (10). (b) Effect of α on HCCI emission at various boost pressures.

Fig. (**11**) shows the effect of the excess air ratio on the load extension limit under various NVOs. Pmax and $(dp/d\varphi)_{max}$ had a linear relationship with the excess air ratio, and both of these parameters reached their maximum values when the excess air ratio was the lowest. With an increasing amount of dilution mixing gas, it is easier to misfire and more unstable for combustion; thus, COV increased with the increase in the excess air ratio. Under a low excess air ratio, the effect of NVO on the load extension limit was not obvious.

Fig. (**12**) shows variations of the load range limit with the change of excess air ratio at various boost pressures. Upon increasing the boost pressure, Pmax increased obviously. At a boost pressure of 0.18 MPa, the excess air ratio varied from 3.36 to 5.07, which was the widest range, and misfire occurred when the excess air ratio exceeded the maximum

value of 5.07.Under the lowest excess ratio, Pmax could reach 10.02 MPa, and no clear increase in $(dp/d\varphi)_{max}$ was apparent with the highest value of 0.579 MPa/ º CA. At the boost pressure of 0.13 MPa, the excess air ratio varied from 2.68 to 3.32, which was the narrowest range, and misfire occurred similarly when the excess air ratio exceeded the maximum value of 3.32. Pmax could only reach 8.25 MPa; however, $(dp/d\varphi)_{max}$ was at the highest level, approximately 0.631 MPa/ º CA. Compared with the two different boost pressures, it can be observed that the misfire range of the excess air ratio increased with an increase in the boost pressure.
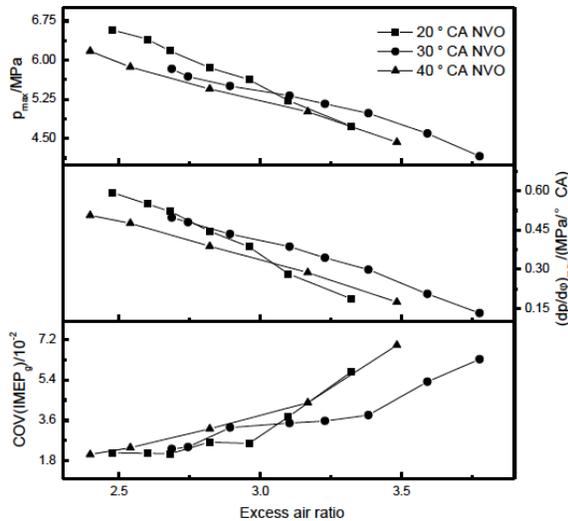
Fig. (11). Effect of excess air ratioon HCCI Limit at various NVOs.
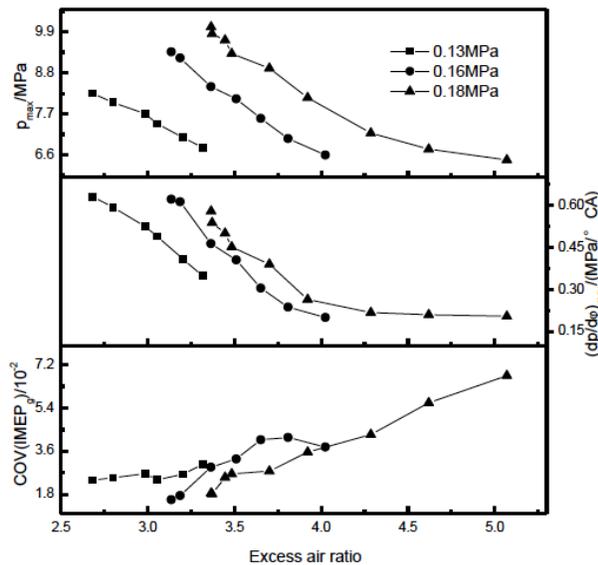
Fig. (12). Effect of excess air ratioon HCCI limit at various boost pressures.

CONCLUSION

The following conclusions were drawn from the experimental results.

At 1500r/min in the HCCI combustion mode, the engine can achieve optimum fuel economy when the start of injection is at 370 º CA BTDC. For constant fuel injection per cycle, the maximum combustion pressure increases, the peak of HRR increases and the combustion phase advances as the NVO duration increases. As the intake pressure increases, the maximum combustion pressure decreases, the peak of HRR decreases and the combustion phase is postponed when the NVO duration increases for constant fuel injection per cycle.

A reasonable internal EGR strategy can extend the load range of HCCI combustion. A large NVO or internal EGR can promote fuel evaporation but also leads to a high combustion temperature, which is harmful to NOx emission. If the NVO or internal EGR is small, serious fuel impingement occurs at a high load. Therefore, selecting 30 º CA NVO for the research was reasonable.

The load extension is mainly limited by the maximum combustion pressure, maximum pressure rising rate and cycle-to-cycle variation of $IMEP_g$. These parameters are all relevant to the excess air ratio. As the excess air ratio decreases, the maximum combustion pressure and maximum pressure rising rate increase. As the excess air ratio increases, the cycle-to-cycle variation of $IMEP_g$ increases and the engine becomes easier to misfire. In the research on load extension realized by combining internal EGR with supercharging, the high load limit depends on the maximum pressure rising rate, and the low load limit depends on the cycle-to-cycle variation of $IMEP_g$.

Supercharging can extend the high load limit of HCCI combustion and enhance combustion stability at low loads. At 1500r/min, 30 º CA NVO, and 0.18 MPa boost pressure, the low load limit and high load limit of HCCI combustion reached 0.27 MPa and 0.723 MPa, respectively.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

ACKNOWLEDGEMENTS

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