Automotive Experiences
Vol. 7 No. 1 (2024) pp. 48-62
p-ISSN: 2615-6202 e-ISSN: 2615-6636

Research Paper

Investigating Knocking Potential, Cycle Stability, and Emission Characteristics in Lean Spark Ignition Engine with Gasoline, Ethanol, and Methanol

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https://doi.org/10.31603/ae.10607

Published by Automotive Laboratory of Universitas Muhammadiyah Magelang

Article Info
Submitted:
29/11/2023
Revised:
04/04/2024
Accepted:
05/04/2024
Online first:
27/08/2024

Abstract

This research examined the use of gasoline-ethanol-methanol on the performance of Spark ignition engine with a focus on a ternary fuel mix (gasoline, ethanol and methanol). It also investigated the various combustion characteristics in lean conditions, such as the potential for knocking, ignition delay, and engine performance. Methanol was added to mitigate knocking potential when used in small quantities and reduce ignition delay times during combustion, specifically at leaner air-fuel mixtures. The best decrease in ignition delay was observed with the E5M15 blend, where λ at values of 1.3 and 1.0 had E5M15 SoC of 325 CA° and 3215 CA°, respectively. The CCV results showed a more sloping increase in COV (coefficient of variation) value when using GEM fuel, particularly with the addition of more methanol. Furthermore, methanol was used to increase combustion progression and the ability of the fuel blend to sustain combustion under lean conditions. The torque and power units are not significantly different at values of 1.0, 1.1, and 1.2, but different below 1.3.

Keywords: Gasoline Ethanol Methanol; Spark ignition engine; SoC; AFR; COV; Performance

1. Introduction

Alcohol has been used in gasoline mixtures since the 1970s, and in Indonesia, the adoption as a fuel has become more prominent due to the implementation of Presidential Decree Number 22 of 2017. Currently, the Indonesian government aims to increase the blend use of bioethanol and fossil energy by approximately 20% (E20) in 2025 [1]. Ethanol has similar characteristics to gasoline, thereby making it possible to be substituted or used as a mixture in vehicle engines [2]–[4]. In addition, this alternative fuel is cultivated in Indonesia and is mainly obtained from biomass through a plant fermentation process called bioethanol [5].

Alcohol is used in diesel oil mixtures [6], although it is more commonly associated with spark ignition engines as a gasoline mixture [7]–[9] or in a pure state [10], [11]. Ethanol mixed with gasoline leads to fuel separation [12], and high cycle-to-cycle variation due to the different properties [13], [14]. Irrespective of the higher Research Octane Number (RON), which enhances the resistance of ethanol to pressure and prevents autoignition [15], [16], it also has a faster Laminar Flame Speed (LFS) compared to gasoline [17]. The volatile nature of ethanol affects the vapor pressure of the fuel [16], [18]. While the water content negatively impacts flame propagation, reducing the maximum temperature and pressure in the combustion chamber [19].

Preliminary research from Wouters et al. [20], conducted to evaluate the use of machine to measure temperature and pressure reported that methanol showed an atomization performance comparable to gasoline. Furthermore, under realistic engine operation, the penetration length of methanol spray increased due to the required injection duration attributed to the lower energy content. The efficiency of indicative mean effective pressure (IMEP) increased under normal operating conditions, illustrated that lean methanol is highly feasible.

Amine et al. [21] studied the physical properties of the fuel, with focus on evaporation and vapor pressure characteristics by mixing three types of fuel, namely gasoline, ethanol, and methanol. The results showed that mixing ethanol and methanol with gasoline reduced the severity of the vapor pressure compared to using only methanol. This improvement was attributed to the boiling point of ethanol, which falls between methanol and gasoline, moderating the vapor pressure effectively.

Prior research on both chemical and physical properties during combustion is essential, as exemplified by Wang et al. [22] who studied the laminar burning velocity. The results showed that adding ethanol increases heat release, particularly at low temperatures. However, raising the initial temperature increases this effect. Nanlohy [23], examined variations in ignition °CA points at 9°CA, 12 °CA, and 15 °CA. It was reported that the best results for both Power, SFC, and Emission were consistently obtained at 12°CA.

The adoption of modeling simulations and experiments is essential to determine the physical and chemical properties of the combustion process [24]. In this research, two fuels were sprayed separately using dual injectors. The results showed that the addition of isopropanol increased and decreased IMEP and Coefficient of Variation at Indicative Mean Effective Pressure(COV_{IMEP}), consequently enhancing power output. Furthermore, the rise in IMEP was more pronounced in lean combustion conditions. This improvement was attributed to the more complete combustion, which reduced HC and CO emissions. However, a significant drawback observed was the high corrosion rate of isopropanol to gradually damage engine components.

Methanol is characterized by a simpler C group and faster LFS than gasoline. Moreover, the oxygen content causes methanol to burn more efficiently in lean conditions, leading to more complete combustion [25]. When used as a fuel mixture, methanol is subjected to rapid oxidation, which is crucial for enhancing the SoC and overall efficiency [26]. Meanwhile, mixing methanol with gasoline can lead to separation due to the high polarity of the molecule, which forms hydrogen bonds with water. To prevent this separation, ethanol is used as a cosolvent to ensure a stable mixture of methanol and gasoline [27].

With the regenerative and biodegradable characteristics, ethanol is widely used as an alternative fuel. The use of gasoline containing 3 to 10 vol% bioethanol has been promoted in many parts of the world in recent years [28]. However, the high affinity of ethanol for water presents challenges when mixed with gasoline, affecting combustion pressure. This issue is also applicable to methanol due to the high polarity, leading to separation from non-polar gasoline through hydrogen bonds with water. To overcome this, ethanol acts as a cosolvent to maintain stability [27]. The research by Waluyo et al. [12], stated that ethanol can effectively serve as a cosolvent in gasoline-methanol mixtures, leading to reduced IMEP [27], Statistical analysis, particularly on COV_{IMEP}, is crucial to validate these results.

In lean-burn operations, methanol achieved an impressive net efficiency of more than 45% and an extended limit of 0.1 units compared to gasoline [20]. Preliminary research has examined the potential use of methanol in combustion conditions with excess air, to determine the unique property of releasing hydrogen on evaporation with less fuel [26]. Additives are often required when exploring engine stability in ethanol-gasoline blends to minimize cycle-to-cycle variation (CCV) parameters, a challenge also observed in methanol-gasoline mixtures [29]. According to Waluyo et al. [12] the addition of ethanol in small quantities is able to stabilize combustion. Meanwhile [25], reported that the use of methanol in lean conditions reduces COV_{IMEP}, thereby enhancing the overall stability of the machine.

The research conducted by Waluyo and Purnomo [4], in 2022 investigated the effects of adding ethanol-methanol to gasoline on gas emissions. The mass fraction used was determined from previous research on gasoline and methanol separation. The addition of ethanol improved molecular stability, thereby preventing separation issues. Moreover, increasing the methanol fraction tends to reduce emissions of CO and HC. The higher enthalpy rate facilitated easy vaporization, leading to improved volumetric efficiency. These results are in accordance with the research conducted by Iorio et al. [30] in 2023, using GDI and turbocharge SI Engine. It was reported that ethanol generally increased combustion due to the effect of volumetric efficiency [31].

Previous research [32] examined the use of ethanol blended with gasoline and supplemented by oxygenated cyclohexanol as an additive to reduce CCV and SFC. An alternative method of reducing COV is by adding ethanol to gasoline methanol blends with a limited mass fraction [12], However, Chen et al. [25] stated that the use of methanol produced lower COV values under lean combustion conditions. This research aims to investigate the application of methanol and ethanol mixed with gasoline, including the combustion process in SI engine under varying AFR conditions. The result obtained was used to analyze cylinder pressure, assess knocking potential, and determine combustion duration across several fuel blends. Subsequently, the research examined cycle-to-cycle variation and the effects on power, Specific Fuel Consumption (SFC) and fuel consumption.

2. Methods

The experiment was conducted at the Thermodynamic Motor and Propulsion Laboratory, a facility operated by the National Research and Innovation Agency, shown in **Figure 1**. Engine being examined was placed in the test cell, where the power and torque parameters were measured with a dynamometer, and the flowmeter monitored the fuel flow rate. An instrument module connected to the control computer regulated the throttle opening and engine rotation while monitoring the oil and exhaust temperatures, including sensor data from the test cell. The components of this test cell include the test engine, dynamometer, and fuel system.

Engine used was a single-cylinder 125 cc SOHC SI Honda engine type, known as the JBN1E or Honda Supra AFX12U21C07. It was equipped with an electronically controlled injection system, with the general specifications of the test engine shown in **Table 1**.

2.1. Fuel

The base fuel used was RON 90 gasoline sourced from Pertamina gas stations, with detailed specifications shown in **Table 2**. The bioethanol used was locally produced by PT. Molindo Raya Industry and was tested at four different mass percentages of 5%, 10%, 15%, and

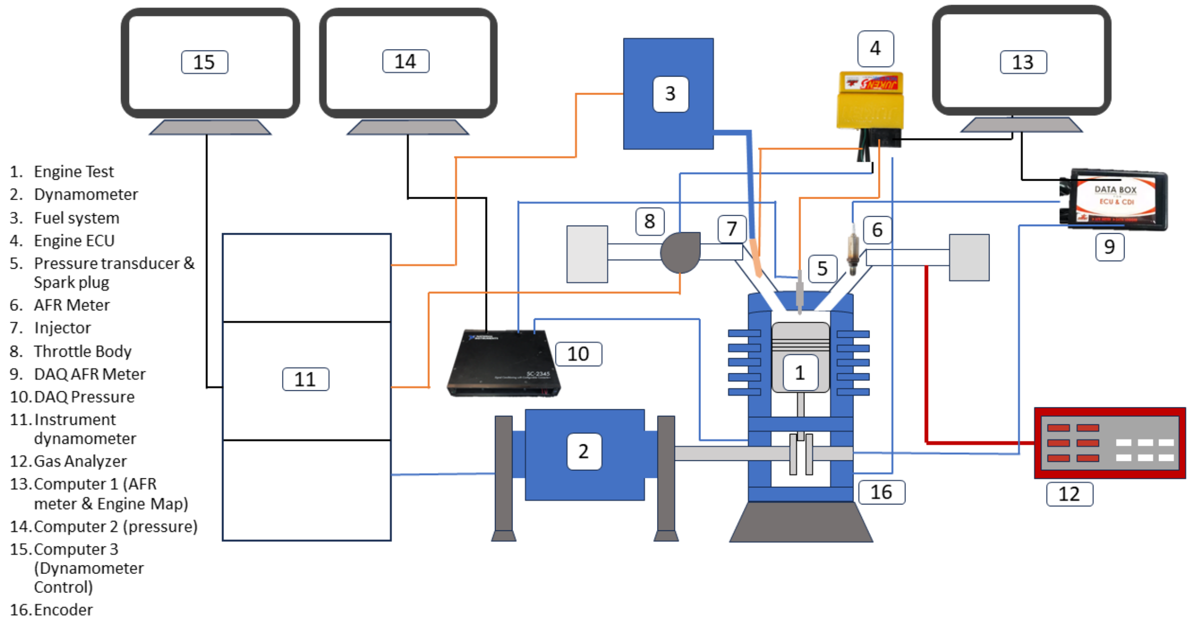

Figure 1. Experimental scheme

Table 1. Engine Test Specification

Property	Specification
Manufacture	Honda JBN1E / Supra AFX12U21C07
Engine type	Spark ignition (SI), 4-stroke, Single Overhead Camshaft (SOHC)
Cooling type	Air Cooling
cylinder	single
Piston Diameter	52.,4 mm
Stroke	57.9 mm
Volume Cylinder	124.89 cc
Compression Ratio	9.3: 1
Power Max	7.4 Kw @ 8000 rpm
Torque Max	9.3 Nm @ 4000 rpm
Fuel system	PGM-FI modified with ECU by BRT

Property	Dynamometer Specification
Type	Bull
Max Speed	4000 rpm
Max Power	30 kW
Max Torque	95.5 Nm
Torque Calibration Accuracy	± 0.25 Nm
Moment of Inertia	0.13 Kgm^2

Instrument Tools	Range	Accuracy
Pressure (bar)	0-200 bar	1.5%
Flow meter	1-10 l/h	0.001%
Thermocouple	0-1200 °C	0.1 °C
Dynamometer	0-30 Nm	0.25 Nm

Table 2. Fuel specification [14], [18]

No	Property	Unit	Gasoline	Ethanol	Methanol
1	Density	Kg/L	0.729	0.793	0.796
2	Stoichiometric AFR	-	14.7	8.9	6.4
3	Lower Heating Value (LHV)	MJ/Kg	44	27	20
5	Oxygen content	Wt%	1.01	35.7	49.9
6	Molecular Weight	g/mol	95-120	46	32.34
7	Boiling Point	°C	25-215	78.4	64.6
8	RVP at 38 °C	kPa	58.4	17.4	32
10	Autoignition temperature	°C	300-400	363	465

20%. In addition, the methanol used was a fuel-grade type product of PT Kaltim Methanol Industry, tested across the same mass variations 5%, 10%, 15%, and 20%. The mass fractions of the fuel samples used in the experiments are shown in **Table 3**.

2.2. *AFR Calculation*

The preparations made for this research included calculating the target actual AFR value with Eq. (1) based on the excess air or lambda (λ) values of 1, 1.1, 1.2, and 1.3 from Eq. (2). The estimated actual AFR values are presented in **Table 4**. These calculations relied on the mass composition of gasoline, which consisted of 63% n-heptane, 20% isooctane, and 17% toluene [33], as used in previous research conducted by Auzani et al. [17] it was assumed that ethanol and methanol had a purity of 100%. In addition, the AFR formula was used for these calculations.

$$\phi = \frac{AFR_{stoichiometric}}{AFR_{actual}} \tag{1}$$

$$\lambda = \frac{1}{\phi} = \frac{AFR_{actual}}{AFR_{stoichiometric}} \tag{2}$$

2.3. *Experimental Procedure*

After preparing the fuel mixture, the test engine was started and allowed to warm up, giving the new blend time to adjust to engine conditions. Subsequently, the throttle valve opening was increased to 100%, and engine speed set at 4000 rpm. The fuel amount was adjusted to

Table 3. Fuel mixture variation

Fuel Sample	Gasoline (m/m%)	Ethanol (m/m%)	Methanol (m/m%)
Gasoline	100	0	0
E20	80	20	0
E15M5	80	15	5
E10M10	80	10	10
E5M15	80	5	15
M20	80	0	20

Table 4. Target actual AFR value

Sample	λ			
	1	1.1	1.2	1.3
Gasoline	14.8	16.2	17.76	19.24
E20	13.63	14.99	16.36	17.72
E15M5	13.50	14.85	16.20	17.56
E10M10	13.38	14.72	16.05	17.39
E5M15	13.25	14.58	15.90	17.23
M20	13.13	14.44	15.75	17.07

match the AFR value shown on the meter. After calculating the AFR. the collected data included the following parameters power. torque. SFC. exhaust emissions. cylinder pressure. and crank angle. Immediately data for one lambda value had been collected. the process was repeated for the others (λ) (1. 1.1. 1.2. and 1.3). After obtaining all lambda values. engine speed is raised to 6000 rpm and data retrieval was performed. Finally. the speed was further increased to 8000 rpm for additional data collection.

3. Result and Discussion

3.1. *Combustion Pressure*

Figure 2 shows the pressure contour graph of lean combustion process ($\lambda = 1.3$) at engine speeds of 4000 rpm. 6000 rpm. and 8000 rpm. The smoothest surface was produced at 4000 rpm by an engine with pure gasoline fuel. while an uneven contour was produced with the use of alcohol-based fuels. particularly ethanol and methanol. Blends with higher ethanol concentrations. such as E20 and E15. produced a smoother contour compared to E5M15. E10M10. and M20. This showed that increase in ethanol concentration rises the pressure contour in spark ignition engine. However. at 6000 rpm and 8000 rpm. the effect of alcohol on the combustion pressure contour reduced as shown in **Figure 2b** and c. The contours generated by alcohol-based fuels become smoother with increase in engine speed.

Wei et al. [34]. stated that mixing isooctane with methanol or ethanol affects the stability of combustion pressure. The addition of methanol led to less stable combustion pressure. making knocking more prevalent compared to isooctane mixed with ethanol. This result holds great significance due to dominance of isooctane in gasoline. The increase in methanol concentration of GEM mixture under leaner fuel-air conditions. led to a rise in knocking potential. specifically at medium to low engine speeds. as shown in **Figure 2**. These observations are in accordance with the results of Chen et al. [35]. that swirling during air mixing and combustion in the cylinder raised the speed of flame propagation. depicted through optical engine analysis and recorded combustion pressure profiles.

The jagged contour shown in **Figure 2** depicts mild knocking. a common phenomenon in spark ignition engine operating under fuel-deficient combustion conditions. In addition. it could occur when the throttle is completely opened at maximum load. The uneven contour shows that peak pressure occurred earlier than gasoline. depicting rapid combustion under lean combustion conditions. This explains the minimal difference in COV between the use of gasoline and gasoline-alcohol fuel mixture. While alcohol-based fuel combustion is faster and reduces COV. it also leads to mild knocking due to too excessively rapid combustion. In the middle to the upper revolutions. as shown in **Figure 3b** and

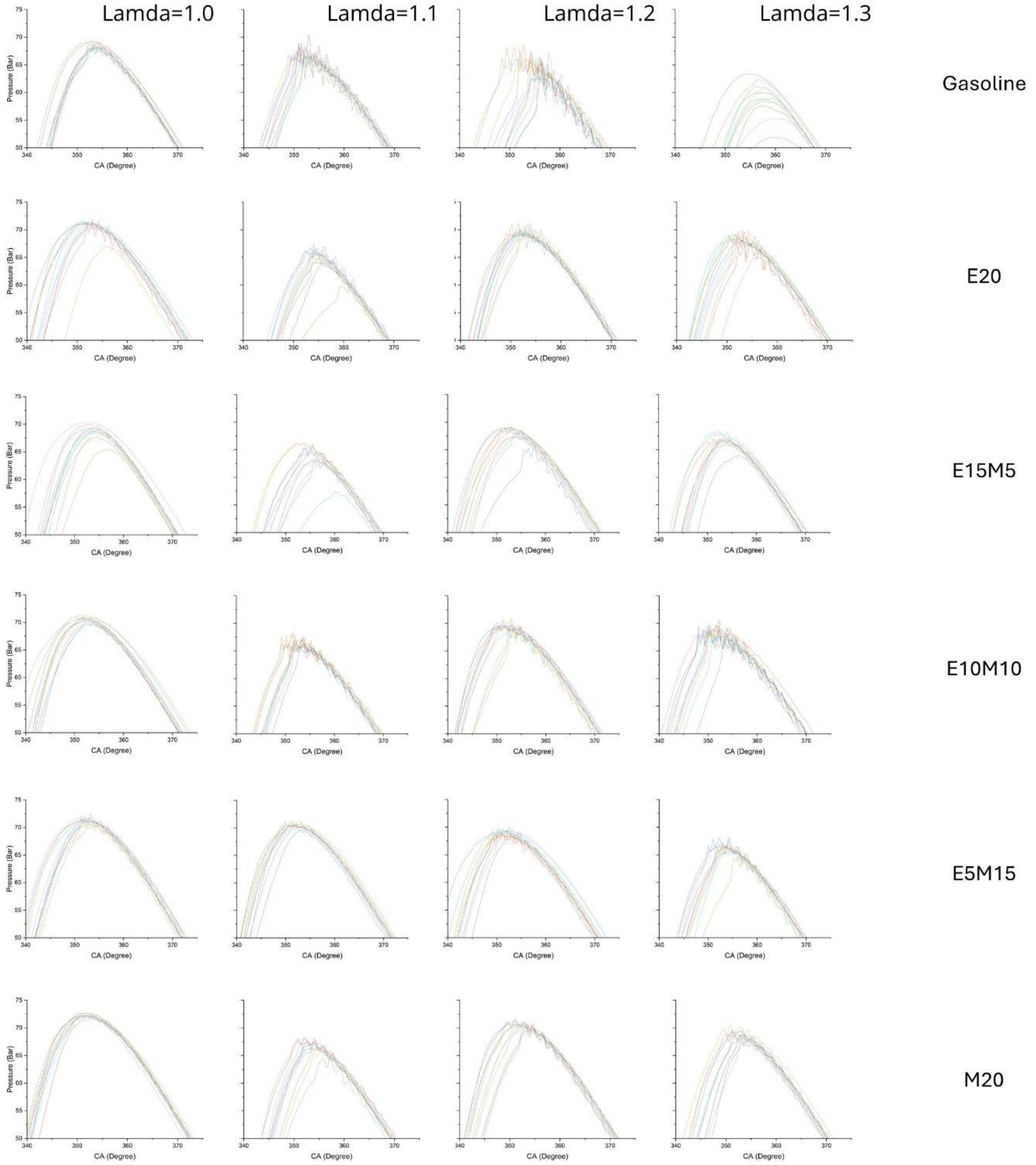

Figure 2. Contour plot of peak pressure at 4000 rpm engine speed

Figure 3c. a smoother contour shape was observed due to the earlier peak pressure. indicating a positive impact of alcohol fuel on engine performance at higher speed.

Figure 3a. and **Figure 3b** shows the heat release from the fuel. with values of λ=1.0. and =1.3. respectively. Considering the preliminary SoC at λ=1.0. the fuel samples with the fastest SoC are E5M15. M20. E20. E10M10. E15M5. and Gasoline with respective values of 321.5 CA°. 322.5 CA°. 323 CA°. 323.75 CA°. 324.75 CA°. and 328.25 CA°. However. at λ=1.3 the sequence of fuels with the fastest SoC starts with E5M15. followed by E15M5. M20. E10M10. Gasoline. and E20 respective values of 325 CA°. 325.25 CA°. 327 CA°. 329 CA°. 329.5 CA°. 331 CA°. Fuels characterized by higher ethanol mass fractions. namely E15M5 and E20. burn with gasoline to complete the combustion sequence. This phenomenon was attributed to the lower vapor point and evaporation energy of methanol. leading to the earlier vaporization compared to other fuels. Consequently. fuels with higher methanol fractions experience earlier combustion. The combustion reaction speed was influenced by the LFS. with methanol having a faster LFS value compared to ethanol or gasoline fuels.

Gasoline showed a delayed release of heat compared to the alcohol mixture under combustion conditions with a lambda value of 1.3. Adding alcohol to gasoline leads to an earlier SoC due to the LFS of the three primary fuels. **Figure 3** shows that fuels containing methanol burn faster with insignificant influence on the rate of heat released. Fuels with a higher methanol mass fraction show a steeper heat release slope. The observed phenomenon was attributed to the influence of LFS. particularly with the higher values associated with methanol. which promote faster combustion and a more significant increase in heat release. The experiment conducted by Aghahasani et al. showed that methane with a mass fraction of 25% has a more advanced SoC compared to a higher mass fraction [36]. Methane and methanol are characterized by a similar carbon chain structure because methane is one of the raw materials used in the production of methanol. The advanced SoC from the addition of alcohol to gasoline leads to a faster release of heat. thereby reducing the overall combustion duration. While the actual combustion duration remains constant. the accelerated start leads to the perception of a shorter combustion process time.

3.1.1. *Coefficient of Variation (COV)*

In this experiment. combustion pressure data was plotted to show the increase in pressure at intervals of every 0.25° crank angle across 100 cycles with varying λ. The pressure data obtained was analyzed using the statistical method known as Coefficient of Variation (COV). Calculations were performed from the beginning of combustion to the opening of the exhaust valve. with the results typically reported as percentages. Furthermore. these percentages depict the consistency of repeated combustion cycle [37].

COV represents the deviation ratio of pressure from the mean within a dataset. Significant indicators such as P_{max} and IMEP are used for measuring cyclic variation. Therefore. the

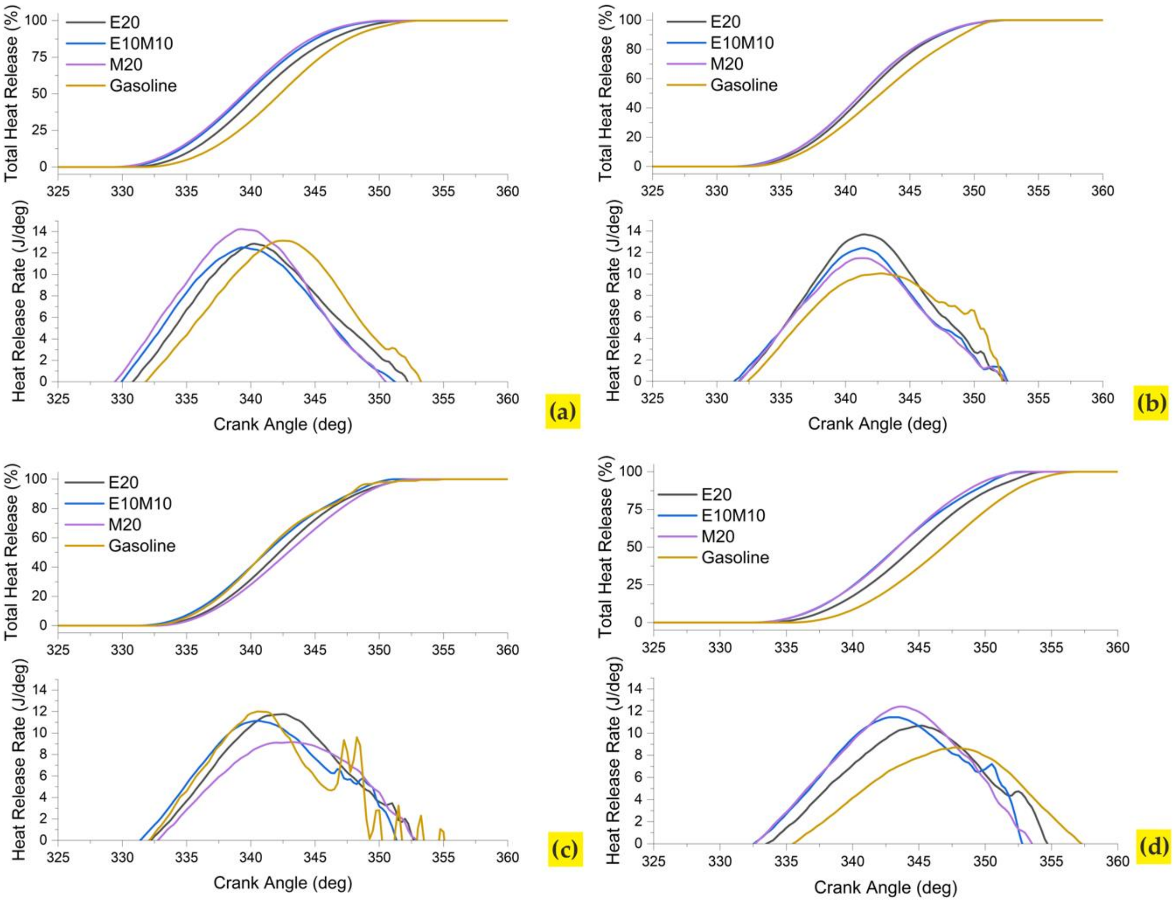

Figure 3. Total heat release (THR) and heat release rate (HRR) a)λ=1.0 b)λ=1.1 c)λ=1.2 d)λ=1.3 at engine speed 4000 rpm

measured COV is termed COVIMEP as it evaluates IMEP. Hedging is used to uphold objectivity and precision in the analysis Hedging is used to maintain objectivity and precision. during the analysis. Furthermore. grammatical correctness is ensured by avoiding filler words or ambiguous language. The formula for COV entails dividing the standard deviation σ_{IMEP} by the average pressure in a dataset μ_{IMEP} (Eq. (3)). IMEP is the ratio of work done (W$_C$) to volume displacement (V$_d$) of engine per cycle. as stated in Eq. (4). Technical term abbreviations were clarified based on initial usage. while biased or figurative language was avoided. to maintain a formal register. Throughout the discourse. consistent technical vocabulary and sentence structure should be used. A clear. concise. and logical structure was followed. establishing causal connections between statements. Subjectivity in evaluations was minimized. and adherence to style guides was ensured. including consistent citation and footnote formatting.

$$COV = \frac{\sigma_{IMEP}}{\mu_{IMEP}} \times 100\% \tag{3}$$

$$IMEP = \frac{W_C}{V_d} \tag{4}$$

When observing the variation in λ. it becomes evident that the higherλ values. correspond to lower combustion pressure. decreasing by approximately 5 bar from λ=1 to =1.3. The decrease in peak pressure was a consequence of slower combustion. leading to less pronounced pressure increases per crank angel in stoichiometric mixtures. Consequently. the net IMEP was lower than the stoichiometric mixture [38].

COVIMEP method is the most common analysis used to research combustion pressure variations. including result COV for each Otto cycle. Of the tested fuel mixtures. E20 had the highest COVIMEP value of 6.518% achieved at engine speed of 4000 rpm with λ=1 as shown in **Figure 4**. However. M20 had the lowest COVIMEP value at λ=1 and engine speed of 8000 rpm. recorded at 4.133%. As shown in **Figure 4**. it was observed that the thinner the fuel-air mixture. the higher COVIMEP value. The increased in COVIMEP value was attributed to the combustion process. where the occurrence under lean conditions slows down. leading to higher cyclic variation.

Research on the perspective of combustion in excess air. stated that an increase in the methanol concentration led to a slight rise in COVIMEP. According to **Figure 5**. lower cyclic variations. led to minor difference in combustion pressure between each cycle. This phenomenon was attributed to the fact that methanol has a better capability for combustion under lean conditions with higher LFS compared to ethanol. butanol. or gasoline [25]. [39]. Furthermore. as the mass fraction of methanol increases. the combustion pressure in each cycle remained constant with decrease in variation as shown in **Figure 5**.

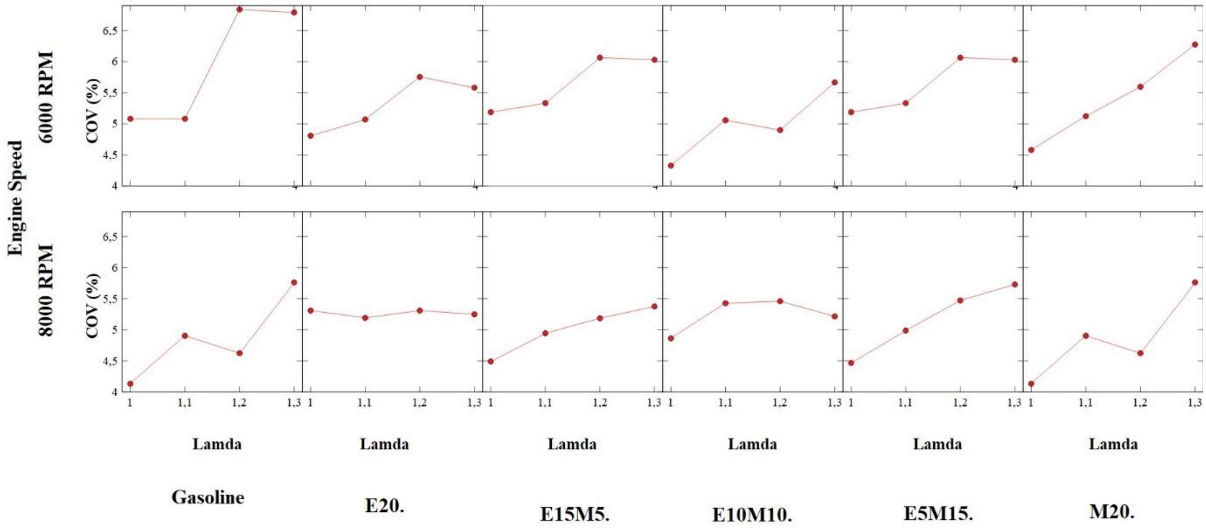

Figure 4. In all mixtures for all λ Variation

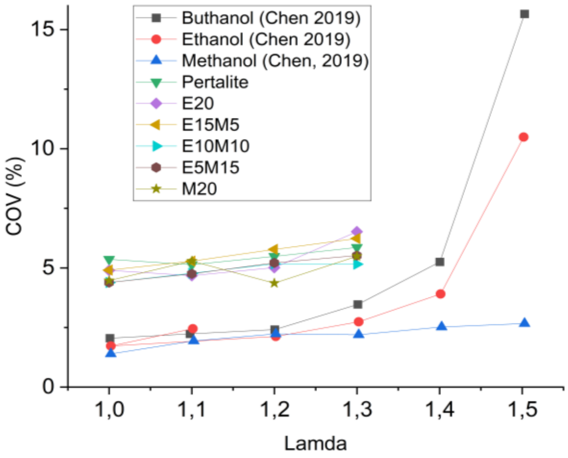

Figure 5. Experiment VS Chen et al. [25]

3.2. *Torque*

Figure 6 shows a graph of the peak torque generated by spark ignition engine. The highest torque of 8.46 Nm was achieved at λ=1.1. at a engine speed of 6000 rpm using the E5M15 mixture. Comparing the three mixtures. it was observed that the E5M15 mixture produced slightly higher torque at λ=1. Additionally. there exists a correlation between torque and pressure. with the GEM fuel producing higher pressure than the base fuel. This result was consistent with previous research. showing that the addition of alcohol groups improved engine performance [40]. Cycle variation on the combustion process is necessary because two reason. first optimum ignition timing settup for average cycle. so advance cycle or retard cycle from average can reduce torque and efficiency [37].

LFS has an impact on the initial combustion process. specifically during the burning of 0 to 10% of the fuel fraction. In this process. methanol is capable of burning 10% of the fraction in less than 24°CA at λ=1.1. Despite the increasing λ. methanol consistently had a lower value compared to ethanol or n-butanol. A similar trend was observed during the combustion process of the fraction from 10 to 90%. including when 50% of the mass fraction was burned [25]. Therefore. fuels with higher methanol content showed enhanced resistance to lean combustion conditions. leading to the reduction of CCV.

3.3. *Power*

In internal combustion engine. peak power output typically occurred at the highest rpm. In this experiment. the highest power was obtained at 8000 rpm using the M20 mixture with λ=1.1. This was because methanol initiated combustion earlier. particularly during the initial 0 to 10% of fuel mass fraction burning. enabling gasoline to react more rapidly. As gasoline has a higher calorific value compared to other alcohol fuels. the M20 mixture had the highest power output. Additionally. the faster reaction rate of methanol facilitates rapid heat release at high engine speeds.

According to **Figure 6** each GEM mixture achieved maximum power at 8000 rpm. with minimal differences in power output and a decrease in the E5M15 mixture. Moreover. the addition of λ significantly influenced power output. particularly at λ=1.3. due to the limited fuel available for combustion. The fuel burned rapidly. which led to the detection of a significant amount of oxygen and release of lower calorific value with cleaner emissions. The highest power output was observed between λ=1.0 and λ=1.2. with complete combustion occurring at λ=1.1 and λ=1.2. This was attributed to combustion in lean conditions promoting more complete oxidation of the fuel.

3.4. *Specific Fuel Consumption*

Fuel consumption. also known as SFC. is the amount of fuel used per unit of power generated during engine operation. In **Figure 7**. spark ignition engine achieved optimal fuel conversion at 8000 rpm when using the fuel mixture. leading to an SFC value of 224.8 g/KWh. However. a lower SFC value shows a more efficient conversion process. The variations in λ and fuel mixtures. excluding E10M10 showed the lowest SFC with a value of approximately 266 g/KWh at λ = 1.3 and engine speed of 6000 rpm.

Methanol has a lower calorific value compared to ethanol. therefore. a higher SFC must correspond to a lower calorific value. This is because a higher amount of calorific energy is released with the same mass. leading to a smaller SFC [41]. Under normal combustion conditions. gasoline had the lowest SFC value. This was attributed to the higher calorific value compared to alcohol-based fuels. Therefore. the same mass of alcohol-based fuel emits less heat compared to gasoline.

In lean combustion conditions. a slight adjustment occurs where the SFC difference between the base and alcohol-based fuel narrows.

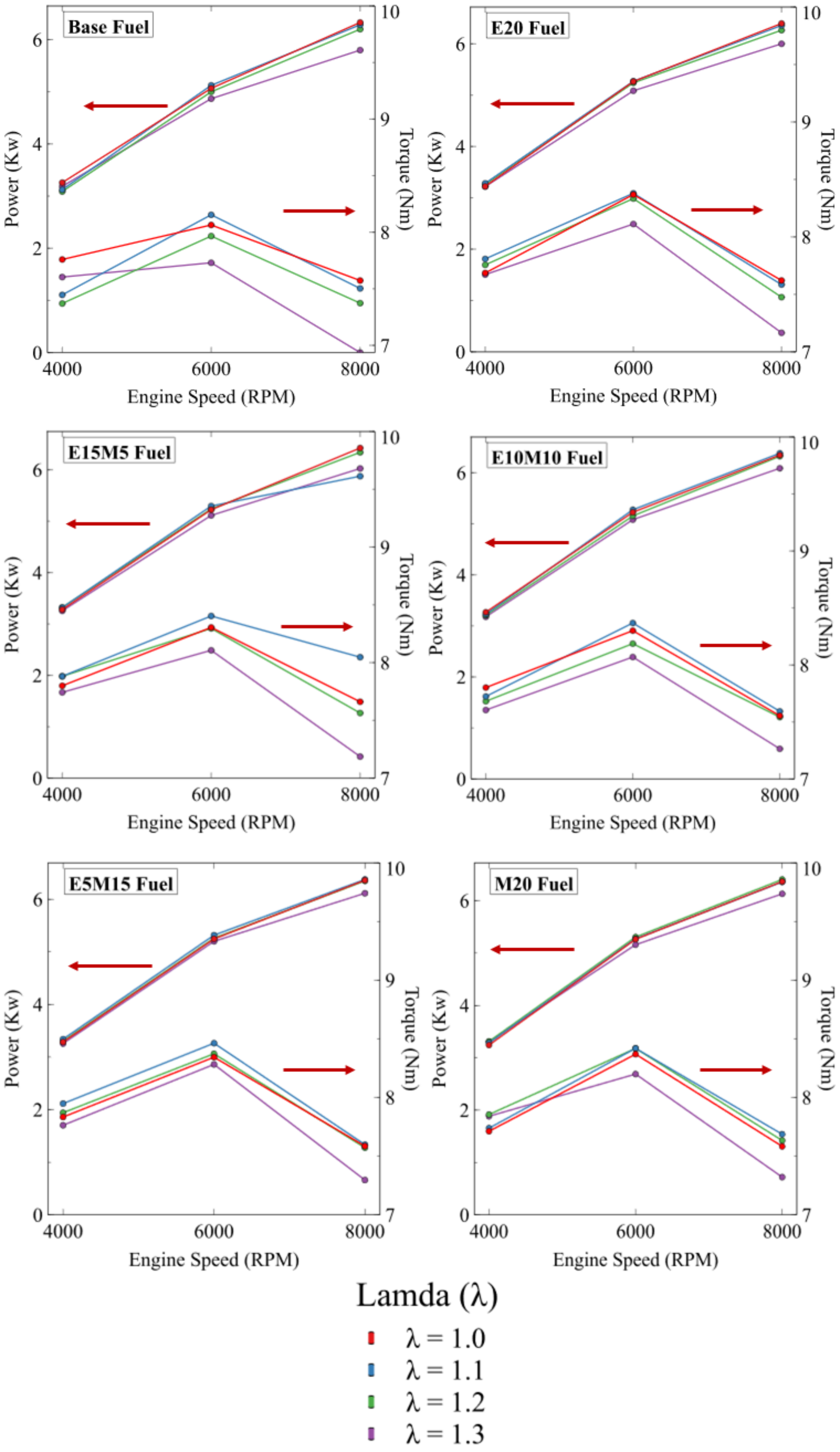

Figure 6. Engine power and torque

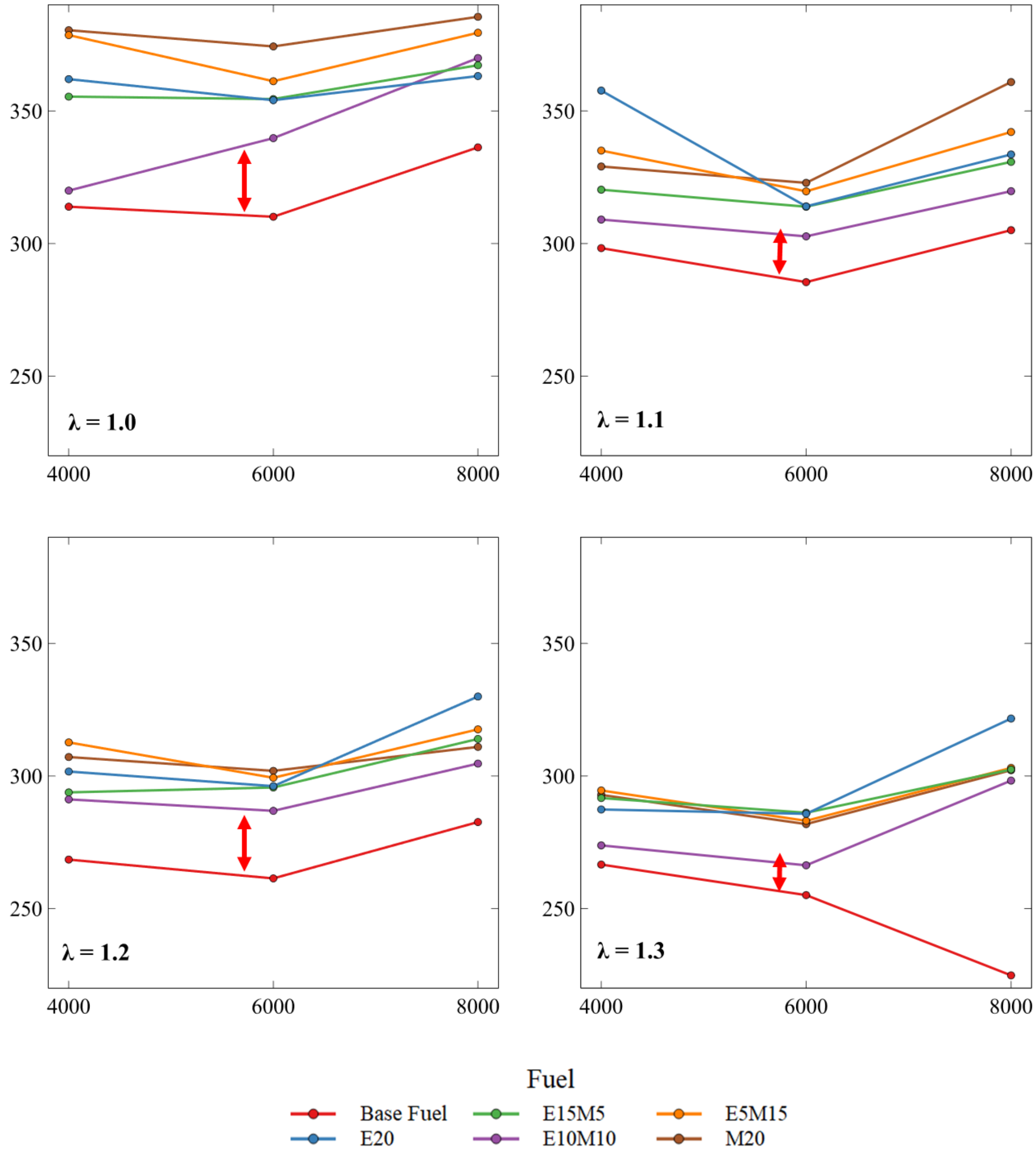

Figure 7. SFC Deviation of gasoline to alcohol fuel mixture

This shift was attributed to the influence of lean combustion conditions. Higher COV_{IMEP} showed increased cycle-to-cycle variation. which led to reduced engine torque. and power output. Furthermore. a decrease in engine power with the same fuel mass led to an increase in SFC. Higher engine power results in a decrease in SFC with better resistance to lean combustion in methanol at lower COV_{IMEP} value of 1.3. The decreases in power is insignificant under lean conditions. thereby leading to a reduction in SFC when using an alcohol-based fuel mixture.

Figure 7 shows SFC for each fuel sample. Generally. SFC decreases with increasing λ for all fuels. but at λ=1.2 and 1.3. the reduction is not significant. On closer examination. it became evident that the distance between gasoline and GEM fuel tends to narrow. This suggested that the decrease in SFC for GEM is more significant compared to gasoline. In lean conditions. the combustion reaction tends to be slow. leading to incomplete combustion and the wastage of unburned fuel when the exhaust valve opens. However. fuels containing methanol burn slowly.

leading to complete combustion. This difference significantly impacts the decrease in SFC. The mixture of methanol contributes to accelerating the reaction more effectively than ethanol and gasoline. thereby facilitating faster lean combustion conditions [42].

4. Conclusion

In conclusion. this research was conducted using a motorcycle engine installed on a dynamometer and tested with a specific AFR value. To simplify AFR calculations. gasoline. ethanol. and methanol were used as fuels and mixed based on mass units. Data were collected and analyzed based on the CCV. torque. power. and emissions of these fuels.

Under lean combustion conditions. an increase in CCV was typically observed. However. based on the data obtained. the fuel with a higher methanol content showed better resistance to CCV compared to other fuel mixtures. This suggested that methanol-rich fuels showed improved stability in cyclic combustion variations during the experiment. The addition of methanol to gasoline and ethanol mixture increased the heat release time due to the high LFS value of methanol. thereby shortening ignition delay during combustion. effectively. The torque and power values reached the peak λ value of 1.1. indicating that the addition of an appropriate air concentration led to higher power and torque production. Furthermore. the SFC obtained was higher when the fuel was mixed with an alcohol base. This was attributed to the higher density of alcohol-based fuels. thereby leading to an increase in the volume of mass released. The reduction of SFC for gasoline is not significant against to lambda. while the reduction of SFC for GEM decreases significantly against to lambda. Therefore. under lean combustion conditions. the difference in SFC between gasoline and GEM becomes smaller due to the slower reaction speed of gasoline compared to GEM fuel. It is important to note that no new content has been added to the text. The rise in the amount of heat was compounded by the lower calorific value. and led to lesser power output.

Future research need to be conducted on the experimental comparison of the calorific value of ethanol and methanol with gasoline using the same volume. This method would have provided more accurate data on the respective values and offered further insights into the performance of alternative fuels.

Acknowledgements

This work was supported by Universitas Indonesia for funding this study according to the contract PUTI No. NKB-247/UN2.RST/HKP.05.00/2023 and Laboratorium *Teknologi Termodinamika Motor dan Propulsi* - National Research and Innovation Agency Republic Indonesia for providing space. laboratory facilities. and knowledge.

Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis. interpretation and discussion of results. The authors read and approved the final manuscript.

Funding

The research was funded by Universitas Indonesia with contract PUTI No. NKB-247/UN2.RST/HKP.05.00/2023.

Availability of data and materials

All data are available from the authors.

Competing interests

The authorsdeclare no competing interest.

Additional information

No additional information from the authors.

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