AEEJ : Journal of Automotive Engineering and Vocational Education
Volume: 07, Number: 01, 2026
ISSN: 2722-4031 [online]; 2722-404X [printed]
DOI: https://doi.org/10.24036/aeej.v6i1.313

Fuel Consumption and Air–Fuel Ratio of a Modified-Compression-Ratio Engine Using 8- and 10-Hole Injectors with E90–E100 Bioethanol Blends

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Abstract

High-bioethanol blends require appropriate fuel-injection control, particularly in engines with modified compression ratios. This study evaluated fuel consumption and air–fuel ratio (AFR) of a modified-compression-ratio spark-ignition engine using 8- and 10-hole injectors with E90, E95, and E100 blends. Experiments were conducted at engine speeds from 2000 to 8000 rpm. Fuel consumption was measured using a flow meter, while AFR was recorded during dynamometer testing. Fuel consumption increased with engine speed for both injector types. E90 produced the lowest average fuel consumption, at 1.102 L/hour for the 8-hole injector and 1.209 L/hour for the 10-hole injector. Across all fuel blends, the 8-hole injector showed lower average fuel consumption, whereas the 10-hole injector showed a narrower AFR range. These findings indicate that injector-hole configuration and high-bioethanol blend composition should be considered when tuning fuel delivery in modified-compression-ratio engines.

Keywords
E90–E100 bioethanol blends; injector-hole configuration; modified compression ratio; fuel consumption; air–fuel ratio.

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Submitted : March 13, 2026. Accepted : June 17, 2026. Published : June 30, 2026

INTRODUCTION

Bioethanol has become an important renewable fuel candidate for spark-ignition engines because it can be produced from biomass resources and blended with gasoline to support cleaner and more diversified transportation fuels. Its oxygenated molecular structure and relatively high octane number can improve several combustion-related properties, particularly in engines that require better knock resistance and mixture reactivity [1]. However, the use of bioethanol in gasoline engines is not always followed by lower fuel consumption because ethanol has a lower heating value than gasoline. As a result, higher ethanol fractions may require a larger fuel supply to produce comparable engine output under certain operating conditions [2], [3]. Recent studies on ethanol–gasoline blends have also shown that the response of spark-ignition engines depends not only on the ethanol fraction but also on fuel delivery control, engine speed, and calibration strategy [4]. Therefore, the evaluation of high-bioethanol blends should not be limited to general engine performance or emission indicators; fuel consumption and air–fuel ratio (AFR) must also be examined as key parameters for understanding fuel delivery and mixture formation.

AFR is particularly important when ethanol content increases because ethanol-based fuels have different stoichiometric air requirements from gasoline. If the engine control system does not adequately adjust fuel delivery, the actual mixture may shift toward leaner or richer combustion conditions, depending on engine speed, injection behavior, and fuel composition. Previous work on gasoline blended with ethanol has shown that even a relatively small change from E5 to E10 can alter AFR requirements and lambda regulation, indicating that fuel composition must be considered when evaluating mixture control [5]. This issue becomes more critical for high-bioethanol blends such as E90, E95, and E100 because their fuel properties differ substantially from conventional gasoline.

In addition to fuel composition, injector design also plays a major role in determining fuel atomization and mixture homogeneity. The number of injector holes affects spray formation, droplet breakup, spray penetration, and the distribution of fuel vapor in the intake or combustion region. A more suitable spray pattern can support better air–fuel mixing, while an unsuitable configuration may increase fuel consumption or create less stable AFR behavior. Numerical and experimental studies on injector spray characteristics have shown that in-nozzle flow, breakup processes, nozzle-hole configuration, and injection pressure can strongly affect atomization quality and fuel–air mixing [6], [7]. Therefore, injector-hole variation is a relevant technical variable when evaluating high-bioethanol blends, especially in engines that require precise fuel delivery.

The use of bioethanol is also closely related to compression-ratio modification. Because ethanol has higher knock resistance than conventional gasoline, it can theoretically support operation at a higher compression ratio. A higher compression ratio may improve the potential thermal efficiency of a spark-ignition engine, but the actual outcome depends on the compatibility between fuel properties, injector characteristics, and mixture formation under different engine-speed conditions. Experimental studies on high-compression-ratio spark-ignition engines using ethanol, ethanol–water blends, methanol, or ethanol–gasoline blends have shown that compression-ratio adjustment can influence combustion phasing, efficiency, and operating stability [8], [9]. Nevertheless, these benefits cannot be generalized without considering fuel blend level, injector configuration, and actual AFR behavior.

Although previous studies have widely examined ethanol–gasoline blends, injector spray characteristics, and compression-ratio modification, limited attention has been given to the combined evaluation of injector-hole variation and high-bioethanol blends in a modified-compression-ratio vehicle engine. Recent bioethanol–gasoline studies have shown that bioethanol blends can change engine performance and fuel-use behavior, but the specific comparison between 8-hole and 10-hole injectors under E90, E95, and E100 blends remains insufficiently discussed [10]. This study addresses that gap by evaluating fuel consumption and AFR in a modified-compression-ratio spark-ignition engine using two injector configurations, namely 8-hole and 10-hole injectors, and three high-bioethanol fuel blends, namely E90, E95, and E100, across engine speeds from 2000 to 8000 rpm. The findings are expected to provide preliminary technical insight into how injector-hole configuration and high-bioethanol blend composition are associated with fuel-consumption patterns and AFR behavior under the tested engine conditions.

METHOD

This study used a descriptive experimental method to evaluate fuel consumption and Air–Fuel Ratio (AFR) in a modified-compression-ratio four-stroke spark-ignition engine. The experiment was designed to compare two injector-hole configurations and three high-bioethanol fuel blends under different engine-speed conditions. The injector variations consisted of an 8-hole injector and a 10-hole injector, while the tested fuels consisted of E90, E95, and E100. The engine was operated at 2000–8000 rpm, and the main measured parameters were volumetric fuel consumption and AFR. This experimental design is relevant because injector configuration can influence fuel atomization and mixture formation, while ethanol content affects fuel delivery requirements and AFR behavior in spark-ignition engines [5], [6], [11]–[13].

The test engine used in this study was a modified 132 cc spark-ignition engine equipped with a PGM-FI fuel injection system. The engine had a bore × stroke of 55.25 × 55.1 mm, an automatic V-Matic transmission, and a modified compression ratio of 14:1. The main specifications of the modified engine are presented in Table 1.

Table 1. Specifications of the modified test engine

Specification	Description
Engine capacity	132 cc
Fuel supply system	Injection system (PGM-FI)
Bore × stroke	55.25 × 55.1 mm
Transmission type	Automatic, V-Matic
Compression ratio	14:01
Starter type	ACG starter, pedal, and electric starter
Clutch type	Automatic, centrifugal, dry type

Two injector configurations were used in the experiment. The first injector had eight holes, while the second injector had ten holes. The injector configuration was treated as the main technical variable because the number of nozzle holes can influence fuel spray distribution, atomization characteristics, and mixture homogeneity [6], [12]. The injector types used in this study are shown in Table 2.

Table 2. Injector configurations used in the experiment

Injector type	Number of holes
8-hole injector	8 holes
10-hole injector	10 holes

The fuel variable consisted of three high-bioethanol blends, namely E90, E95, and E100. E90 consisted of 90% ethanol and 10% gasoline, E95 consisted of 95% ethanol and 5% gasoline, and E100 consisted of 100% ethanol. The fuel blends were prepared by volume according to the composition shown in Table 3. These blend levels were selected to observe the behavior of high-ethanol fuel mixtures in a modified-compression-ratio engine, particularly in relation to fuel consumption and AFR response [11], [13]–[15].

Table 3. Fuel blend variations tested in the experiment

Fuel type	Blend composition	Ethanol percentage (%)	Gasoline percentage (%)
E90	90% ethanol + 10% gasoline	90	10
E95	95% ethanol + 5% gasoline	95	5
E100	100% ethanol	100	0

The experimental setup is illustrated in Figure 1. The setup consisted of a test motorcycle mounted on a chassis dynamometer, a fan for cooling airflow, a monitor display for measurement observation, a fuel-mixture supply system, a temperature indicator with thermocouple, a fuel-consumption measurement unit, and an exhaust gas analyzer connected through an exhaust sampling line. The chassis dynamometer was used to support controlled engine-speed testing, while the flow meter was used to measure the volume of fuel consumed during each test condition. AFR was recorded through the exhaust-gas measurement system during the dynamometer test. Similar engine-test arrangements using dynamometer-based operation, fuel-consumption measurement, and exhaust-gas/AFR observation have been used in previous ethanol-blend engine studies [12], [13].

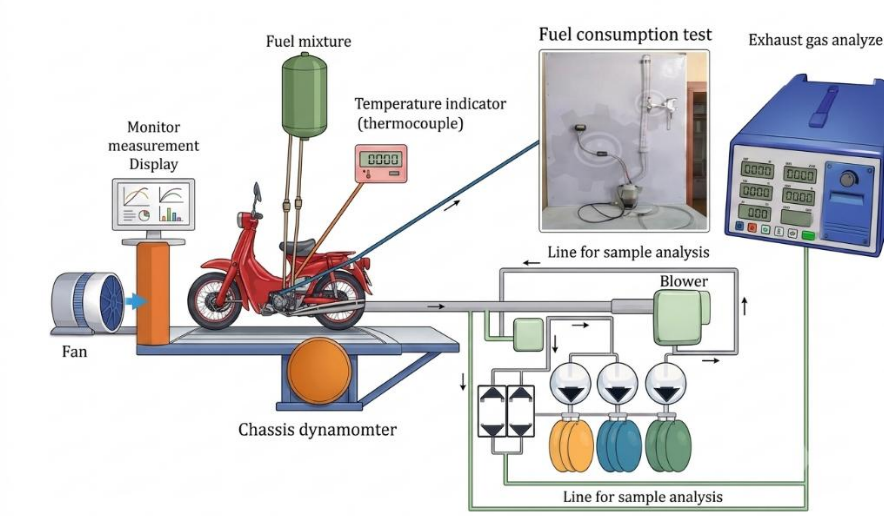

Figure 1. Experimental setup for engine fuel-consumption and AFR measurement

The test procedure began by preparing the engine and ensuring that it was in a proper operating condition for measurement. Each injector configuration was installed and tested separately. For each injector type, the three fuel blends were tested sequentially. The engine was operated at engine speeds from 2000 to 8000 rpm. At each speed condition, the engine was maintained in a stable operating state for 60 s. During this period, the fuel volume consumed was recorded using the flow meter, and the AFR value was recorded from the exhaust-gas measurement system. The same measurement sequence was applied to the 8-hole and 10-hole injector configurations to maintain comparability among the test conditions.

Fuel consumption was calculated as a volumetric fuel consumption rate using the measured fuel volume and the measurement duration. The equation used in this study is expressed as follows.

$$BFC = \frac{V_f}{t} \times \frac{3600}{1000} \qquad (1)$$

where BFC is the volumetric fuel consumption rate (L/hour), Vf is the volume of fuel consumed during the test period (mL), and t is the measurement duration (s). The factor 3600 converts seconds to hours, while the factor 1000 converts milliliters to liters.

The collected data were tabulated and compared descriptively based on injector type, fuel blend, and engine speed. Fuel-consumption data were used to compare the fuel-use pattern of the 8-hole and 10-hole injectors, while AFR data were used to observe the air–fuel mixture response under E90, E95, and E100 fuel conditions. The analysis focused on identifying the lowest average fuel consumption, the variation of fuel consumption across engine speeds, and the AFR range produced by each injector and fuel-blend combination.

RESULT AND DISCUSSION

Results

The results are presented according to the two main measured parameters, namely fuel consumption and Air–Fuel Ratio (AFR). Fuel consumption was evaluated for the 8-hole and 10-hole injectors using E90, E95, and E100 fuel blends at engine speeds from 2000 to 8000 rpm. AFR was then observed under the same injector and fuel-blend variations.

The first test examined fuel consumption using the 8-hole injector. The fuel-consumption data for the 8-hole injector are presented in Table 4 and visualized in Figure 2.

Table 4. Fuel consumption of the 8-hole injector

RPM	Fuel Consumtpion (L/hour)		
	E90	**E95**	**E100**
2000	0.56	0.568	0.544
3000	0.648	0.688	0.616
4000	0.748	0.796	0.808
5000	0.98	0.916	1.052
6000	1.38	1.408	1.464
7000	1.58	1.504	1.572
8000	1.816	1.888	1.764
Average	**1.102**	**1.11**	**1.117**

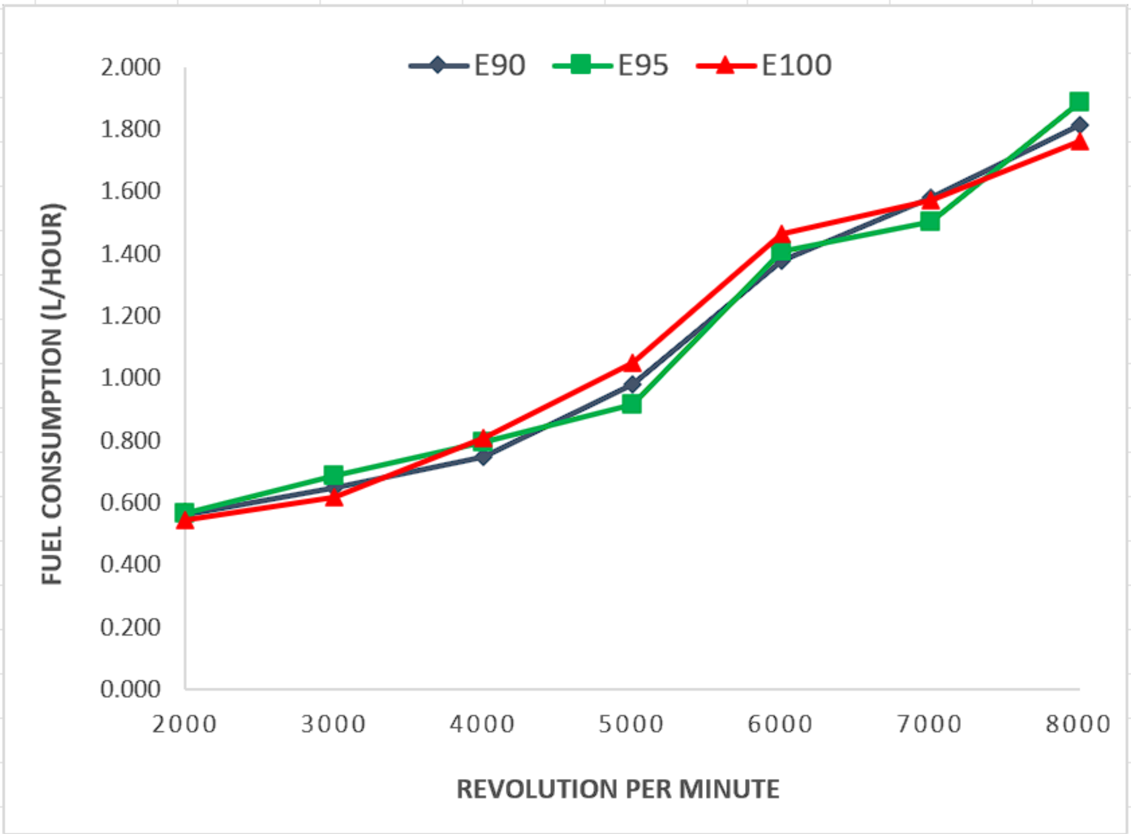

Figure 2. Fuel-consumption trend of the 8-hole injector using E90, E95, and E100 fuel blends

Table 4 and Figure 2 show that fuel consumption for the 8-hole injector increased as engine speed increased for all fuel blends. At 2000 rpm, fuel consumption was 0.560 L/hour for E90, 0.568 L/hour for E95, and 0.544 L/hour for E100. At 8000 rpm, the values increased to 1.816 L/hour for E90, 1.888 L/hour for E95, and 1.764 L/hour for E100. Based on the average values, E90 produced the lowest average fuel consumption at 1.102 L/hour, followed by E95 at 1.110 L/hour and E100 at 1.117 L/hour. The difference among the average values was relatively small.

The second test examined fuel consumption using the 10-hole injector. The results are presented in Table 5 and Figure 3.

Table 5. Fuel consumption of the 10-hole injector

RPM	**Fuel Consumtpion (L/hour)**		
	E90	**E95**	**E100**
2000	0.624	0.564	0.636
3000	0.792	0.632	0.676
4000	0.884	0.928	0.98
5000	1.044	1.108	1.156
6000	1.596	1.572	1.64
7000	1.632	1.76	1.752
8000	1.888	1.94	1.884
Average	**1.209**	**1.215**	**1.246**

Figure 3. Fuel-consumption trend of the 10-hole injector using E90, E95, and E100 fuel blends

Table 5 and Figure 3 show that fuel consumption for the 10-hole injector also increased with engine speed across all fuel blends. The highest fuel-consumption values were recorded at 8000 rpm for all fuel variations, namely 1.888 L/hour for E90, 1.940 L/hour for E95, and 1.884 L/hour for E100. The average fuel consumption was lowest for E90 at 1.209 L/hour, followed by E95 at 1.215 L/hour and E100 at 1.246 L/hour. When compared with the 8-hole injector, the 10-hole injector produced higher average fuel consumption for all tested fuel blends.

The next test examined AFR behavior using the 8-hole injector. The AFR data for the 8-hole injector are presented in Table 6 and visualized in Figure 4.

Table 6. Air–Fuel Ratio of the 8-hole injector

RPM	E90	E95	E100
2000	12.653	13.377	13.273
3000	13.55	14.08	14.89
4000	15.353	15.637	16.86
5000	16.843	16.697	18.08
6000	15.213	16.163	17.18
7000	14.067	14.16	14.563
8000	13.693	13.973	14.177

Figure 4. AFR trend of the 8-hole injector using E90, E95, and E100 fuel blends

Table 6 and Figure 4 show that the AFR values of the 8-hole injector generally increased from low engine speed to the mid-speed range and then decreased at higher engine speeds. The highest AFR value was recorded for E100 at 5000 rpm, reaching 18.080. The lowest AFR value was recorded for E90 at 2000 rpm, with a value of 12.653. Among the tested fuel blends, E100 generally produced higher AFR values than E90 and E95, especially from 3000 to 7000 rpm.

The final test examined AFR behavior using the 10-hole injector. The results are presented in Table 7 and Figure 5.

Table 7. Air–Fuel Ratio of the 10-hole injector

RPM	E90	E95	E100
2000	12.707	12.837	12.573
3000	14.307	14.403	13.46
4000	13.55	14.313	14.363
5000	15.473	15.177	15.08
6000	13.583	13.98	14.393
7000	13.703	13.443	13.623
8000	13	12.993	12.863

Figure 5. AFR trend of the 10-hole injector using E90, E95, and E100 fuel blends

Table 7 and Figure 5 show that the AFR values of the 10-hole injector varied within a narrower range than those of the 8-hole injector. The highest AFR value was recorded for E90 at 5000 rpm, reaching 15.473, while the lowest value was recorded for E100 at 2000 rpm, with a value of 12.573. Across the tested fuel blends, the AFR values for the 10-hole injector remained relatively close to one another, particularly at 5000 rpm and 8000 rpm.

Discussion

The fuel-consumption results for the 8-hole injector show a clear increase as engine speed increased from 2000 to 8000 rpm, as presented in Table 4 and Figure 2. This pattern is expected because higher engine speed requires more frequent combustion cycles and a greater fuel supply per unit time. Among the tested blends, E90 produced the lowest average fuel consumption at 1.102 L/hour, followed by E95 and E100. The relatively small difference among the average values indicates that the three high-bioethanol blends produced comparable fuel-use behavior under the tested 8-hole injector condition. However, the slightly lower average consumption of E90 may be related to the presence of a small gasoline fraction, which can improve the energy contribution of the blend compared with fuels containing a higher ethanol fraction. Previous studies on bioethanol–gasoline blends have reported that increasing ethanol concentration can modify fuel-consumption behavior because ethanol has a lower heating value than gasoline, even though it offers a higher oxygen content and octane advantage [16], [17].

A similar fuel-consumption pattern was observed for the 10-hole injector, as shown in Table 5 and Figure 3. Fuel consumption increased with engine speed for all fuel blends, and E90 again produced the lowest average value at 1.209 L/hour. The average fuel consumption of the 10-hole injector was higher than that of the 8-hole injector for all tested blends. This finding suggests that, under the specific experimental conditions of this study, the 10-hole injector configuration was associated with a higher volumetric fuel-use rate. This does not necessarily mean that the 10-hole injector was less suitable in all operating contexts, because injector behavior depends on spray distribution, injection pressure, injector flow capacity, engine load, and calibration strategy. In modified-compression-ratio engines, the final fuel-use response is influenced not only by ethanol fraction but also by the interaction between fuel properties, mixture preparation, and compression-ratio compatibility [18], [19].

The comparison between the 8-hole and 10-hole injectors also indicates that fuel consumption and mixture behavior should not be evaluated from injector-hole number alone. Although more injector holes may support wider spray distribution and better atomization under certain conditions, this benefit depends on whether the injected fuel quantity and spray pattern match the engine's air demand and combustion chamber conditions. In this study, the 8-hole injector produced lower average fuel consumption, while the 10-hole injector showed a different AFR response. This indicates a trade-off between fuel-use rate and mixture-control behavior. Studies on alcohol-containing fuels have shown that oxygenated fuel blends can change combustion stability, mixture reactivity, and engine response depending on the fuel composition and combustion system [20]. In high-compression-ratio SI engines, ethanol–gasoline blends may improve knock resistance and combustion tolerance, but their effects on fuel consumption and mixture formation remain sensitive to operating speed and calibration [21].

The AFR results for the 8-hole injector, shown in Table 6 and Figure 4, reveal that AFR increased from low engine speed to the mid-speed range and then decreased at higher engine speeds. The highest value was recorded for E100 at 5000 rpm, while the lowest value was recorded for E90 at 2000 rpm. This pattern suggests that the 8-hole injector produced a wider AFR variation across fuel blends and engine speeds. The higher AFR values observed for E100 from 3000 to 7000 rpm may be associated with the oxygenated nature of ethanol and the different stoichiometric air requirement of high-ethanol fuels. Nevertheless, the AFR values should be interpreted carefully because the stoichiometric AFR of ethanol-rich blends differs from that of gasoline. Therefore, a high numerical AFR value does not automatically indicate the same lean-combustion condition as in gasoline operation. Modeling and experimental studies of ethanol–gasoline blends have similarly shown that ethanol content can alter combustion behavior, fuel requirement, and exhaust-gas characteristics because of its different chemical and thermophysical properties [22], [23].

The AFR results for the 10-hole injector, presented in Table 7 and Figure 5, show a narrower AFR range than that observed with the 8-hole injector. The highest AFR value was recorded for E90 at 5000 rpm, while the lowest value was recorded for E100 at 2000 rpm. The narrower AFR variation indicates that the 10-hole injector provided a more consistent air–fuel mixture response under the tested conditions. This may be associated with the spray-distribution characteristics of the injector, which can influence how the fuel is atomized and mixed with air before combustion. However, because this study did not directly measure spray angle, droplet size, injection pressure, or in-cylinder mixture distribution, the explanation should be treated as a possible interpretation rather than a definitive mechanism. Previous studies on DI SI engines and ethanol-containing fuels have shown that alcohol blends can affect mixture preparation, combustion response, and fuel-conversion behavior, but the final outcome strongly depends on injection strategy, engine configuration, and operating condition [24], [25].

Overall, the findings show that injector-hole configuration and high-bioethanol blend composition produced different fuel-consumption and AFR patterns in the modified-compression-ratio engine. E90 gave the lowest average fuel consumption for both injector types, while the 8-hole injector showed lower average fuel consumption than the 10-hole injector across the tested fuel blends. In contrast, the 10-hole injector produced a narrower AFR range, indicating a more consistent mixture response during the test. These results suggest that the selection of injector configuration for high-bioethanol operation should consider the intended control target. If the priority is lower fuel consumption under the tested conditions, the 8-hole injector is more favorable. If the priority is a narrower AFR variation, the 10-hole injector may provide an advantage. However, these conclusions remain limited to the tested engine, compression ratio, fuel blends, rpm range, and measurement conditions. Additional testing involving engine load variation, repeated trials, injection pressure measurement, lambda-based AFR correction, power output, torque, and exhaust emissions would be required before a broader performance claim can be made.

CONCLUSION

Conclusion

This study evaluated fuel consumption and Air–Fuel Ratio (AFR) in a modified-compression-ratio spark-ignition engine using 8-hole and 10-hole injectors with E90, E95, and E100 bioethanol blends. The results show that fuel consumption increased with engine speed for both injector configurations and all tested fuel blends. Among the tested fuels, E90 produced the lowest average fuel consumption in both injector configurations, with 1.102 L/hour for the 8-hole injector and 1.209 L/hour for the 10-hole injector. The comparison between injector configurations indicates that the 8-hole injector produced lower average fuel consumption than the 10-hole injector under the tested conditions. In contrast, the 10-hole injector showed a narrower AFR variation than the 8-hole injector, indicating a more consistent air–fuel mixture response across the tested fuel blends and engine-speed range. These findings suggest that injector-hole configuration and high-bioethanol blend composition should be considered together when evaluating fuel delivery behavior in modified-compression-ratio engines.

Overall, the 8-hole injector with E90 may be more favorable when the main target is lower fuel consumption, while the 10-hole injector may be more suitable when the priority is maintaining a narrower AFR variation. However, these conclusions are limited to the tested engine configuration, fuel blends, injector types, and engine-speed range. Further studies should include repeated trials, different engine loads, broader compression-ratio variations, injection-pressure measurement, power and torque evaluation, thermal-efficiency analysis, and exhaust-emission testing to provide a more comprehensive assessment of high-bioethanol fuel application in spark-ignition engines.

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