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Original Research

Conceptual and experimental study of an Atkinson cycle engine of a Series-Parallel hybrid electric vehicle

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ABSTRACT

The Atkinson cycle engine plays a crucial role in advancing Hybrid Electric Vehicles (HEVs) due to its superior fuel efficiency compared to the Otto cycle engine. Thermodynamic analysis highlights the Atkinson cycle's significant advantage in cycle efficiency, with factors such as the expansion ratio and effective compression ratio, influencing overall efficiency. This investigation focuses on converting an Otto cycle engine to an Atkinson cycle engine by implementing late intake valve closing and increasing the compression ratio. The optimization of the high geometric compression ratio from 10.7 to 12.4 aims to overcome the Atkinson cycle's drawback, where combustion performance deteriorates due to a reduction in the effective compression ratio. GT-Power software is used to simulate engine performance under various operating points, and comprehensive experiments are conducted to determine the performance, fuel consumption, and combustion characteristics of the developed Atkinson engine. Experimental results show that the Atkinson cycle engine exhibits substantially lower overall fuel consumption compared to the Otto cycle engine, with an improvement in maximum thermal efficiency from 34% to 34.6%. Additionally, the fuel-efficient range of the Atkinson cycle engine surpasses that of the Otto cycle engine, with the minimum fuel consumption area now occurring at low-medium speed and medium-high-load operational conditions.

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1- Introduction

The urgency to address rising fuel prices, reduce pollutant emissions, and enhance urban air quality necessitates the development of efficient and low-emission green automotive products [1]. Given that gasoline engines in vehicles, especially during city traffic, often operate at part load, such operation scenarios represent the majority of common driving situations [2]. Hybrid Electric Vehicles (HEVs) emerge as a viable technical solution for the automotive industry, effectively meeting power, fuel economy, and pollutant emission requirements during operation [3]. Traditional gasoline engines, beset by shortcomings mentioned earlier, no longer suffice to meet the economic and emission demands of HEVs [4].

To surmount the efficiency penalty, the Atkinson cycle, or an over-expanded cycle, can be employed. The Atkinson cycle, conceived by James Atkinson in 1882 [5], enables the delivery of more energy from the combusted gas to the piston during the over-expansion process compared to the Otto cycle.

Moreover, the increase in geometric compression ratio (CR) can offset the decrease in effective CR resulting from overexpansion. Consequently, the Atkinson engine proves more effective than the Otto cycle engine. Research suggests that 20%–30% of the fuel economy improvement in HEVs is attributed to the development and application of the Atkinson cycle engine [6]. The HEV engine operates within a higher brake mean effective pressure (BMEP) area and achieves higher engine thermal efficiency than conventional engines, enhancing the maximum engine thermal efficiency for improved fuel economy in HEVs.

In recent years, significant efforts have been devoted to exploring the potential of Atkinson cycle engines due to their promise of lower fuel consumption and higher thermal efficiency.

Researchers [7, 8] have analyzed the thermal efficiencies of various engine cycles, determining that the Atkinson cycle, specifically the over-expanded cycle, represents the optimum thermodynamic cycle contributing to thermal efficiency.

Hatano et al. [9] introduced a multi-mode Variable Valve Timing (VVT) system enabling the engine to transition between three different sets of cams, adjusting valve lifts, opening durations, and cylinder shutdowns as needed. Their study demonstrated a 16% improvement in fuel economy and a 20% increase in power over the Japanese test-driving cycle.

Tuttle [10, 11] conducted a comprehensive investigation into engine load control using early intake valve closing (EIVC) and late intake valve closing (LIVC) strategies based on a cam-based VVT system. The findings revealed that adopting EIVC and LIVC strategies at 3.5–4 bars of indicated mean effective pressure (IMEP) could reduce indicated specific fuel consumption by approximately 7% and 5%, respectively.

Implementing LIVC in the Atkinson cycle diminishes engine power, necessitating compensation through an increased compression ratio. However, this action may lead to an engine knock. Li et al. [12] discovered that the Atkinson cycle mitigates the engine knock issue by reducing the temperature and pressure of the air-fuel mixture before combustion. Molina et al. [13] suggested that the Miller strategy extends ignition delay and reduces pressure gradients by lowering in-cylinder temperatures. Wei et al. [14] found that both LIVC and EIVC efficiently suppress knock.

In the automotive industry, the integration of high-compression engines and variable valve actuation technologies is common and widely utilized. Various automotive manufacturers, including Mazda [15], Ford [16], GM [17], and Toyota [18], employ LIVC to implement the Atkinson cycle in the production of Spark Ignition (SI) engines with advanced valvetrains.

2- Method: Otto & Atkinson Cycle Engine Configuration

The naturally aspirated (NA) Spark Ignition (SI) engine, featuring four cylinders, and four-stroke configuration, was employed in this investigation. It operated with a compression ratio of 10.7, and the detailed specifications for this Otto cycle engine can be found in Table 1.

Table 1 Engine Specification

Type	Inline, water-cooled, NA
Number of Cylinders	4
Bore	78.5 mm
Stroke	85 mm
Displacement	1587 cc
Compression ratio	10.7

To achieve decreased fuel consumption and compliance with Hybrid Electric Vehicle (HEV) requirements, modification of the original Otto cycle engine into an Atkinson cycle engine was deemed necessary. Optimization of certain parameters, including engine camshaft profile and compression, was carried out during the modification process. This process took into consideration the use of different fuel qualities in terms of octane number, leading to an increase in the compression ratio to 12.4. Figure 1 depicts the modified piston shape designed to accommodate the higher compression ratio. Furthermore, the expansion duration was increased by modifying the camshaft profile. A comprehensive comparison of Camshaft Profile Characteristics between the initial Otto cycle (base) engine and the subsequently modified Atkinson cycle engine is provided in Table 2.

Figure 1 Atkinson Cycle Piston – CR 12.4 (left) - Otto Cycle Piston – CR 10.7 (Right)

Table 2 Camshaft Profile Characteristics

Parameter	Base Cam Values	Atkinson Cam Values
IVO_{1mm}	33 (ATDC)	33 (ATDC)
IVC_{1mm}	55 (ABDC)	78.8 (ABDC)
$IV_{max\ lift}$	133.5 (ATDC)	144.5 (ATDC)
EVO_{1mm}	21.5 (BBDC)	21.5 (BBDC)
EVC_{1mm}	2.5 (BTDC)	2.5 (BTDC)
$EV_{max\ lift}$	117.5 (BTDC)	117.5 (BTDC)

3- Engine Modeling

In the present study, a 4-cylinder gasoline engine serves as the base engine, and it is subsequently modeled in GT-Suite, along with its specifications. A GT-Suite model of the baseline engine is constructed, as depicted in Figure 2 and accurately calibrated using data obtained from bench tests. All necessary parameters, including all geometrical parameters such as detailed Intake and Exhaust Manifold and runners, Intake filter box and connecting pipes, Exhaust gas catalysts, mufflers and connecting pipes, etc., are modeled precisely. Furthermore, physical parameters such as lift-dependent forward and reverse discharge coefficients at both the intake and exhaust valves, tumble intensity of cylinders, pressure losses, etc., are experimentally acquired from pre-tests.

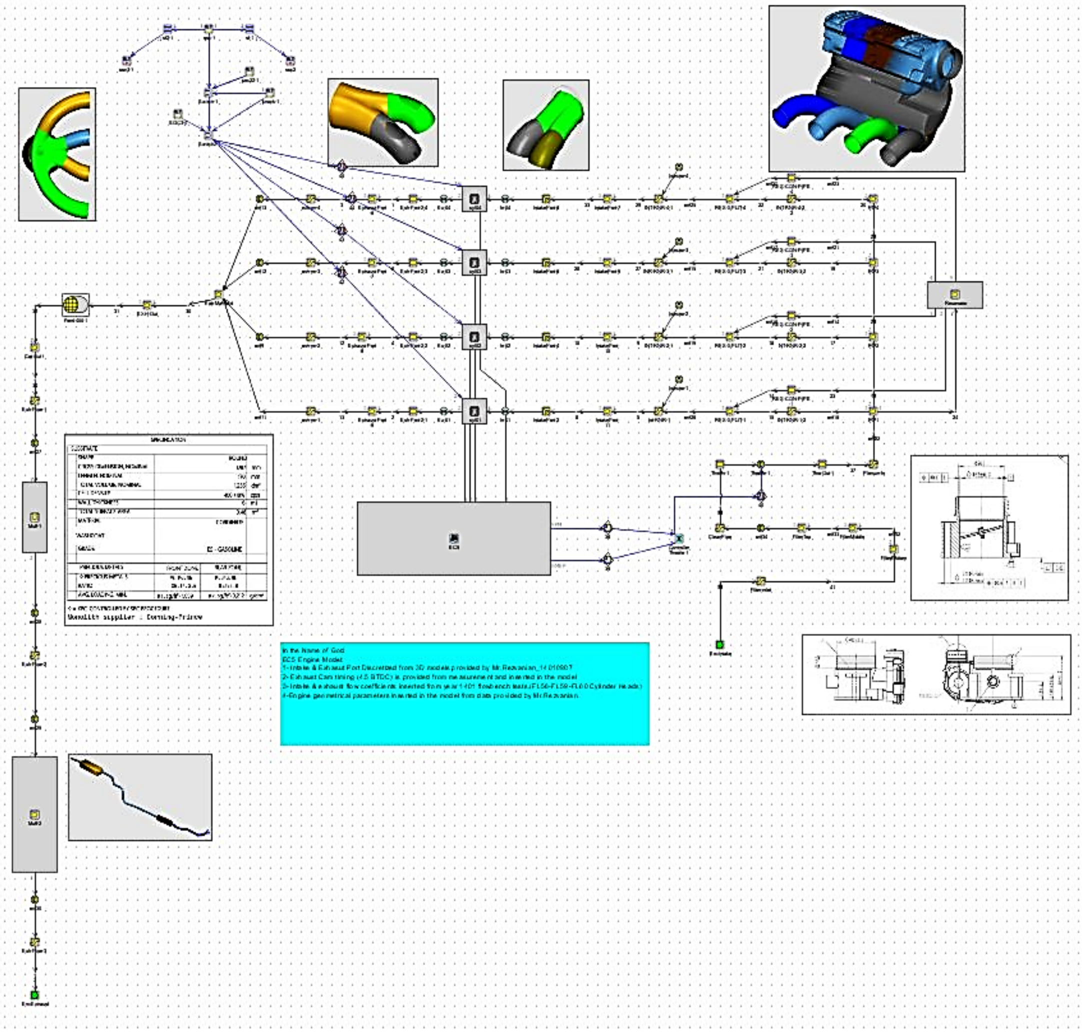

Figure 2 GT-Power Model of Engine

Figures 3 to 6 illustrate the fuel consumption improvement comparison of the simulated values that closely align with the experimental data across the entire sampled speed range.

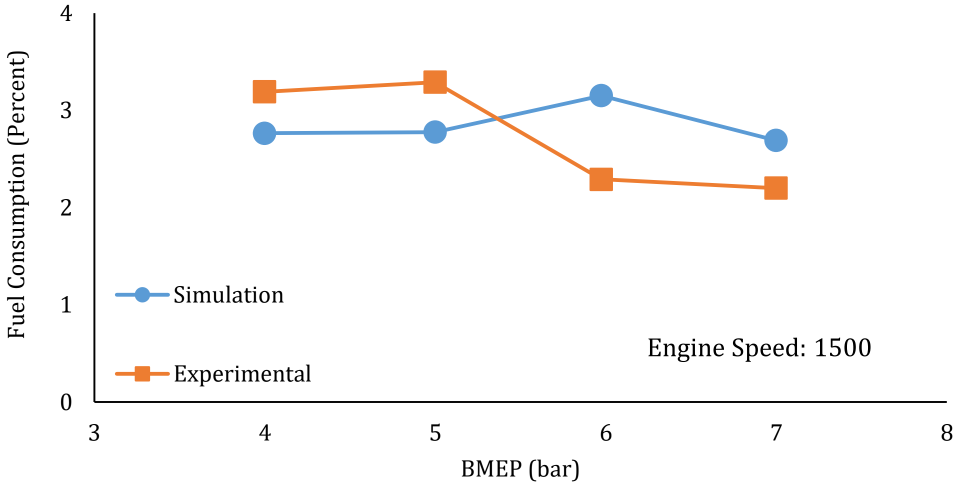

Figure 3 Fuel Consumption Improvement in ENSP 1500, Simulation and Experimental

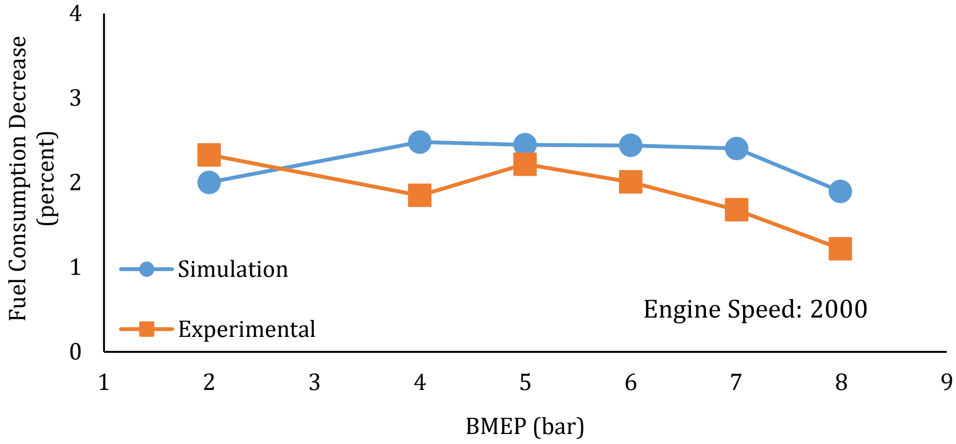

Figure 4 Fuel Consumption Improvement in ENSP 2000, Simulation and Experimental

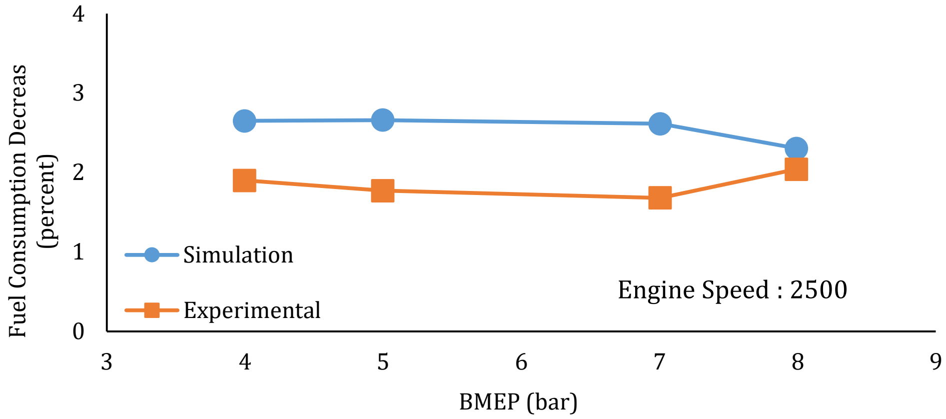

Figure 5 Fuel Consumption Improvement in ENSP 2500, Simulation and Experimental

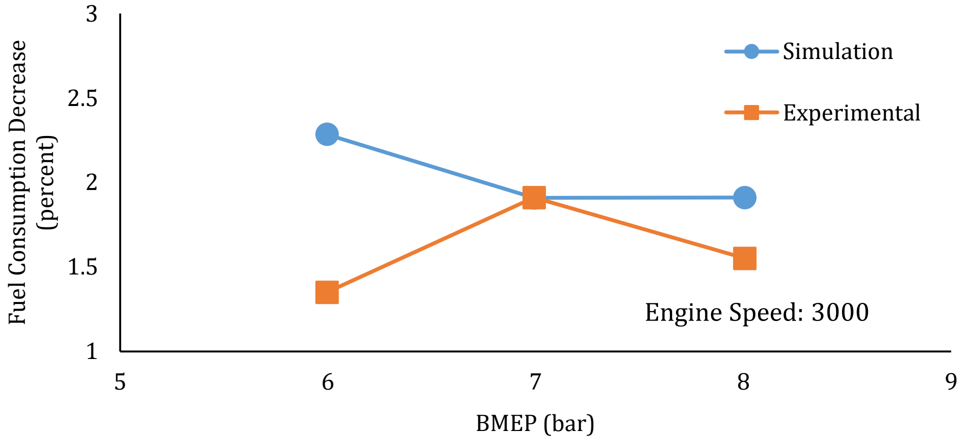

Figure 6 Fuel Consumption Improvement in ENSP 3000, Simulation and Experimental

4- Experimental Investigation

In this investigation, comprehensive testing procedures were conducted for both the base and converted engines. Experiments on the base engine aimed at calibrating the GT-Power model and assessing the initial engine conditions. Subsequently, the Atkinson cycle engine underwent testing to validate the predicted fuel consumption and overall engine performance. Additionally, a detailed combustion analysis was carried out to scrutinize combustion stability and duration for both the base and Atkinson cycle engines.

The AVL PUMA Open system facilitated engine operation, data collection, and processing of engine performance data throughout the experiment. The AV2 LAPI 1F4-E0509 Dynameter was employed to calculate useful output power, designed for engines with up to 220 kW output power. The AVL 733 measured the fuel flow rate, while the air flow rate was determined by the sensor through the measurement of the fuel-to-air ratio.

Cylinder pressure was monitored with the assistance of the AVL Indicom system, with sensors placed in three cylinders. Control of ignition timing, throttle valve, fuel flow, and valve timing were accomplished using a programmable Engine Control Unit (ECU) through the ETAS INCA system. The engine test bench and related equipment are shown in Figures 7 and 8.

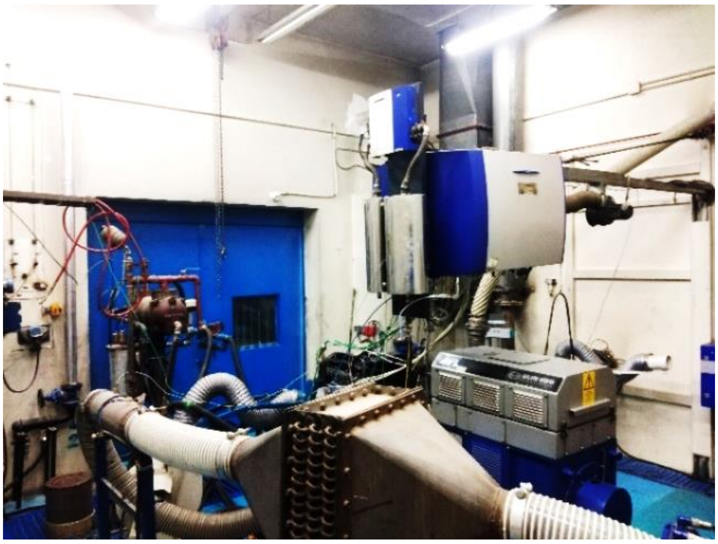

Figure 7 Engine Test Bench

Figure 8 Engine in test bench

5- Results and Discussion

5-1- Fuel Economy and Thermal Efficiency

Fuel consumption serves as an important indicator in engine evaluation, and the main objective of this study is the improvement of engine fuel economy and thermal efficiency. Comparisons of Thermal Efficiency between the original Otto cycle and Atkinson cycle engines are presented in Tables 3 and 4. It is observed that the Thermal efficiency of the Atkinson cycle engine surpasses that of the original Otto cycle engine from an overall perspective. Specifically, the thermal efficiency of the Atkinson cycle engine is higher than that of the original Otto cycle engine, particularly under low-medium speed and medium-high load conditions, which are the most frequently encountered operating conditions for HEVs. This phenomenon is attributed to the increased expansion duration facilitated by the Atkinson cycle, leading to enhanced backflow phenomena and a consequent de-throttling effect, increasing throttle angle position, and a decrease in related pumping loss effects at part load conditions. Furthermore, the high thermal efficiency region of the Atkinson cycle engine is broader than that of the original Otto cycle engine. Therefore, in the medium to high load range, the Atkinson cycle engine exhibits a higher level of fuel economy compared to the original Otto cycle engine. The maximum Thermal efficiencies of the original Otto cycle and Atkinson cycle engines are 34 and 34.6, respectively.

Table 3 Thermal Efficiency of Atkinson Cycle Engine

BMEP (bar)		Engine_Atkinson_Thermal Efficiency				
	9					34.6
	8			34.0	34.3	34.1
	7		33.1	33.5	33.3	33.4
	6	30.6	32.1	32.5	32.2	32.1
	5	29.8	31.1	31.2	30.9	30.8
	4	28.1	29.1	29.2	28.9	28.9
	3	25.8	26.5	26.4	26.3	26.3
	2	21.9	22.5	22.6	22.2	22.1
	1	15.3	15.6	15.5	15.0	15.1
		1000	1500	2000	2500	3000
		Engine Speed (rpm)				

Table 4 Thermal Efficiency of Otto Cycle Engine

BMEP (bar)		Engine_Base_Thermal Efficiency				
	9					34.0
	8			33.5	33.6	33.6
	7		32.4	32.9	32.8	32.8
	6	30.5	31.4	31.8	31.7	31.7
	5	29.2	30.1	30.5	30.4	30.3
	4	27.3	28.2	28.7	28.4	28.4
	3	24.6	25.7	26.0	25.7	25.7
	2	20.7	21.8	22.1	21.7	21.8
	1	14.8	15.2	15.2	15.0	15.1
		1000	1500	2000	2500	3000
		Engine Speed (rpm)				

5-2- Full Load Performance

As depicted in Figure 9, a higher torque drop is observed at lower engine speeds. This trend is attributed to the higher backflow effect experienced at low engine speeds, resulting in a lower volume of air encapsulated in the cylinders. However, since this engine is designed for a full series-parallel hybrid electric vehicle, this torque drop can be compensated for with the assistance of an electric motor/generator and a high-voltage system. The improved power performance at 6000 rpm is a result of the better calibration of air/fuel ratio, ignition timing, and variable valve timing compared to the base engine. The maximum torque of the Atkinson cycle engine is 141.2 N.m at 5000 rpm, and the maximum power of the Atkinson cycle engine is 81.7 kW at 6000 rpm.

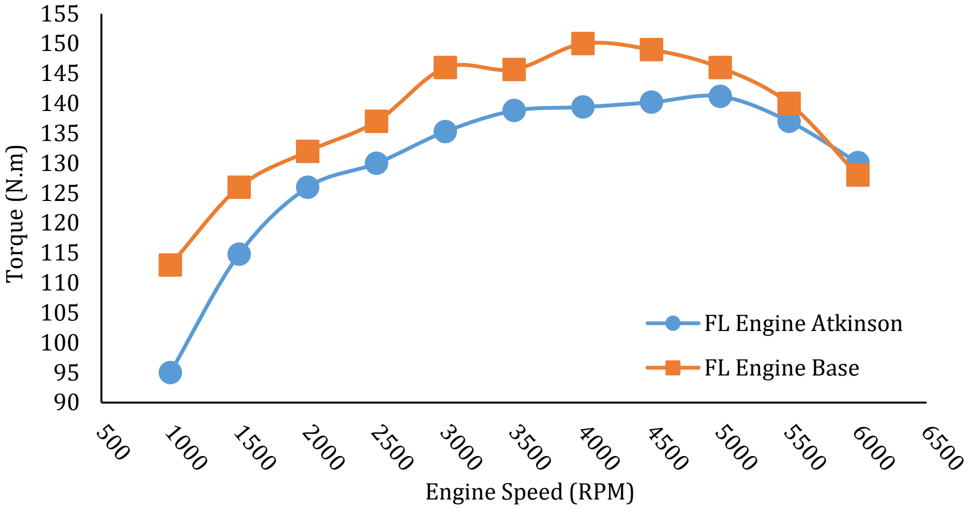

Figure 9 Torque Comparison of Atkinson and Base Engine

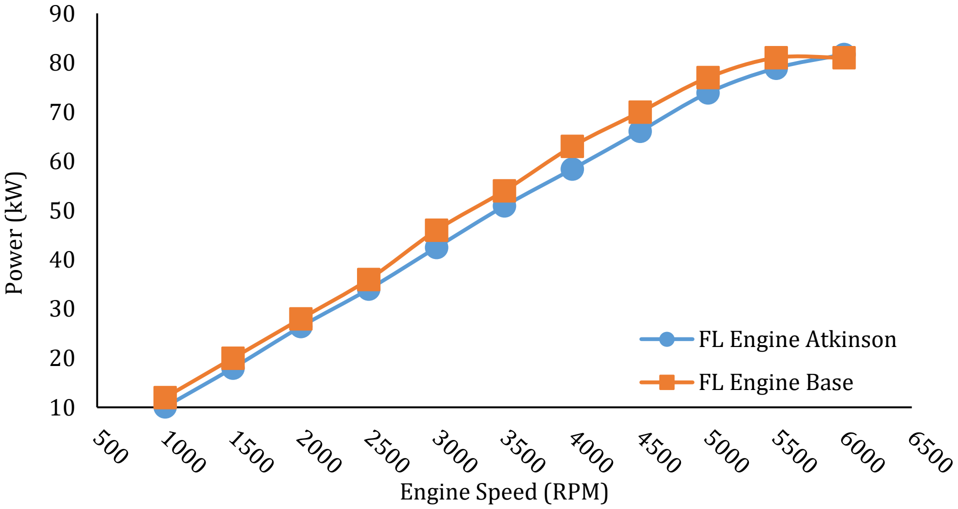

Figure 10 Power Comparison of Atkinson and Base Engine

5-3- Combustion Analysis

The combustion performance of the engine is highly influenced by the turbulency of in-cylinder flow motion and the EGR rate of the mixture. With the increasing expansion duration of the intake valve, the mixture has more time to flow into the cylinder, resulting in improved turbulency and mixture formation within the engine. Consequently, this can lead to a decrease in combustion duration. The combustion durations of the Atkinson cycle and Otto cycle engines are depicted in Figures 7 and 8, respectively. As shown, the Atkinson cycle exhibits shorter combustion durations in almost all operating points. Furthermore, by retarding the intake valve timing, the EGR rate is decreased compared to the base engine, leading to enhanced combustion stability, as illustrated in Figures 5 and 6. Combustion stability is determined in this study through the covariance of indicated mean effective pressure.

Table 5 Combustion Stability (COV IMEP) of Atkinson Cycle Engine

BMEP (bar)	Engine_Atkinson_Combustion_ Stability (bar)				
9					1.00
8			0.76	0.70	0.72
7		0.58	0.57	0.71	0.59
6	0.65	0.58	0.74	0.82	0.50
5	0.63	0.70	0.86	0.90	0.59
4	0.70	0.80	0.97	0.81	0.78
3	1.01	0.90	0.96	1.12	0.94
2	1.29	1.40	1.16	1.50	1.06
	1000	1500	2000	2500	3000
	Engine Speed (rpm)				

Table 6 Combustion Stability (COV IMEP) of Otto Cycle Engine

BMEP (bar)	Engine_Base_Combustion Stability (bar)				
9					1.2
8			1.2	1.2	1.2
7		1.0	1.1	1.1	1.1
6	0.9	1.0	1.2	1.1	1.3
5	1.0	1.1	1.2	1.3	1.3
4	1.1	1.3	1.3	1.3	1.4
3	1.3	1.5	1.5	1.6	1.5
2	1.8	2.0	1.9	2.0	1.9
	1000	1500	2000	2500	3000
	Engine Speed (rpm)				

Table 7 Combustion Duration of Atkinson Cycle Engine

BMEP (bar)	Engine_Atkinson_Combustion Duration (CA)				
9					23.1
8			19.6	20.4	22.5
7		17.8	19.2	21.4	22.3
6	16.8	16.8	18.1	19.5	22.4
5	14.3	17.3	19.6	21.0	23.3
4	14.6	17.9	19.5	22.2	23.7
3	16.3	18.2	20.1	23.5	25.2
2	15.9	18.9	22.2	22.9	27.5
1	17.4	23.4	23.0	27.0	31.1
	1000	1500	2000	2500	3000
	Engine Speed (rpm)				

Table 8 Combustion Duration of Otto Cycle Engine

BMEP (bar)	Engine_Base_Combustion Duration (CA)				
9					24.2
8			20.4	23.1	24.5
7		19.0	20.6	23.7	24.7
6	15.8	19.1	20.7	23.8	24.6
5	15.5	19.3	20.7	23.9	25.3
4	15.7	19.5	21.3	23.8	25.3
3	16.1	20.7	22.7	25.1	26.8
2	16.6	21.4	24.1	26.5	27.7
1	20.6	25.0	25.2	27.7	29.1
	1000	1500	2000	2500	3000
	Engine Speed (rpm)				

6- Conclusions

- BSFC and Thermal Efficiency are improved in comparison with the base engine on average in different speeds 2.174 percent.
- In the Atkinson Cycle engine, the Torque (WOT condition) is decreased (expect ENSP= 6000) at different speeds of 4.71 percent, where the max torque drop is in ENSP 1000 with 12 percent, and the min torque drop is in ENSP 6000, with 3.2 percent improvement thanks to better calibration in comparison with the base engine.
- The Max power of the Atkinson Cycle engine is 81.7 kw in comparison with the Otto cycle engine with 80 kw both at ENSP 6000.
- Combustion Duration is improved by 1.7 degrees on average in comparison with the Otto Cycle engine.
- Combustion Stability (Covariance of Indicated mean effective Pressure of Cylinder) is improved by 0.45 bar on average in comparison with the Otto Cycle engine.

Acknowledgment

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List of Abbreviation

After Top Dead Center	*ATDC*
After Bottom Dead Center	*ABDC*
Before Bottom Dead Center	*BBDC*
Before Top Dead Center	*BTDC*
Natural Aspirated	*NA*
Engine Speed	*ENSP*
Break Specific Fuel Consumption	*BSFC*
Intake Valve Opening Position at 1mm lift	IVO_{1mm}
Intake Valve Closing Position 1mm lift	IVC_{1mm}
Intake Valve Maximum Lift Position	$IV_{max\ lift}$
Exhaust Valve Opening Position at 1mm lift	EVO_{1mm}
Exhaust Valve Closing Position at 1mm lift	EVC_{1mm}
Exhaust Valve Maximum Lift Position	$EV_{max\ lift}$
Full Load	*FL*
Hybrid Electric Vehicle	*HEV*
Crank angle	*CA*
Indicated mean effective pressure	*IMEP*
Covariance	*COV*

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مقاله پژوهشی

مطالعه مفهومی و تجربی موتور احتراق داخلی با چرخه آتکینسون برای خودروی دورگه دنباله- موازی

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اطلاعات مقاله

کلیدواژه‌ها:
خودروی دورگه
چرخه آتکینسون
مصرف سوخت
بازده حرارتی
تحلیل احتراقی

چکیده

موتور احتراقی با چرخه آتکینسون نقش مهمی را در پیشرفت خودروهای دورگه به واسطه مصرف سوخت بهتر در مقایسه با موتور با چرخه اتو ایفا می‌کند. تحلیل ترمودینامیکی بر مزیت بازده چرخه اتکینسون با در نظر گرفتن عواملی از جمله افزایش نسبت انبساط و نسبت تراکم که به طور کلی تأثیر بر بازده کلی دارد، تأکید می‌کند. این مقاله تغییر چرخه اتو در یک موتور به چرخه آتکینسون با دیرتر بسته شدن دریچه‌های هوا و افزایش نسبت تراکم را بررسی می‌کند. افزایش نسبت تراکم از ۱۰,۷ به ۱۲,۴ با هدف غلبه بر نقص چرخه آتکینسون، که با کاهش نسبت تراکم واقعی رخ می دهد بهینه شده است. نرم افزار جی تی پاور برای شبیه‌سازی عملکرد موتور در نقاط کاری مختلف استفاده شده است و آزمون‌های جامعی برای ارزیابی عملکرد، مصرف سوخت و مشخصه‌های احتراقی موتور آتکینسون اجرا شده است. نتایج تجربی نشان می‌دهد که موتور آتکینسون مصرف سوخت کمتری نسبت به موتور با چرخه اتو دارد و بهترین بازده ترمودینامیکی از ۳۴ به ۳۴٫۶ افزایش یافته است. همچنین بازه نقاط کاری با بازدهی زیاد در موتور آتکینسون افزایش یافته است. علاوه بر این ناحیه کاری با کمترین مصرف سوخت موتور در دورهای متوسط و کُند و در بارهای متوسط و قوی قرار گرفته است.

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