Simulation study on effect of late-intake-valve-closing Atkinson cycle on the performance of a direct injection engine based on fuel economy

Yue Li[1], *Zhi* Ning[1], *Ming* Lü[1,*], *Xin* Zhi[1], and *Xian* Luo[2]

[1]School of Mechanical Electronic and Control Engineering, Beijing Jiao tong University, Beijing 100044
[2]China Nuclear Engineering Consulting Co., Ltd, Beijing 100073

Abstract: Given the wide application of hybrid engines, how to improve hybrid engine fuel economy is being more and more studied, and using the Atkinson cycle to improve fuel economy is considered effective. In this study, the in-cylinder direct injection engine model was established with the data obtained from a benchmarking test using the GT-POWER simulation software. The working process of this engine was simulated after using Atkinson cycle. This simulation primarily focused on the research of the impact on engine fuel economy with different late intake valve closing strategies. The simulation results were calculated under the partial load conditions which are typically used in hybrid engines. The results indicated that engine fuel economy improved and fuel consumption decreased by using the Atkinson cycle. However, the Atkinson cycle would cause a decrease in power.
Keywords: Atkinson cycle; Fuel economy; LIVC; GDI.

1 Introductions

As government regulations for vehicle emissions and fuel consumption become increasingly stringent, improving engine thermal efficiency is required urgently. Recently, hybrid vehicles have attracted increasing interests, and the engine for hybrid vehicles which is a primary energy-consuming components determines the development prospects of hybrid vehicles. Hybrid engines are required to operate at high thermal efficiencies, which can result in lower fuel consumption and emissions [1].

The Atkinson cycle is a type of over-expansion cycle whose effective expansion ratio is greater than the effective compression ratio. There is a reverse flow process between the intake stroke and compression stroke. The Atkinson cycle can improve engine fuel economy under partial load [2–3]. Delaying the intake valve closing time is one of the methods to realize the Atkinson cycle. Therefore, the effective compression ratio of the engine can be reduced and then an operating cycle in which the expansion ratio is greater than the compression ratio can be achieved [4]. The application of the Atkinson cycle can reduce the pumping loss at part load [5–8]; simultaneously, it can also suppress the knocking

* Corresponding author: lvming@bjtu.edu.cn

phenomenon [9–11] which is negative for the thermal efficiency of the engine. Nonetheless, the high-precision and flexible valve control mechanism are needed to achieve the Atkinson cycle. Moreover, the reverse flow process decreases the engine power density [1]. Hybrid engines often operate at partial loads and do not require higher power. Thus, applying the Atkinson cycle to hybrid engines can further reduce the fuel consumption and improve the engine performance.

In summary, most studies focused on the impact of the Atkinson cycle on engine fuel economy, and fewer studies have analyzed the reasons from the aspect of pumping losses. In this study, the reasons for its impact from aspects of pumping losses and fuel energy distribution have been explored apart from analyzing the impact of the Atkinson cycle on fuel economy and dynamics. In addition, the operating conditions with the highest thermal efficiency which are the typical operating conditions of the hybrid engine were studied,. The results will provide a basis for the Atkinson cycle to improve the thermal efficiency of the hybrid engine.

In this study, based on the benchmark data obtaining from engine bench test, a three-cylinder direct injection supercharged engine model was established by using the one-dimensional simulation software GT-POWER. The influence of the Atkinson cycle on the fuel economy of the engine was investigated and its impact on the dynamics was also analyzed.

2 Model Setup and Calibration

In this study, a three-cylinder supercharged direct injection gasoline engine was used as the research object. The primary technical parameters are listed in Table 1. Through the one-dimensional simulation software GT-POWER, the operating process of the engine was simulated and performance of the engine was obtained. Combined with the structural data of the three-cylinder supercharged direct injection gasoline engine and the benchmark test data, the simulation model of the direct injection gasoline engine established by GT-POWER is shown in Fig. 1.

Table 1. Primary parameters of the gasoline engine

Item	Content	Item	Content
Rated speed	5500 r/min	Power Max	100 kW
Torque Max	230 N·m	Displacement	1.199 L
Bore×Stroke	75×90.5 mm	Number of cylinders	3
Compression Rod	9.5 : 1	Number of valves	4

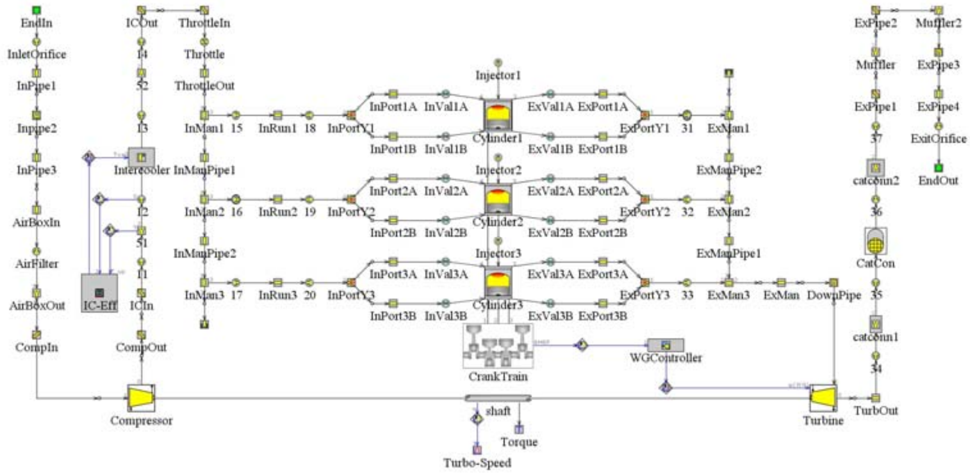


Fig. 1. GT-POWER model of gasoline engine

To ensure the accuracy of the established gasoline engine simulation model, a multi-objective optimization calibration of the gasoline engine model was performed using the ModeFrontier optimization software coupled with the GT-POWER software. The correlation coefficients, performance parameters, and bench test data in the gasoline engine model were used as the calibration variables, calibration parameters, and calibration targets, respectively. The optimized calibration model was established, as shown in Fig. 2.

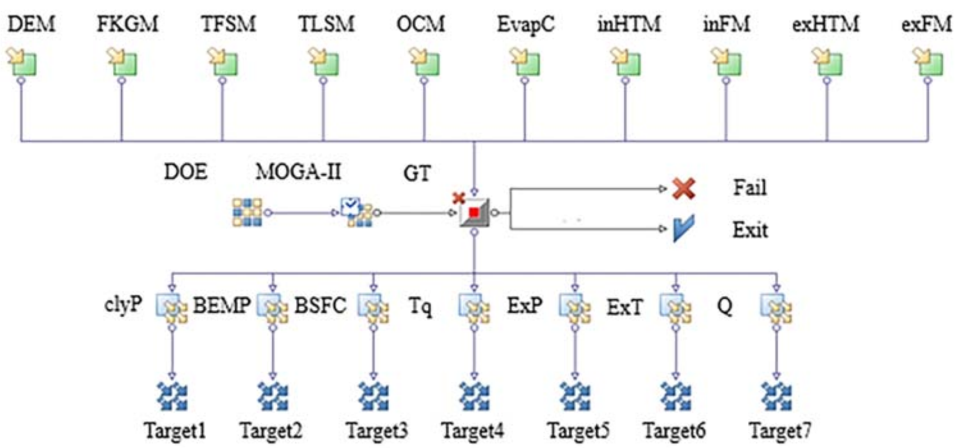
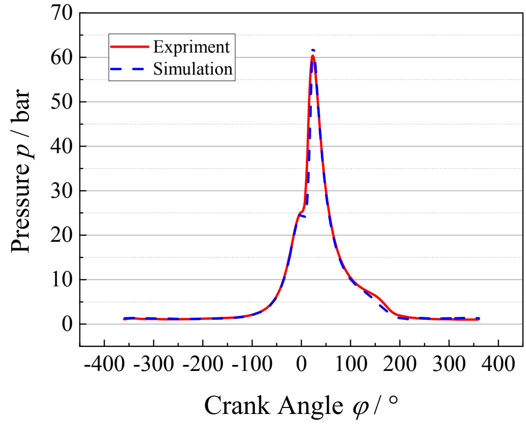
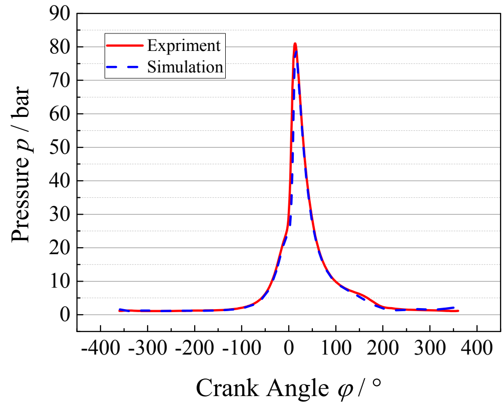


Fig. 2. Multi-objective optimization calibration model

The simulation model was adjusted under high thermal efficiency conditions (14 bar, 2000 r/min; 14 bar, 3000 r/min). After calculation, the optimal correlation coefficients' values were selected as the input parameters of the gasoline engine simulation model. The simulation was performed using the calibrated GT-POWER model to obtain the cylinder pressure curves and the power and fuel economy simulation values. The simulation results were compared with the bench test data, as shown in Fig. 3.



(a) 2000 r/min (14 bar)



(b) 3000 r/min (14 bar)

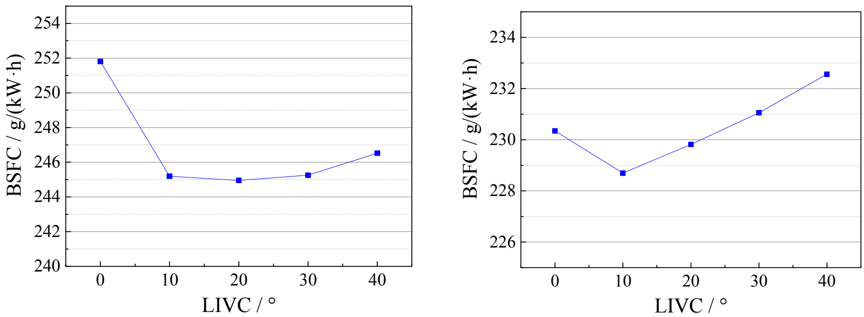
Fig. 3. Comparison of in-cylinder pressure curve between the test and simulation (14 bar)

As shown in Fig.3, the cylinder pressure curves calculated by the calibrated gasoline engine simulation model agrees well with the cylinder pressure curves obtained by the test. The peak pressure and the appearance of peak pressure are very close to the test results.

3 Results and discussion

The gas exchange process is critical in the performance of the engine. The quality of the gas exchange process affects the power and fuel economy. Compared with the traditional engine operating cycle, the Atkinson cycle has an effective expansion ratio that is greater than the effective compression ratio, which improves the engine's ability to work. Therefore, the engine with different degrees of Atkinson cycle will be analyzed to explore the influence of the Atkinson cycle on the engine power and fuel economy.

As described in the experimental method, the engine load was set to 14 bar, the speed was set to 2000 r/min and 3000 r/min, and the engine fuel consumption rate and power under the conditions of LIVC0–LIVC40 were calculated. Figure 4 shows the changes in engine fuel consumption rate under different engine operating conditions with different intake valve closing times.



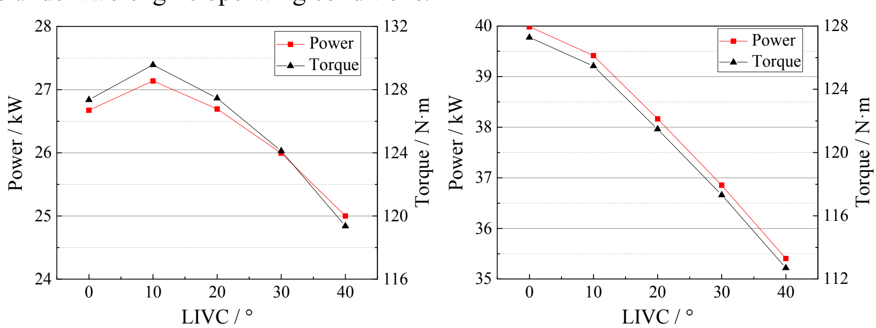
(a) 2000 r/min (b) 3000 r/min

Fig. 4. Brake-specific fuel consumption varying with the LIVC

As shown in Fig. 4 that when the engine speed is 2000 r/min, the fuel consumption rate of the engine decreases first and subsequently increases with increasing the intake valve closing time, and both are lower than that of the original engine. After applying the Atkinson cycle, the engine fuel consumption rate can be reduced significantly. When the intake valve was closed 20° late, the fuel consumption rate decreased the most. Compared with the original engine, the fuel consumption has decreased by 2.7%. When the engine speed is 3000 r/min, the engine fuel consumption rate decreases first and subsequently increases with increasing the intake valve closing time. When the LIVC = 10° and LIVC = 20°, the fuel consumption rate is lower than that of the original engine. However, when the closing time continues to be retarded, the fuel consumption rate will be higher than that of the original machine. Under this condition, when LIVC = 10°, the fuel consumption rate decreased by 0.7%.

An analysis of the results implies that, using the Atkinson cycle can reduce the engine fuel consumption rate, such that the fuel economy of the engine can be improved. However, as the rotational speed increases, the effect of the Atkinson cycle in improving the fuel economy becomes worse. Furthermore, an excessive intake valve closing time will result in the deterioration of fuel economy as well.

Figure 5 shows the changes in engine power based on different intake valve closing times under two engine operating conditions.



(a) 2000 r/min (b) 3000 r/min

Fig. 5. Brake power varying with the LIVC

As shown in Fig. 5, at the speed of 2000 r/min, the engine power increases first and subsequently decreases with the delay of the intake valve closing time, and the power reduction is small. Similar to the change law of power, the torque first increases and subsequently decreases with the delay of the intake valve closing time. At the speed of

3000 r/min, the engine power indicates a significant downward trend with increasing the intake valve closing angle. When LIVC = 40°, the power decreased from 40.0 kW to 35.4 kW, and the maximum decrease was nearly 12%. Similarly, the torque continues to decrease, and it decreases by 14.6 N·m when LIVC = 40°. Compared with the traditional engine operating cycle, using Atkinson cycle will result in decreased engine power and torque; the higher the speed, the more obvious the impact is. The Atkinson cycle has a large impact on the dynamics of the engine, which will deteriorate the power and torque.

After the analysis above, it can be concluded that the Atkinson cycle can improve the fuel economy of the engine at 2000 r/min, while the engine's power is slightly reduced. However, the use of a weak Atkinson cycle will result in a slight increase in power and torque. At 3000 r/min, the Atkinson cycle can be used to improve the fuel economy of the engine slightly, but simultaneously reduce the engine's power and torque output significantly. Next, the reasons for this effect will be investigated thoroughly.

4 Conclusion

In conclusion, the variation law of fuel economy and power performance of the Atkinson cycle engine under different degrees were studied numerically.

Under the condition of 2000 r/min and 14 bar, the engine fuel consumption rate decreased first and subsequently increased with the increase of the intake valve closing angle. When the intake valve was closed 20° late, the fuel consumption rate decreased the most. Compared with the original engine, the fuel consumption has decreased by 2.7%. Besides, the power increased first and subsequently decreased. Under the condition of 3000 r/min and 14 bar, the engine fuel consumption rate decreased first and subsequently increased with increasing the intake valve closing angle. When LIVC = 10°, the fuel consumption rate decreased by 0.7%. When LIVC = 40°, the power decreased from 40.0 kW to 35.4 kW, and the maximum decrease was nearly 12%. The Atkinson cycle improved the engine fuel economy, but also caused the decrease of engine power.

Acknowledgements

Project supported by the National Key Research and Development Program (Grant No. 2017YFB0103401).

References

1. Zhao J. Research and application of over-expansion cycle (Atkinson and Miller) engines – A review [J]. Applied Energy, 2017, 185:300-319.
2. Li T, Gao Y, Wang J, et al. The Miller cycle effects on improvement of fuel economy in a highly boosted, high compression ratio, direct-injection gasoline engine: EIVC vs. LIVC [J]. Energy Conversion & Management, 2014, 79:59-65.
3. Zheng B, Li T, Yin T. Mechanism of Improvements on Thermal Efficiency of Turbocharged Direct Injection Gasoline Engines by Miller Cycle: Partial Load Analysis [J]. Chinese Internal Combustion Engine Engineering, 2016, 6: 116-120.
4. Cordier M, La O, Duffour F, et al. Increasing Modern Spark Ignition Engine Efficiency: A Comprehension Study of High CR and Atkinson Cycle [M], SAE Technical Paper Series, 2016.

5. Pertl P, Trattner A, Abis A, et al. Expansion to Higher Efficiency - Investigations of the Atkinson Cycle in Small Combustion Engines [M]. SAE Technical Paper Series. 2012.
6. Ca L, Teng H, Miao R, et al. A Comparative Study on Influence of EIVC and LIVC on Fuel Economy of A TGDI Engine Part III: Experiments on Engine Fuel Consumption, Combustion, and EGR Tolerance [M]. SAE Technical Paper Series. 2017.
7. Zheng B, Li T, Yin T. Analysis of Thermal Efficiency Improvement Implemented with Miller Cycle for High Compression Ratio Gasoline Engine at High Load [J]. Vehicle engine, 2015, 5:20-25.
8. Jiang W. Research on Improving Fuel Economy of GDI Engine Using Miller Cycle [D]. Jilin University, 2016.
9. Wan Y, Du A. Reducing Part Load Pumping Loss and Improving Thermal Efficiency through High Compression Ratio Over-Expanded Cycle [M]. SAE Technical Paper Series. 2013.
10. Zhao J, Li Y, Xu F. The effects of the engine design and operation parameters on the performance of an Atkinson engine considering heat-transfer, friction, combustion efficiency and variable specific-heat [J]. Energy Conversion and Management, 2017, 151:11-22.
11. Wei H, Shaao A, Hua J, et al. Effects of applying a Miller cycle with split injection on engine performance and knock resistance in a downsized gasoline engine [J]. Fuel, 2018, 214:98-107.