Numerical investigation of Miller cycle with EIVC and LIVC on a high compression ratio gasoline engine

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Abstract
Previous studies have shown that increase compression ratio (CR) is an effective way to improve thermal efficiency of gasoline engine without changing the mechanical structure and working cycle, however, it is limited by engine knock when increasing the intake boosting under high load operation. This study aimed to solve the knock problem of gasoline engine with higher CR by application of Miller cycle, which can be implemented by either early or late intake valve closing (EIVC or LIVC). Therefore, in this paper, based on the engine with CR of 13.5 and electromagnetic valves train (EMVT), a comparative study was carried out to investigate the effects of EIVC and LIVC on engine performance, by theoretical modeling and calculation. The results show that, at high load, EIVC strategy is more preferred than LIVC owing to its lower total power consumption, which can improve the indicated mean effective pressure (IMEP) by 0.0371 bar, while enhance turbulence intensity and improve combustion. And at part load, the advantage for EIVC declines gradually, nevertheless, it can still sensitively adjust the EGR rate and thus reduce NOx. This results of quantitative analysis about two Miller cycles can provide valuable reference for engine designers and researchers.

Keywords
Engine knock, Miller cycle, turbulence intensity, early intake valve closing, late intake valve closing

Introduction
Emissions legislation and energy-saving targets are driving engine manufacturers to develop novel methods to improve the fuel economy of engine.¹ New energy vehicle
is an important development trend of the automotive industry. However, in the current transition period, it is more practical to develop highly efficient internal combustion engines for hybrid electric vehicles.\(^2\)

It can lead to heat loss and pumping loss with the gasoline engine load downsizing, which is unbenefficial to the improvement of engine thermal efficiency. However, the engine knock will be aggregated under of high load condition. At present, the compression ratio of gasoline engine is far lower than that of diesel engine. It shows that each unit increase in compression ratio will lead to 2% increase of thermal efficiency.\(^3\)

An engine with over-expansion cycle (Atkinson or Miller) is the most suitable for hybrid vehicles because of the higher thermal efficiency.\(^4\) Compared with a conventional Otto cycle engine, an over-expansion cycle engine has shorter compression stroke, which can limit the working gas density in the cylinder during the compression to avoid engine knock, thus achieving higher thermal efficiency. Miller cycle can be implemented more easily via LIVC or EIVC based on a conventional engine. Therefore, it is an effective technical to improve engine thermal efficiency by designing engine with high compression ratio, and then applying Miller cycle via valve strategies.\(^5\)–\(^8\)

The effectiveness of both EIVC and LIVC strategies in mitigation of engine knock have been evaluated. For LIVC, it is easier to achieve such goal based on cam. Some scholars have confirmed LIVC is more effective than EIVC through some preliminary investigations, so they focused on LIVC only.\(^9\) Li et al.\(^6\) applied Miller cycle on a boosted DI gasoline production engine and found that at high load operation, the brake specific fuel consumption (BSFC) was improved by 4.7% with CR of 12.0; at low load operation, LIVC and EIVC improved the fuel economy by 6.8% and 7.4%, respectively. The rate of heat generation under EIVC strategy was slower owing to the lowered pressure and temperature at the end of compression stroke.

Millo et al.\(^10\) found that EIVC reduced the level of turbulence in the cylinder, thus leading to a slower flame propagation, while LIVC showed a less negative impact on turbulence and mixture formation, especially at medium engine speeds.

However, in our previous studies, EIVC strategy has some advantages in the engine without cooling EGR compared with LIVC owning to lower temperature in cylinder and less compression work. Chen et al.\(^11\) and Zhou et al.\(^12\) compared the effects of Miller cycle with EIVC or LIVC on the engine performance, and the results also showed that the EIVC strategy was more advantageous for avoiding pumping loss resulted from backflow while LIVC led to a higher pressure during the compression stroke. Therefore, it is necessary to further study the effects of LIVC and EIVC on suppressing engine knock.

Although LIVC can be implemented more easily via a VVT mechanism, it is still limited by the cam profile. Electromagnetic valve train (EMVT) is a typical fully flexible valve control system, driving each valve individually by a linear servo, which can achieve flexible and fully variable for valve-controlling parameters such as valve opening and closing timing, lifts and transition time, so EIVC can be implemented more easily.
Picron et al.\textsuperscript{13–16} proposed an EMVT mechanism by continuously and flexibly adjusting valve motion, then applied Miller cycle to prevent engine knock under high compression ratio. The result shows that the EMVT provided the possibility to suppress engine knock under the condition of increased compression ratio. However, the difference in EMVT under different valve control strategies was not considered when applying Miller cycle.

Chen et al.\textsuperscript{17} investigated the influence of turbulence intensity on knocking characteristics and found that turbulence intensity was closely related to engine knock. Enhancing turbulence intensity can help restrain knocking combustion due to the improvement of flame speed. However, a faster flame propagation has a more significant compression heating effect on the end-gas and can advance the timing of knock onset. This conclusion seems to be inconsistent with Millo et al., who believed that higher level of turbulence always helps to suppress engine knock. Therefore, the influence of turbulence intensity on combustion needs to be further studied.

In this study, for a gasoline engine with fixed compression ratio of 13.5, the flexible and fully variable valve train is applied to suppress engine knocking. A comparative study was carried out to investigate the effects of EIVC and LIVC on engine performance by the quantitative analysis of the factors affecting the engine operation, such as the level of turbulence, temperature, residual exhaust coefficient, etc., the results provide valuable reference for the design and the research on gasoline engine.

**Experimental and simulation model**

In this study, the application method of Miller cycle based on EMVT technology is shown in Figure 1.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{The application method of Miller cycle based on EMVT technology.}
\end{figure}
The compression ratio of engine was increased from 10.5 to 13.5 by changing the top shape of piston, and zero-collision between piston and valve was realized in this work. The corresponding time of EMVT can reach 2.9 ms, which meets the changing requirements of the engine at 6000 r/min. Only 18°CA is needed to complete the valve opening to 8 mm lift at 1000 r/min, which can fully meet the requirements of valve opening for multiple times. The research group has designed and developed a set of valve control strategies for conventional engines, which lay a theoretical and experimental foundation for exploring technical approaches to suppress knocking combustion in the engine.

**Combustion model**

Studies on one-dimensional combustion models at home and abroad have shown that fractal combustion model has a higher accuracy in describing combustion process. The main combustion stage of this model can be expressed as equation (1).\(^{19}\)

\[
\frac{dm_b}{dt} = \rho_u A_T S_L = \rho_u \left( \frac{L_{\text{max}}}{L_{\text{min}}} \right)^{D_3/2} A_T S_L
\]

where \(m_b\) is mass of burned gas; \(\rho_u\) is density of burned gas; \(A_T\) is turbulent flame area; \(S_L\) is laminar burning velocity; \(D_3\) is the fractal dimension; \(L_{\text{min}} - L_{\text{max}}\) is wrinkle scale (\(L_{\text{max}}\) and \(L_{\text{min}}\) are the maximum and minimum fold scales of the flame, respectively). The dimension of \(D_3\) mainly depends on the ratio between the turbulence intensity \(\mu'\) and the laminar flame speed \(S_L\), as shown in equation (2).

\[
D_3 = \frac{2.35 \mu' + 2.05 S_L}{\mu' + S_L}
\]

The computation of the wrinkling scales \(L_{\text{max}}\) and \(L_{\text{min}}\) as well as the fractal dimension \(D_3\) must depend on the characteristics of the turbulent flow field inside the cylinder.\(^{20}\) The interaction between the turbulent flow field and the flame determines the development of turbulent flame surface \(A_T\), which propagates at the laminar flame speed \(S_L\). If a self-similar wrinkling is assumed within the length range of \(L_{\text{min}} - L_{\text{max}}\), then a fractal object is observed at the flame front and the flame surface can be easily computed.

**Engine knock theory**

In this paper, an induction-time empirical formula based on the Arrhenius function is used to analyze engine knock, as shown in equation (3).

\[
\int_0^t \frac{1}{\tau_{ID}(t)} \, dt
\]
where $\tau_{ID}$ is ignition delay for unburned zone. To avoid the occurrence of engine knock, the value of $\tau_{ID}$ is set to be greater than the time required for reaching combustion.

From equation (4), it is known that the ignition delay for the engine knock model depends on the octane number of the fuel and the gas condition.

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$$\tau_{ID}(t) = A \cdot ON^a \cdot P^{-n} \cdot e^{Bt}$$

(4)

where $\tau_{ID}$ represents ignition delay (ms), $ON$ represents anti-knock index of the fuel, $p$ is pressure (bar), $T$ is temperature (K), $A, a, n, B$ are model constants.

### Simulation model

The numerical model of engine working process is established based on the AVL BOOST software, which consists of engine intake system, exhaust system, and cylinder. According to the prototype parameters, the structural parameters of engine components are defined in advance, as shown in Table 1.

Although, the friction loss of the engine will be reduced when the electromagnetic valve train replaces the camshaft and other driving mechanisms, the operation of the electromagnetic valve train will consume part of the electric energy, which will eventually affect the performance of the engine to a certain extent. Therefore, it is necessary to modify the power of the engine equipped with electromagnetic valve train in the simulation model.

According to the measured power consumption of electromagnetic valve, the engine power is corrected by equation (5).

$$P_e' = P_e \cdot \left( \frac{P_e}{P_e + \frac{P_e}{\eta_m}} \right)$$

(5)
where $P'_e$ is the corrected power, $P_e$ is the effective power of the engine, $P_v$ is the power consumption of the EMVTs, and $\eta_m$ is the efficiency of converting mechanical energy into electrical energy (80%).

The power consumption of the EMVT changes greatly when the valve operation mode is switched. According to the measured power consumption of the electromagnetic drive valve, the BSFC of engine is corrected by equation (6).

$$b'_e = b_e \cdot \frac{P_e}{P_e + \frac{P_v}{\eta_m}} \quad (6)$$

where $b'_e$ is the BSFC of the engine after correction, and $b_e$ is the BSFC of the engine before correction.

The change of valve operation mode will cause the changes in the engine pump loss, combustion efficiency, and friction power consumption. These three changes have been included in the engine working process model, so no further external correction analysis is needed, as shown in equation (7).

$$P_e = IMEP \cdot V_D - P_{fr} = V_D \int_{0^\theta}^{720^\theta} p_c \cdot dV - P_{fr} \quad (7)$$

where: $V_D$ is the working volume of the cylinder, $p_c$ is the instantaneous cylinder pressure of the cylinder, $P_{fr}$ is the friction power consumption.

**Model verification**

At present, the engine experiment with EMVT is under way, and the compatibility between engine ECU program and electromagnetic actuated valve train program needs to be solved, there is no experimental data of the engine after modification in this paper. The accuracy of the proposed model is validated by the experiments of prototype engine, as shown in Figure 2. Data analyses demonstrate that the model can make accurate predictions, with the errors less than 5%. The lift profiles of EMVT are applied for each operating point in the proposed model. For the prototype engine with cam mechanism, the engine’s performance is simulated for comparison.

Figure 2 shows the data of effective torque and effective fuel consumption under full load condition. As it shown, the errors between simulated model and experimentally measured valves are acceptable. The simulation model of camless engine is modified based on prototype engine, so the simulation results are reliable and accurate.

**Results and discussion**

**High engine load**

Engine knock is most likely to occur under the condition of low speed and large load, so the calculation is performed under large load condition at engine speed of
1000 r/min. Through calculation based on engine model, the volume efficiency boundary with no engine knock is 77.46%. To avoid knock, the Miller cycle can be achieved by either EIVC or LIVC. As shown in Figure 3, the valve opening decreases gradually in the valve closing stage under both strategies, and there is a
transition period for air charging into cylinder, such as from $A'B'$ to $AB$ and $C'D'$ to $CD$; therefore, for EIVC, the air charging can be controlled at the boundary when IVC time is $499.9^{\circ}CA$ (0.4405 g per cylinder); for LIVC, air charging can be controlled at the boundary when IVC time is $600.9^{\circ}CA$ with 0.0793 g air returning into intake pipe, which is a more suitable condition for the excess gas to exit from the cylinder.

The change of the mean turbulent velocity during the charging/compression process is shown in the Figure 4, The 494, 499, 504, 602, 600, 599 in the figures refer to the timing (crankshaft angle) of intake valve closing, while the theoretical time of intake valve closing is $540^{\circ}CA$.

As it shown, a peak turbulence intensity occurs near $360^{\circ}CA$ under LIVC strategy at the beginning of intake process (in range I), and then decreases rapidly to the same level as that under EIVC strategy at $390^{\circ}CA$. After the time, the turbulent velocity under EIVC is higher than that under LIVC, which is consistent with the trend before $480^{\circ}CA$ (in range II). In range III, a peak is formed quickly at $499^{\circ}CA$, which is much higher than that of LIVC. However, it is difficult for LIVC to form a peak due to the influence of continuous charging gas.

To further analyze the influence of intake valve opening strategy on turbulence intensity, the two strokes of intake and compression are calculated based on CFD (Computational Fluid Dynamics) model, where the initial time is the opening time of the intake valve. The three-dimensional turbulent kinetic energy and turbulence intensity in the cylinder based on CFD model are shown in the Figure 5. The conservative partial differential equations include continuity equation, momentum equation, and energy equation. The turbulence model uses the standard $k-\varepsilon$ model to complete the energy transport. The turbulence intensity and turbulent kinetic energy are higher under EIVC strategy than that under LIVC. From $600^{\circ}CA$ to
680°CA, the turbulence intensity under both strategies declines quickly, which is consistent with the one-dimensional simulation trend. This due to that the macro charging gas continuously enter into the cylinder, leading to the weakening of shear compression and micro motion. Although turbulent intensity is greater at the early stage, it weakened gradually by the air charging and becomes far weaker than that under EIVC till end of the compression.

The turbulence intensity in cylinder under EIVC is higher than that under LIVC (shown in Figure 6), so the flame front area is larger, and the combustion speed is faster under EIVC. From Figure 7 that the temperature of unburned area in cylinder under LIVC is lower than that under EIVC strategy at the initial stage of intake (before 390°CA). Which is mainly due to the effect of inlet pressure wave.
In the region of 500°CA–600°CA, the valve is closed under EIVC, so the quality of working medium in the cylinder will not change any more. However, under LIVC, heat exchange between the cylinder wall and charging air is on-going, and the gas temperature in cylinder will be lower than that under EIVC strategy till the end of compression.

As shown in Figure 8, the antiknock index (Octane Number) under EIVC is better than that under LIVC. It can be seen from the previous comparative research that the temperature of unburned area under EIVC is higher, the turbulence
intensity are both higher under EIVC than under LIVC, so the faster flame can offset the negative impact of temperature.

As shown in Figure 9, the mean pressure in the process of intake stroke (MEP-in) under EIVC is significantly lower than that under LIVC. Under EIVC, the intake valve closes at the angle of $500^\circ$CA, the IMEP-in decreases firstly due to the throttling derived from excessive closing of valve, then further decreases as the piston continues to go down after the valve is fully closed, and finally starts to increase because of the compression. Moreover, the IMEP-in under LIVC scheme is 0.9701 bar closed to atmosphere, which is higher than 0.9633 bar under EIVC scheme.

In the range from $540^\circ$CA to $600^\circ$CA, excess gas in cylinder needs to be discharged, which will consume a certain amount of power. Therefore, it is necessary to further analysis the power consumption comprehensively.

Through quantitative analysis under LIVC (600) and EIVC (504), the compression process power consumption and EMVTs power consumption are both increased, and the pump loss is improved, as shown in the Figure 10.

Compared with EIVC strategy, LIVC strategy has a positive effect only on the intake stroke (the active work per cycle increases by 0.012 bar), and the excess gas needs to be removed to reduce the effective compression ratio. What’s more, the power consumption of EMVTs are increased with the extending of the opening duration. Therefore, the total power consumption is increased by 0.0371 bar under LIVC compared with that under EIVC, which causes a negative impact on the power performance and fuel economy.

**Partial engine load**

As shown in the Figure 11, with the decrease of engine load, the indicated mean effective pressure (IMEP) decreases gradually during the intake process under
EIVC, but pumping loss is increased compared with that under LIVC (the IMEP-in remains unchanged basically). For example, under the volumetric efficiency of 46.5%, IMEP-in under EIVC strategy is 0.16 bar lower than that under LIVC strategy.

**Figure 10.** Classification and quantification of power consumption under LIVC and EIVC.

**Figure 11.** The IMEP-in and IMEP under LIVC and EIVC.

EIVC, but pumping loss is increased compared with that under LIVC (the IMEP-in remains unchanged basically). For example, under the volumetric efficiency of 46.5%, IMEP-in under EIVC strategy is 0.16 bar lower than that under LIVC strategy.
With the decrease of the load, the difference in pumping loss under the two strategies becomes increasingly significant (as shown in Figure 12), but the difference in IMEP remains insignificant. This is due to that the pumping loss is increased under EIVC strategy. The power consumption of EMVTs under EIVC strategy is far less than that under LIVC due to the less power consumption in the holding process. Therefore, the advantage in IMEP under EIVC strategy gradually declines with the decrease of engine load.

What’s more, with the engine load decreasing, the residual exhaust gas (EGR) remains unchanged under EIVC strategy, while a part of the exhaust gas will be discharged out of the cylinders with the air EIVC strategy. So, the EGR ratio will be higher at the same loading with EIVC. And properly increasing the EGR ratio can help to reduce NOx generation under partial load. As shown in Figure 13, under 46.5% load, the EGR ratio of EIVC strategy is 1% more than LIVC strategy, and the rate of it NOx is 0.54 g/kWh less than that of LIVC.

**Conclusions**

In order to suppress the engine knock for a high compression ratio engine via EMVT, a comparative study was carried out to investigate the effects of EIVC and LIVC on the engine performance. Conclusions are drawn as follow.

(1) Improved anti-knock performance is achieved when implementing either EIVC or LIVC strategies for the engine with CR of 13.5 at speed of 1000 rpm. Compared with a conventional Otto cycle engine, an over-expansion cycle engine can realize a larger expansion ratio while maintaining a normal effective compression ratio.
The turbulence intensity in cylinder is higher under EIVC strategy than that under LIVC at the end of compression, which helps to promote the flame propagation. From 600°CA to 680°CA, the turbulence intensity results of one-dimensional calculation are consistent with that of CFD simulation.

Compared with EIVC strategy, LIVC strategy has a positive effect on the intake stroke and needs more power consumption to maintain valve opened with a longer time. Therefore, more total power consumption is needed under LIVC, so EIVC is more suitable for the engine in this work.

At low engine load, pumping loss under EIVC will be increased, while the IMEP-in remains unchanged basically with LIVC. Therefore, the advantage of EIVC strategy declines gradually with engine load further decreasing.

Compared with LIVC, the EIVC strategy is capable of sensitively adjusting the EGR rate, which helps reduce NOx and suppress combustion.

Author contributions
Jiangtao Xu designed the study, carried out definition of intellectual content, literature search, data acquisition, data analysis and manuscript preparation. Yong Feng provided funding assistance for the study, Tongjun Guo and Mengxin Sun revised the manuscript. Tongjun Guo also carried out grammar modification and manuscript editing.

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Availability of data and material
The authors confirm that the data supporting the findings of this study are available within the article.

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