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EFFECT OF THE NUMBER OF INJECTOR HOLES AND GASOLINE ETHANOL BLENDED ON FUEL CONSUMPTION, AFR, AND ENGINE PERFORMANCE

Summary. This study examines the effect of variations in the number of injector holes and bioethanol blended on fuel consumption, Air-Fuel Ratio (AFR), torque, and power in a four-stroke petrol engine through laboratory experiments. The injectors tested included 6 holes (compression ratio 9.5:1) and 8 and 10 holes (compression ratio 14.0:1), with E0-E80 fuel for 6 holes and E90-E100 for 8-10 holes. The results show that fuel consumption increases with engine speed in all configurations. The 6-hole injector was relatively efficient at low to medium speeds, but consumption increased sharply at high speeds, especially with high ethanol blends. The 8- and 10-hole injectors showed a more linear increase in consumption. The AFR pattern for the 6-hole injector tended to decrease with increasing RPM, while for the 8- and 10-hole injectors, it increased up to medium speeds and then decreased again. Peak torque and power occur at medium RPM and shift to higher RPM at a compression ratio of 14.0:1. The results confirm that

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performance is influenced by the interaction of injector configuration, compression ratio, and RPM range.

Keywords: bioethanol, hole injector, compression ratio, fuel consumption, air fuel ratio, power torque

1. INTRODUCTION

Improved sustainable and lower-emission fuels are required for the transportation sector's energy transition due to rising fuel usage and diminishing oil sources [1]. Bioethanol is emerging as a promising alternative to gasoline, as highlighted in studies [2], [3], [4]. This is due to its biomass origin, high-octane number, and the possibility of improved combustion quality, leading to a reduction in specific emissions. Despite certain difficulties with implementation, its use is still considered strategically important for Indonesia's energy security, as stated in [5]. Based on empirical [6] evidence on small motorcycle gasoline engines, ethanol-petrol mixtures can change consumption and performance, with some compositions benefiting more than others. However, the outcomes are very conditional on the injection system's suitability, operating conditions, and air-fuel mixture formation strategies.

Ethanol, as an oxygenated fuel, possesses distinct thermophysical properties compared to gasoline, necessitating meticulous mixture control for steady and efficient burning. Numerous studies on small engines such as [7] and [8] fuel-injected motorcycles have demonstrated the presence of an optimal range in low to medium mixtures (E10-E30/E25) that can enhance torque or power, specific fuel consumption, and emissions under specific testing conditions, while also resulting in trade-offs (increased consumption despite reduced CO emissions) contingent upon engine composition and configurations. These findings affirm that the augmentation of the ethanol fraction cannot be assessed exclusively in relation to fuel, but must be comprehended as a consequence of the interplay among fuel characteristics, mixture formation, and combustion regulation.

Bioethanol optimization is intrinsically linked to the injection system, as the study [9] the ECU regulates both the volume and timing of the injection to meet the AFR target. An extended injection duration results in increased fuel discharge, thus; modifications to the injector can directly influence the mixture formation and combustion. The injector is crucial for atomizing the fuel to ensure a uniform mixture, and the quantity of injector orifices (multi-holes) influences the spray characteristics, including droplet distribution, spray angle, penetration, and atomization quality, which in turn affects torque, power, fuel consumption, and emissions [9], [10]. Nonetheless, actual research on variances in the injection hole on single spark ignition engines demonstrates findings that do not consistently align: in certain contexts, 8-hole injectors are deemed more inefficient and produce greater emissions compared to the standard 6-hole configuration, whereas a 12-hole arrangement may decrease consumption within a specific range; some studies even indicate negligible differences in torque, power, and consumption for various hole configurations [10], [11]. Another study [12], [13] suggests that the impact of injector hole quantity is significantly affected by operational conditions and system configurations, consistent with the mechanistic rationale that variations in the effective diameter/area of the hole will alter droplet size and spray formation dynamics.

Despite advancements in the literature about ethanol blends (namely E0-E30) and variations in hole injectors, significant gaps remain in the development of high bioethanol-based engines. Initially, research [14], [15] on single-cylinder spark ignition engines predominantly focuses on low to medium mixes, resulting in scant evidence for the complete spectrum of E0 to E100.

Secondly, the outcomes of hole injector modifications differ among vehicles and testing situations; hence, a design that explicitly examines interaction effects is necessary, rather than only comparing a single variable [12]. Third, comprehensive studies that integrate the E0-E100 range, variations in 6/8/10-hole injectors, and modifications in compression ratios for injection motorcycles are scarce, despite the literature highlighting that enhancing efficiency and minimizing emissions typically necessitates a systemic optimization of combustion rather than merely substituting materials [16]. This study assessed the impact and interaction of E0-E100 bioethanol concentrations with variations in 6-hole, 8-hole, and 10-hole injectors in motorcycle engines that had undergone modifications to their compression ratios. The research aims to delineate performance responses (torque and power), consumption metrics (e.g., BSFC or dynamometer test metrics), and indicators of blend formation (AFR/lambda or injector duration/duty cycle when applicable) to ascertain configurations that facilitate stable and efficient combustion at elevated bioethanol levels while offering more robust technical recommendations than the context-dependent one best blend conclusion.

2. RESEARCH METHODOLOGY

This study used an experimental method to directly analyze the effect of variations in the number of injector holes and bioethanol mixtures on fuel consumption, Air-Fuel Ratio (AFR), and torque and power in four stroke spark ignition engine vehicles as listed in Table 1 with a compression ratio as shown in Table 2.

Tab. 1
Motorcycle Specification

Engine Specifications	
Machine capacity	108.2 cc
Fuel supply system	Injection
Diameter x steps	50 x 55.1 mm
Transmission type	Automatic, V-Matic
Compression ratio	9.5:1
Maximum power	6.38 KW (8.68 PS)/7,500 rpm
Maximum torque	9.01 Nm (0.92 Kgf.m)/6,500 rpm
Starter type	ACG Starter, Pedal & Electric
Clutch type	Automatic, Centrifugal, Dry Type

Tab. 2
Injector Type and Compression

Injector Type	Compression Ratio
6-hole injector (Standard)	9.5:1 (Standard)
Injector 8 hole	14,0:1
Injector 10 hole	14,0:1

Tab. 3

Variations of Mixed Test

Fuel Type	Mixed Composition	Ethanol Percentage (%)	Gasoline Percentage (%)
E0	Ethanol Blend 0% + 100% Gasoline	0	100
E20	Ethanol Blend 20% + Gasoline 80%	20	80
E40	Ethanol Blend 40% + Gasoline 60%	40	60
E60	Ethanol Blend 60% + Gasoline 40%	60	40
E80	80% Ethanol Blend + 20% Gasoline	80	20
E90	Ethanol Blend 90% + Gasoline 10%	90	10
E95	Ethanol Blend 95% + Gasoline 5%	95	5
E100	100% ethanol	100	0

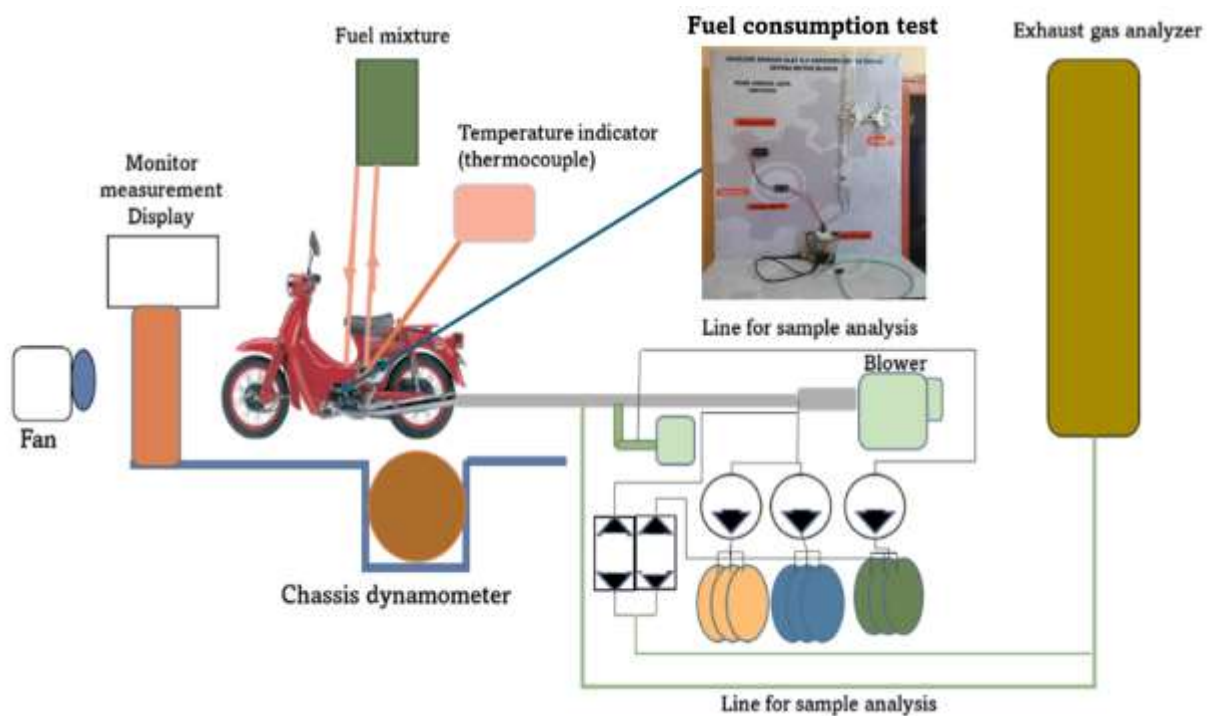


Fig. 1. Engine measurement arrangement

The injector variations used consisted of 6 holes, 8 holes, and 10 holes as shown in table 2, while the fuel tested included eight levels of bioethanol mixtures, namely E0, E20, E40, E60, E80, E90, E95, and E100, as listed in Table 3. Fuel consumption rate measurements were carried out using a flow meter during data collection, while AFR and torque and power

measurements were carried out using dyno tests. The research procedure began by preparing the engine measurement (Fig 1) test-worthy conditions, then installing and testing three injector variations, namely 6 holes, 8 holes, and 10 holes. The test fuel is prepared in eight levels of bioethanol blends (E0, E20, E40, E60, E80, E90, E95, E100) and homogenized before testing. Consumption measurement is carried out by installing a flow meter on the fuel system; the engine is run at the specified RPM and kept constant for 60 seconds, then the volume of fuel used is recorded and converted into a consumption rate (L/h). In this study, fuel consumption is calculated by equation [17]:

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

Description:

BFC – Fuel consumption (L/hour)

V_f – The amount of fuel consumed during *t* seconds (ml)

t – Time taken to consume fuel(s)

Therefore, this research will be carried out using this formula because it will determine fuel consumption in L/hour. AFR, torque, and power measurements were carried out using a dyno test according to a laboratory configuration in the range of 2000-8000 rpm at each point the RPM data is recorded after a stable reading. All stages are repeated for each combination of injectors and bioethanol mixtures, and then the results are presented in tables and graphs to be analyzed based on trends in RPM as well as differences between injector and fuel variations.

3. RESULTS AND DISCUSSION

The test results in the table summarize changes in fuel consumption rate, AFR, and torque and power in four-stroke spark ignition engine vehicles for 6-hole, 8-hole, and 10-hole injector variations, E0-E100 bioethanol blends, and specific RPM ranges. The graph shown shows the consumption rate, AFR shift, and torque-power changes so that the influence of injector configuration and bioethanol content on performance and combustion characteristics under each test condition can be seen.

3.1. Analysis of 6 Hole Injector Fuel Consumption Test Results

The (Fig. 2) showed a 6-hole injector test; the engine still uses a standard compression ratio of 9.5:1. Fuel consumption for E0-E80 is still low at 1500-3500 rpm (± 0.27 -0.34 L/h), then rises sharply starting at around 4500 rpm and peaks at 7500 rpm. At high revs, the high ethanol blends of E60-E80 tend to be the most wasteful (7500 rpm: E80 0.988 L/h and E60 0.984 L/h), while E0 and E40 are more economical (0.764 and 0.788 L/h). This result is in line with Bahri [18] which says consumption is influenced by engine performance and injection timing; in his research, E15 = 0.75 L/hour and the most economical E45 = 0.66 L/hour. The difference is that the most economical mixture in each study can be different because the RPM range, the composition of the mixture being tested, and the engine/injection setting are not the same.

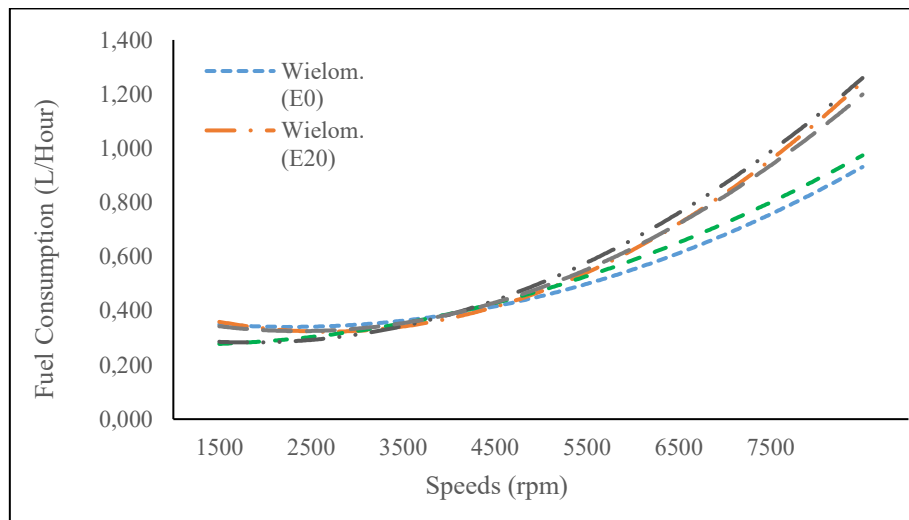


Fig. 2. Comparison of ethanol blend fuel consumption rates in 6-hole injector

3.2. Analysis of 8 Hole Injector Fuel Consumption Test Results

In the 8-hole injector (Fig. 3), the compression ratio has been modified to 14.0:1, so the combustion conditions are different from standard engines. E90-E100 consumption rose almost linearly from ± 0.54 - 0.57 L/h (2000 rpm) to ± 1.76 - 1.89 L/h (8000 rpm), and the difference between mixtures was small and often intersecting. Meanwhile, Farida [19] tested the E100 by changing the injection duration to 5.16-5.96 ms. Reported consumption varied widely, from 10.16-14.11 ml/min (lowest) to 25.57-33.33 ml/min (highest), indicating consumption was highly sensitive to the injection duration setting.

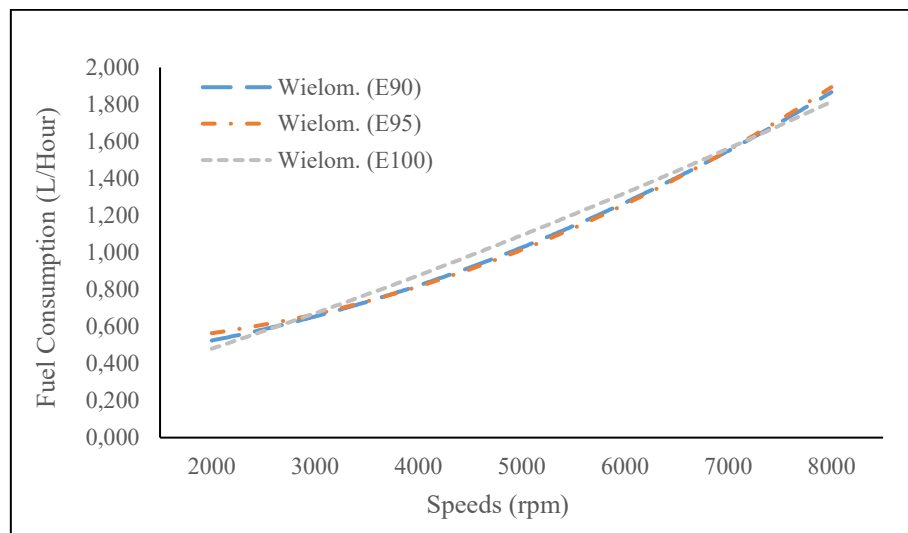


Fig. 3. Comparison of ethanol blend fuel consumption rates in 8-hole injector

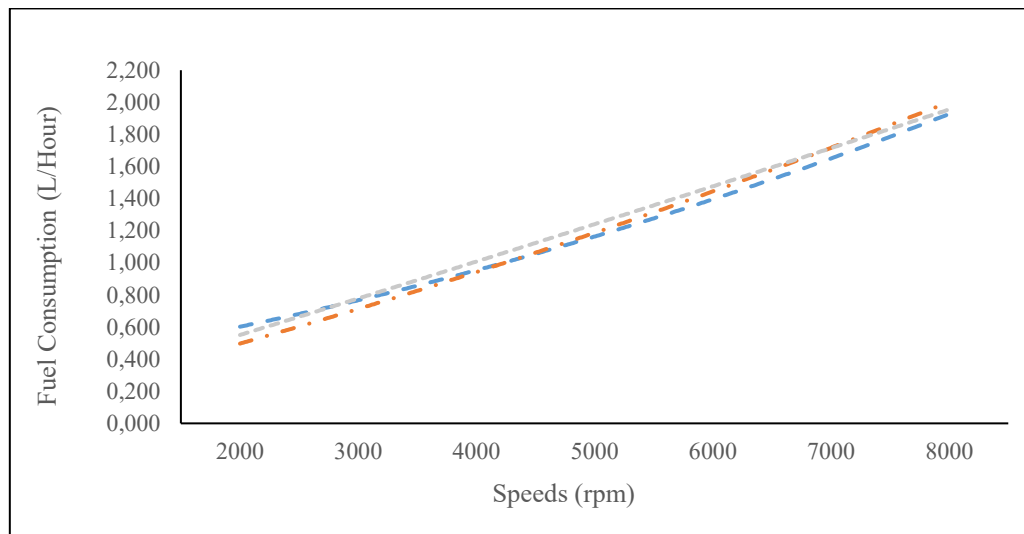


Fig. 4. Comparison of ethanol blend fuel consumption rates in 10-hole injector

3.3. Analysis of 10 Hole Injector Fuel Consumption Test Results

In Figure 4 (10-hole injector configuration with a compression ratio of 14.0:1), it can be seen that fuel consumption for the entire mixture increases almost linearly with increasing RPM, from approximately ± 0.56 - 0.64 L/hour at 2000 rpm to ± 1.88 - 1.94 L/hour at 8000 rpm. Unlike other configurations where the curves are often close together, in the 10-hole injector the curves between mixtures appear more “separated” across most of the rpm range: at 2000-3000 rpm the lowest consumption is shown by E95 (2000 rpm 0.564 L/hour; 3000 rpm 0.632 L/hour), while at 4000-6000 rpm, E90 tends to be the lowest (e.g., 5000 rpm 1.044 L/hour; 6000 rpm 1.596 L/hour), while E100 is relatively higher. Entering the high rev range of 7000-8000 rpm, the difference between the mixtures begins to decrease, but E90 is still the lowest at 8000 rpm (1.888 L/hour) and E95 is the highest (1.940 L/hour). This is also supported by the average values, which show the consumption order as E90 = 1.209 L/hour (lowest), E95 = 1.215 L/hour, and E100 = 1.246 L/hour (highest). Thus, under high compression conditions of 14.0:1, the E90 blend appears to be the most efficient on average for the 10-hole injector, while increasing the ethanol content toward E100 tends to increase consumption at many operating points.

3.4. Analysis of 6 Hole Injector AFR Test Results

Results: The results of this study show (Fig. 5) that in a 6-hole injector with a standard compression ratio of 9.5:1, the AFR value tends to decrease as the RPM increases, meaning that the mixture becomes richer at high revs. For the E0-E40, the AFR is relatively tight and lower: about 14,620-15,197 (2000 rpm) drops to $\pm 12,710$ -13,950 (8000 rpm). In contrast, in high ethanol E60-E80, the AFR is much higher at low-medium (poorer) RPM, for example at 3000 rpm: E60 = 21.573 and E80 = 20.308, then drops to close to ± 15.007 -15.283 at 8000 rpm. This means that high ethanol tends to make the mixture poorer at low-medium RPMs, but the difference is smaller at high RPMs. In contrast, Miti's research [20] tests lower ethanol blends (only up to E25) so that the AFR obtained is more stable and in the narrow range of ± 12 -15. The curve tends to go down in the initial laps, then rises or stabilizes again in the mid-high laps (around 6000-12000 rpm) with a small difference between the mixtures. So, the main difference is in the mixed range: the Miti [20] study showed moderate AFR changes in low ethanol, while

this study shows that in high ethanol (E60-E80) the AFR response can be much more extreme at low-medium RPMs before returning to close to the same range at high RPMs.

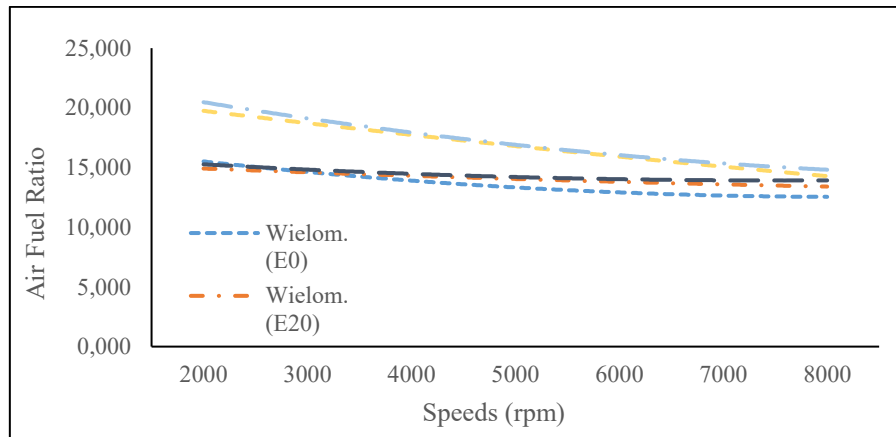


Fig. 5. Comparison of ethanol blend air-fuel ratio in 6-hole injector

3.5. Analysis of 8 Hole Injector AFR Test Results

An 8-hole injector (Fig. 6) with a compression ratio of 14.0:1, the AFR forms an ascending pattern to a medium round and then descending again. The AFR rose from 12,653-13,377 (2000 rpm) to a peak of about 5000 rpm with peak values of E90 = 16,843, E95 = 16,697, and E100 = 18,080, then dropped to 13,693-14,177 at 8000 rpm. In general, the E100 produces the highest AFR (lean), but the difference between mixtures is smaller at high RPMs, so the AFR change is more influenced by the engine operating zone than the thin difference in composition in the E90-E100. In contrast to Adinugroho's research [21] (RON 92; E10-E25), AFR is reported to be relatively stable at low-medium RPMs (about 12.5-14) and only increases markedly at high RPMs, especially after 11,000 rpm, with the largest spike in E25. So, Adinugroho [21] shows that the tendency of the machine is getting more and more lean, especially at very high RPMs, whereas this study shows a tendency to lean that was already strong in the intermediate round (± 5000 rpm) and then approached again at 8000 rpm.

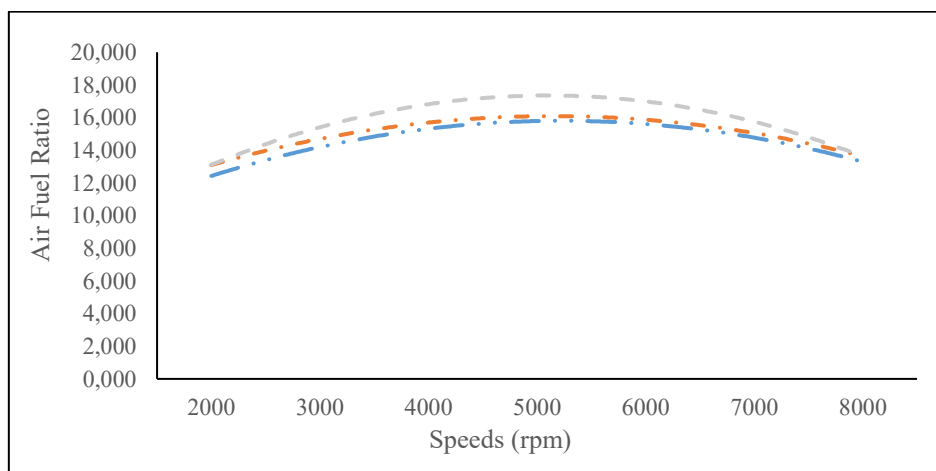


Fig. 6. Comparison of ethanol blend air-fuel ratio in 8-hole injector

3.6. Analysis of 10 Hole Injector AFR Test Results

The AFR of the three mixtures forms an increasing pattern at medium revs and then declining again at high revs, with very tight spacing between the curves as shown in (Fig. 7). The AFR increased from about 12,573-12,837 (2000 rpm) to a peak at around 5000 rpm (E90 15,473; E95 15,177; E100 15,080), then dropped to close to 12,863-13,000 at 8000 rpm. The difference between the mixtures is small throughout the RPM range, but at peak the E90 is slightly higher than the E95 and E100, while at high revs the E100 is the lowest (8000 rpm 12.863). With a compression ratio of 14.0:1, these results indicate that in the 10-Hole Injector configuration, the effect of the E90-E100 mixture variation on AFR is relatively minimal, and the dominant main character is the presence of the AFR peak zone at the intermediate rotation before the AFR drops back down at the high rotation.

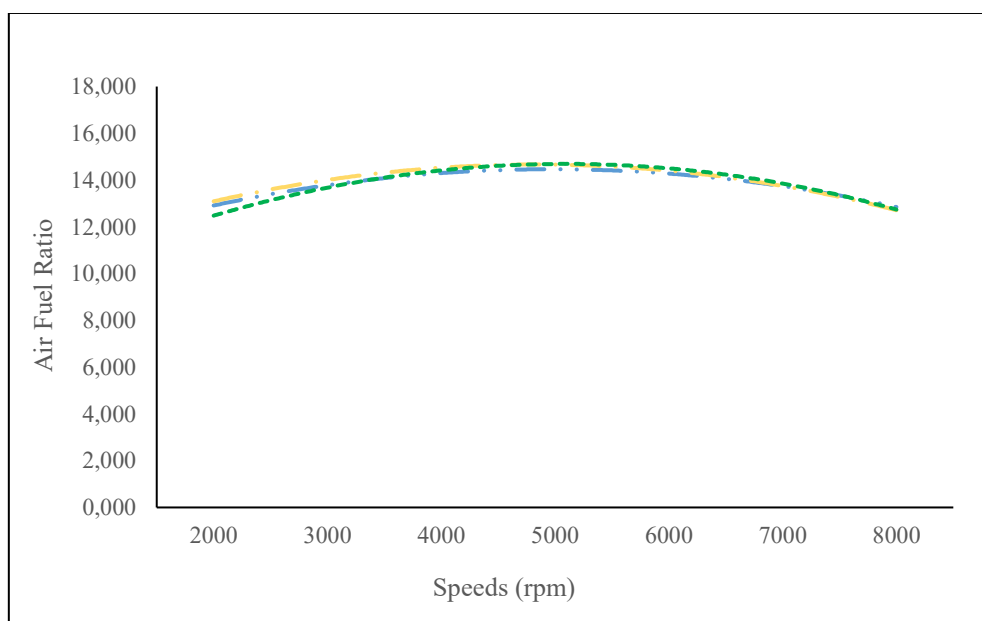


Fig. 7. Comparison of ethanol blend air-fuel ratio in 10-hole injector

3.7. Analysis of 6 Hole E0 Injector Power Torque Test Results

In this study (Fig. 8) engine measurement standard with a 6-hole injector, and a compression ratio of 9.5:1, E0, torque peaked at 5,400 rpm (7.42 Nm) and peak power at 5,800 rpm (6.04 hp) both decreased at higher RPMs with faster torque decreasing than power. This shows that the optimum performance is in the medium round, while at high rounds the loss increases so that the torque weakens first and the power is relatively more durable before descending. Zechariah's Research [22] It shows different peaks, namely maximum torque at 3,500 rpm and maximum power at 7,500 rpm. At 4,500 rpm, torque reportedly rises by about 3% , but power drops by about 10% because the calorific value of the ethanol-gasoline mixture is lower, so changes in fuel composition can increase torque without always increasing power at certain operating points. Meanwhile, Sugati research [23] shows an "up-peak-down" pattern with peak torque at 6,000 rpm and peak power at 7,000 rpm, as well as a drop at high revs associated with friction loss; Sugati also found that low ethanol (E10) slightly improved performance compared to E0 and E5. Overall, the three results confirm that the peak position of torque-power and

response to fuel are strongly influenced by the RPM range, the type of mixture, as well as the difference in test objects and engine configuration.

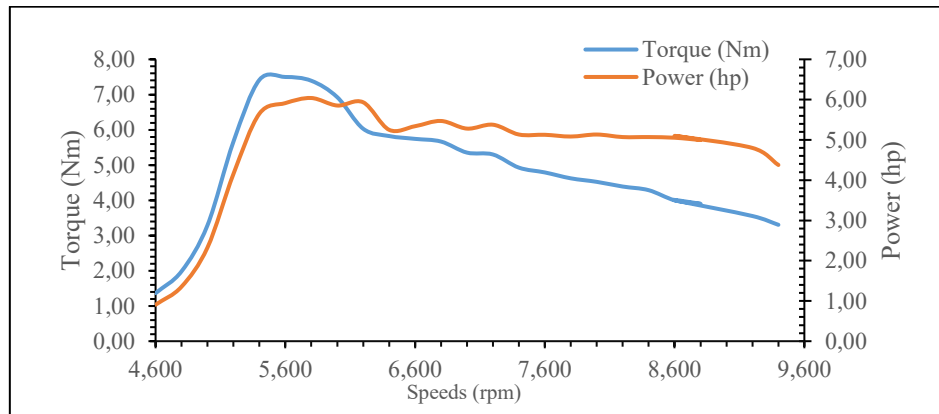


Fig. 8. The effect of E0 power and torque in 6-hole injector

3.8. Analysis of 8 Hole E90 Injector Power Torque Test Results

The 8-hole E90 (Fig. 9) injector configuration with a compression ratio of 14.0:1 indicates optimum performance at mid-rev, characterized by a peak torque of 9.54 Nm at 7,000 rpm and a peak power of 9.74 hp at 7,400 rpm. After passing through the zone, torque decreases gradually at high revs, while power tends to be more stable. This shows that in high-compression conditions, the character of the combustion system can direct the peak torque-power at a given RPM. In the study by Zareei [24], engine performance was significantly influenced by injector parameters such as injection pressure, injection angle, and nozzle configuration. The results showed that an optimal injection pressure of 400 bar and an injection angle of 15° were able to improve combustion efficiency and reduce fuel consumption by up to 6.5%. Additionally, increasing the number of injector holes and injection pressure was found to boost power and efficiency, although this led to higher NO_x emissions. This phenomenon aligns with the study's findings, where torque and power increased until reaching an optimum point before declining at high RPM. This indicates that the characteristics of the 8-hole E90 injector significantly influence the fuel atomization and mixing processes, thereby determining overall engine performance. It affirms that improved performance can also be achieved through the optimization of the ignition system, demonstrated by the use of a treated rotor (extended 2 mm) that consistently produces higher torque and power than standard rotors on a variety of fuels and ethanol blends. The best reported condition is the Pertamina 30% + 70% ethanol with a treated rotor that produces 8.15 Nm of torque and 5.9 kW of power, while in ethanol blends that are too high, the performance decreases due to overheating and unstable engine operation due to inappropriate AFR.

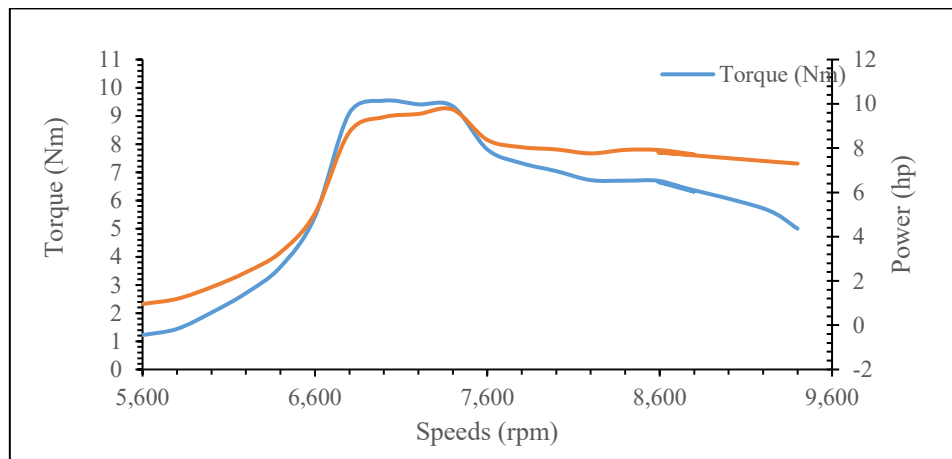


Fig. 9. The effect of E90 Power Torque in 8-hole injector

3.9. Analysis of 10 Hole E100 Injector Power Torque Test Results

The test results showed in (Fig. 10) that the 10-hole injector with E100 on a 14.0:1 compression engine produced optimum performance at medium rounds. Torque increases from 1.20 Nm (5,600 rpm) to a peak of 10.61 Nm (7,200 rpm) and power rises from 0.95 hp to a peak of 10.76 hp at the same RPM, then at high revs, the power is relatively stable, although the torque decreases gradually. This confirms the role of the injector configuration and high compression in maintaining power output when using the E100.

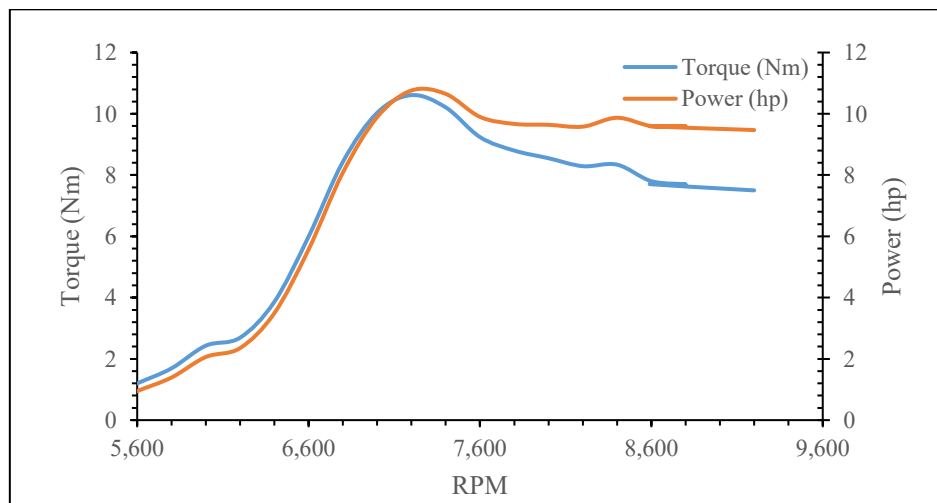


Fig. 10. The effect of E100 Power Torque in 10-hole injector

In line with that, Gajewski [25] showed that increased ethanol levels affected performance, where in a mixture of 0-50% ethanol power and torque were relatively stable (± 45.0 - 46.8 kW and ± 100.8 - 102.4 Nm), but in the E100 there was a significant decrease to 25.4 kW and 68.6 Nm. This difference shows that the performance of the E100 is highly dependent on the conditions and configuration of the test: Gajewski emphasizes the decrease in performance of the E100 compared to the lower ethanol, while this study shows that with system adjustment (10-hole injectors) and a compression ratio of 14.0:1, the E100 can still produce peak

performance in a given RPM zone, so the interpretation should take into account the differences in test variables and engine settings in each study. As illustrated in figs 5-10 for an analysis of the relationship between torque-power characteristics and Air Fuel Ratio (AFR) across 6, 8, and 10-hole injector configurations with differing ethanol concentrations. In internal combustion engine thermodynamics, power is defined as the product of torque and crankshaft rotational velocity, resulting in a power curve that mathematically aligns with the torque trend, exhibiting peaks that typically shift to higher revolutions per minute. Any alteration in combustion quality that influences torque will be readily manifested in the power curve. The quantity of injector holes influences the spray pattern, atomization, and fuel distribution, while concurrently affecting the torque and power characteristics. In the 6-hole injector configuration (E0) as shown in figs 5 and 8, torque escalates significantly at low to medium revolutions, but after attaining its zenith, it diminishes rapidly at elevated RPM. This pattern indicates that during initial loading, the fuel supply can still generate sufficient combustion pressure, but, with elevated RPMs, the mixing quality becomes suboptimal. The air-fuel ratio in this design is typically leaner and diminishes with increasing RPM. Lean situations at elevated RPM can diminish flame speed, elevate exhaust gas temperature, and decrease the mean effective pressure within the cylinder. The atomization through six orifices generates bigger droplets, leading to a less uniform fuel distribution. This induces local discrepancies in the mixture ratio within the combustion chamber, leading to diminished combustion stability and a more accelerated decrease in torque following its peak.

The 8-hole injector configuration (E90) exhibits a more consistent torque curve at mid-range revolutions, characterized by a broader plateau in comparison to the 6-hole configuration (Figs 6 and 9). Power adheres to this tendency, exhibiting flatter characteristics prior to a fall at elevated RPM. The air-fuel ratio in this design approaches the optimal stoichiometric conditions for petrol-ethanol combinations, exhibiting a modest enrichment tendency at mid-range revolutions. Augmenting the quantity of injector apertures enhances atomization, yielding smaller droplets and a more uniform spray distribution. Consequently, the amalgamation of air and fuel is more uniform, combustion occurs more rapidly and consistently, and peak cylinder pressure is better regulated. This enhances the Indicated Mean Effective Pressure (IMEP) and preserves torque stability across an expanded RPM range. Simultaneously, the 10-hole injector design (E100) has the most seamless and uniform performance attributes (Figs. 8 and 10). Torque attains a notably elevated peak value and undergoes a more gradual reduction at elevated RPM. Power remains consistent until nearing the maximum RPM threshold. The AFR is within a range conducive to pure ethanol combustion, which chemically necessitates a distinct air ratio compared to petrol. As the number of holes rises, the droplet size diminishes, resulting in a substantial increase in the contact surface area between the fuel and air. This expedites the evaporation process, reduces the ignition delay, and enhances the velocity of combustible mixture generation. Combustion achieves more uniformity through a more stable flame front and consistent flame propagation. Maximum combustion pressure typically occurs at the ideal TDC, leading to enhanced expansion work and improved energy transfer into torque.

Upon closer examination of combustion quality within the combustion chamber, the quantity of injector orifices significantly influence several critical metrics, specifically droplet size and mixture homogeneity. An increased number of holes results in a reduced droplet size owing to heightened shear pressures during injection. Minute droplets enhance evaporation rates and augment mixture uniformity. A homogenous mixture minimizes localized rich or lean zones that may lead to incomplete combustion or misfires. The rate of creation of the flammable mixture. At six holes, substantial droplets require an extended duration to evaporate, hindering the creation of an ideal combination. At 8 and 10 holes, evaporation occurs more rapidly,

leading to the formation of the combustible mixture earlier and more uniformly before ignition, which results in combustion that is more synchronized with the ignition angle. Additionally, the stability of the flame front and the maximum cylinder pressure. A homogenous mixture yields a stable flame front and uniform flame propagation. At six holes, inconsistencies in the mixture might lead to oscillations in cylinder pressure and incomplete combustion.

At 10 holes, the front flame exhibits enhanced stability, leading to more regulated peak pressure that occurs at a crank angle near the optimal, so augmenting thermal efficiency. The efficiency of turning chemical energy into mechanical energy is enhanced. Swift and uniform combustion generates elevated cylinder pressure throughout the effective expansion phase. Consequently, the network generated per cycle escalates. The 8-hole and particularly the 10-hole layouts have a propensity for enhanced efficiency because of superior atomization quality and mixture uniformity. This study revealed that an increase in the number of injector holes enhances atomization quality, expedites the production of a homogenous mixture, stabilizes the combustion process, and optimizes peak cylinder pressure. The effect is clearly evident in torque and power stability, along with a better regulated air-fuel ratio (AFR). Consequently, the 8- and 10-hole injector configurations yield superior and more consistent combustion quality relative to the 6-hole configuration, particularly when utilizing high-ethanol fuel that necessitates enhanced evaporation and mixing properties.

4. CONCLUSION

The conclusion of this study shows that variations in the number of injector holes and bioethanol content affect the fuel consumption rate, AFR, and torque of the four-stroke spark ignition engine vehicles, and the effect becomes more pronounced when the engine condition changes from the standard compression ratio (9.5:1) to the high compression ratio (14.0:1) in the 8-hole and 10-hole injectors. In 6-hole (9.5:1) injectors with E0-E80, consumption is relatively low at low-medium (1500-3500 rpm) and increases sharply at high revs, with a tendency for high ethanol blends (E60-E80) to be more wasteful at upper rpm; whereas in 8-hole and 10-hole (14.0:1) injectors with E90-E100, consumption increases almost linearly as rpm increases and the difference between mixtures is relatively thin, although in 10-hole injectors E90 tends to be lower on average than E95 and E100. In terms of mixture formation, in 6-hole (9.5:1) injectors, AFR tends to decrease as the rpm rises (the mixture gets richer at high rpm). The E0-E40 group is in the tighter and lower AFR range, while the E60-E80 shows a much higher (poorer) AFR at low-medium rpm and then approaches at high rpm. On 8-hole (14.0:1) injectors, the AFR forms an upward to mid-rev pattern (~5000 rpm) and then down, with the E100 being consistently the „leanest”; while in the 10-hole injector (14.0:1) a similar pattern appears but the distance between the curves is tighter, so that the AFR difference between E90-E100 is relatively small and is more influenced by the engine operating zone. For performance, dyno testing confirms that peak torque and power are at intermediate revs, then decrease at higher revs. In the 6-hole E0 (9.5:1) injector, the peak torque occurs at about 5400 rpm and the peak power shifts slightly higher at about 5800 rpm, and then the torque drops faster than the power. In the 14.0:1 compression ratio condition, the E90 8-hole injector configuration produces peak torque at around 7000 rpm and peak power at around 7400 rpm, while the E100 10-hole injector reaches peak torque and impeller power at around 7200 rpm and power is relatively better maintained at high revs despite the decrease in torque. Overall, this study shows that bioethanol optimization, especially at high fractions, is more accurately understood as a combination of injector configuration, compression ratio, and operating rpm

range, rather than simply choosing one "most economical" or "most powerful" blend for all conditions.

References

1. Collazos J.S.G., L.M.C. Ardila, C.J.F. Cardona. 2024. "Energy transition in sustainable transport: concepts, policies, and methodologies". *Environmental Science and Pollution Research* 31(49): 58669-58686. DOI: <https://doi.org/10.1007/s11356-024-34862-x>.
2. Rifal M., R. Pido, N.S. Dera. 2022. "Pengaruh campuran bahan bakar ethanol bensin terhadap konsumsi bahan bakar dan emisi gas buang pada kendaraan bermotor 125 cc sistem injeksi". [In Infonesian: "The effect of ethanol-gasoline fuel blends on fuel consumption and exhaust emissions in a 125 cc fuel-injected motorcycle"]. *Gorontalo Journal of Infrastructure and Science Engineering* 4(2): 50-57. DOI: <https://doi.org/10.32662/gojise.v4i2.2035>.
3. Wiratmaja I.G., E. Elisa. 2020. "Kajian peluang pemanfaatan bioetanol sebagai bahan bakar utama kendaraan masa depan di Indonesia". [In Infonesian: "A study on the potential of utilizing bioethanol as the primary fuel for future vehicles in Indonesia"]. *Jurnal Pendidikan Teknik Mesin Undiksha* 8(1): 1-8. DOI: <https://doi.org/10.23887/jptm.v8i1.27298>.
4. Siddique M.B.M., N. Khairuddin, N.A. Ali, M.A. Hassan, J. Ahmed, S. Kasem, M. Tabassum, H.N. Afrouzi. 2021. "A comprehensive review on the application of bioethanol/biodiesel in direct injection engines and consequential environmental impact". *Cleaner Engineering and Technology* 3: 100092. DOI: <https://doi.org/10.1016/j.clet.2021.100092>.
5. Setiawan A., D.M. Mentari, D.F. Hakam, R. Saraswani. 2025. "From climate risks to resilient energy systems: addressing the implications of climate change on Indonesia's energy policy". *Energies* 18(9): 2389. DOI: <https://doi.org/10.3390/en18092389>.
6. Rauf W. 2023. "Kajian eksperimental pengaruh campuran etanol dan Pertamina terhadap konsumsi bahan bakar motor injeksi 125cc". [In Infonesian: "Experimental study on the effect of ethanol and Pertamina blends on the fuel consumption of a 125cc fuel-injected motorcycle"]. *RADIAL: Jurnal Peradaban Sains, Rekayasa dan Teknologi* 11(2): 330-342. DOI: <https://doi.org/10.37971/radial.v11i2.412>.
7. Mohammed M.K., H.H. Balla, Z.M.H. Al-Dulaimi, Z.S. Kareem, M.S. Al-Zuhairy. 2021. "Effect of ethanol-gasoline blends on SI engine performance and emissions". *Case Studies in Thermal Engineering* 25: 100891. DOI: <https://doi.org/10.1016/j.csite.2021.100891>.
8. Mardani M., J. Herreros, A. Tsolakis. 2023. "The impact of thermochemical exhaust energy recovery using ethanol-gasoline blend on gasoline direct injection engine performance". *Topics in Catalysis* 66(13-14): 1045-1056. DOI: <https://doi.org/10.1007/s11244-022-01757-5>.
9. Mahendra F.A., S. Sumarli, M. Harly. 2023. "Pengaruh perubahan variasi jumlah hole injektor terhadap daya, torsi, dan konsumsi bahan bakar sepeda motor Vario 125cc". [In Infonesian: "The effect of varying the number of injector holes on the power, torque, and fuel consumption of a Vario 125cc motorcycle"]. *Jurnal Teknik Otomotif: Kajian Keilmuan dan Pengajaran* 7(1): 15-22. DOI: <https://doi.org/10.17977/um074v7i12023p15-22>.

10. Hermawan M.V., A.E. Winarta. 2020. "Studi eksperimen pengaruh jumlah lubang nosel injektor terhadap performa mesin sepeda motor". [In Infonesian: "Experimental study on the effect of the number of injector nozzle holes on motorcycle engine performance"]. *Teknika* 6(3): 77-84.
11. Yousef Yousef O., M. Mashkour. 2024. "Effects of nozzle diameter and holes number on the performance and emissions of a gasoline direct injection engine". *International Journal of Thermodynamics* 27(1): 1-12. DOI: <https://doi.org/10.5541/ijot.1272871>.
12. Maulana I.A., W. Simatupang, D. Fernandez, A. Arif. 2023. "Perbandingan penggunaan varian hole injektor terhadap konsumsi bahan bakar pada sepeda motor 155 cc". [In Infonesian: "Comparison of injector nozzle variants regarding fuel consumption in 155 cc motorcycles"]. *JTPVI: Jurnal Teknologi dan Pendidikan Vokasi Indonesia* 1(4): 463-472. DOI: <https://doi.org/10.24036/jtpvi.v1i4.74>.
13. Safiullah, S.C. Ray, K. Nishida, V. McDonell, Y. Ogata. 2023. "Effects of full transient injection rate and initial spray trajectory angle profiles on the CFD simulation of evaporating diesel sprays: comparison between single-hole and multi-hole injectors". *Energy* 263: 125796. DOI: <https://doi.org/10.1016/j.energy.2022.125796>.
14. Dhande D.Y., N. Sinaga, K.B. Dahe. 2021. "Study on combustion, performance and exhaust emissions of bioethanol-gasoline blended spark ignition engine". *Heliyon* 7(3): e06380. DOI: <https://doi.org/10.1016/j.heliyon.2021.e06380>.
15. Walle M., K. Yeneneh, G. Sufe. 2025. "Investigation of spark ignition engine performance in ethanol-petrol blended fuels using artificial neural network". *Scientific Reports* 15: 25516. DOI: <https://doi.org/10.1038/s41598-025-07964-w>.
16. Liu S., Z. Lin, H. Zhang, Q. Fan, N. Lei, Z. Wang. 2023. "Experimental study on combustion and emission characteristics of ethanol-gasoline blends in a high compression ratio SI engine". *Energy* 274: 127398. DOI: <https://doi.org/10.1016/j.energy.2023.127398>.
17. Priatama M.H.F., I. Rosyadi, Y. Yusuf. 2020. "Analisa performa dan konsumsi bahan bakar pada mesin 4-tak 113cc menggunakan bahan bakar campuran premium dan ethanol". [In Infonesian: "Analysis of performance and fuel consumption of a 113cc 4-stroke engine using a blend of Premium gasoline and ethanol"]. *Rotor* 13(2): 49-54. DOI: <https://doi.org/10.19184/rotor.v13i2.21367>.
18. Bahri S., A. Fahrudin, P.H. Tjahjanti, I. Iswanto. 2025. "Analisis pengaruh perbandingan timing injeksi menggunakan variasi bahan bakar Pertamina dan etanol terhadap performa motor matic 110cc". [In Infonesian: "Analysis of the effect of injection timing variations using Pertamina and ethanol fuels on the performance of a 110cc automatic motorcycle"]. *Otopro* 20(2): 44-50. DOI: <https://doi.org/10.26740/otopro.v20n2.p44-50>.
19. Farida N.N., A. Maulana, A.D. Putra. 2025. "Pengaruh perubahan durasi injeksi terhadap konsumsi bahan bakar pada kendaraan Ken Arok berbahan bakar Ethanol E100". [In Infonesian: "The effect of injection duration changes on fuel consumption in the Ken Arok vehicle fueled by E100 ethanol"]. *Metrotech: Journal of Mechanical and Electrical Technology* 4(2): 62-67. DOI: <https://doi.org/10.70609/metrotech.v4i2.6887>.
20. Miti A., M. Taufiqurrahman, G.S. Lubis, J. Jumiyanto, A.D. Nugroho. 2025. "Analisa performa mesin motor 4 langkah 150 cc injeksi terhadap campuran bioetanol dalam bahan bakar Peralite". [In Infonesian: "Performance analysis of a 150 cc 4-stroke fuel-injected motorcycle engine using bioethanol blends in Peralite fuel"]. *JTRAIN: Jurnal Teknologi Rekayasa Teknik Mesin* 6(1): 15-20.

21. Adinugroho M.F., T. Permana, R.A.M. Noor. 2025. "Effect of gasoline RON 92 and ethanol mixture on engine performance and emissions". *Journal of Automotive Engineering Education* 3(1): 1-12.
22. Zacarías A., M.R. Grijalva, J. de J. Rubio, G. Ramage, V.Y. Mena, R. Hernández, I. Carvajal, A. Flores, O. Guarneros, B.A. Rodríguez. 2025. "Improvement efficiency and emission reduction in used cars for developing regions using gasoline-bioethanol blends". *Energies* 18(3): 638. DOI: <https://doi.org/10.3390/en18030638>.
23. Sugati D., A.A. Salim, M. Abdulkadir, N. Efendi. 2025. "The effect of adding bioethanol to RON 92 gasoline on performance and exhaust emissions". *Jurnal Rekayasa Mesin* 16(3): 1239-1250. DOI: <https://doi.org/10.21776/jrm.v16i3.2030>.
24. Zareei J., K.D.V. Prasad, A.K. Kareem, S. Chandra, N. Shavkatov, C. Rodriguez-Benites, J.W.G. Guerrero, N.M. Ghazaly, E.M. Akhmetshin. 2024. "Optimizing diesel engine performance and emissions with diesel-hydrogen mixtures: impact of injector configuration, angle, and pressure". *Energy Conversion and Management: X* 23: 100678. DOI: <https://doi.org/10.1016/j.ecmx.2024.100678>.
25. Gajewski M., S. Wyrąbkiewicz, J. Kaszkowiak. 2025. "Effects of ethanol-gasoline blends on the performance and emissions of a vehicle spark-ignition engine". *Energies* 18(13): 3466. DOI: <https://doi.org/10.3390/en18133466>.

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