Infotekmesin
Vol.15, No.01, Januari 2024
p-ISSN: 2087-1627, e-ISSN: 2685-9858
DOI: 10.35970/infotekmesin.v15i1.2128, pp.128-134

Investigation on Exhaust Emission and Performance of SI-Matic Engine Applied Acetone-Butanol-Ethanol (ABE) Fuel Mixtures

Gatot Setyono[1*], Navik Kholili[2], Galih Ageng Kurniawan[3], Deny Surya Pratama[4]
[1,2,3,4]Study Program of Mechanical Engineering, Wijaya-Putra University (UWP)
[1,2,3,4]Jl. Raya Benowo No. 1-3 Surabaya 60197, Indonesia
E-mail: gatotsetyono@uwp.ac.id[1], navikkholili@uwp.ac.id[2], galihagengkurniawan@gmail.com[3], denysuryapratama@gmail.com[4]

Info Naskah:
Naskah masuk: 15 November 2023
Direvisi: 8 Desember 2023
Diterima: 19 Desember 2023

Abstrak

Aseton-Butanol-Etanol (ABE) merupakan energi alternatif diunggulkan untuk mesin SI. Penelitian ini menggunakan metode eksperimen dengan mesin-SI matic, bahan bakar RON-90 dicampurkan dengan ABE1 (12:8:1)v/v, ABE2 (15:10:1)v/v dan ABE3 (18:12:1)v/v. kecepatan mesin 4000-10000rpm dan rasio kompresi 11.6:1. Pengujian emisi dan performansi mesin menggunakan EPSG4-Gas analyzer dan Dynotest-chassis tipe 50L-BRT. Tujuan penelitian ini untuk mengeksplorasi percampuran RON-90 dan ABE sehingga dapat mengoptimalkan performa dan emisi gas buang. Penelitian ini menunjukkan bahwa Torsi mengalami peningkatan rata-rata 14,7% pada kecepatan mesin 6000rpm. Daya meningkat signifikan dengan nilai rata-rata sebesar 9,5% pada kecepatan mesin 8000rpm, MEP meningkat sebesar 0,5%, dan efisiensi termal juga meningkat sebesar 7%. SFC mengalami penurunan yang cukup optimal rata-rata sebesar 15,6%. Emisi gas buang yang dihasilkan adalah CO dan HC. Penurunan CO dan HC terjadi pada varian ABE3 dengan nilai masing-masing sebesar 8,2% dan 1,6%.

Keywords:
exhaust emission;
performance;
si-matic engine;
acetone-butanol-ethanol.

Abstract

Acetone-butanol-ethanol (ABE) is a preferred alternative energy for SI engines. This research uses an experimental method with an automatic SI engine, RON-90 fuel mixed with ABE1 (12:8:1)v/v, ABE2 (15:10:1)v/v and ABE3 (1i8:12:1) v/v. Engine speed is 4000-10000rpm, and compression ratio is 11.6:1. Emission and engine performance testing used EPSG4-Gas analyzer and Dynotest-chassis type 50L-BRT. This research aims to explore the mixture of RON-90 and ABE to optimize performance and exhaust emissions. This research shows that torque increases by an average of 14.7% at an engine speed of 6000rpm. Power increased significantly with an average value of 9.5% at an engine speed of 8000rpm, MEP increased by 0.5%, and thermal efficiency increased by 7%. SFC experienced a fairly optimal decrease of 15.6% on average. The exhaust gas emissions produced are CO and HC. The reduction in CO and HC occurred in the ABE3 variant with values of 8.2% and 1.6%, respectively.

***Penulis korespondensi:**
Gatot Setyono
E-mail: gatotsetyono@uwp.ac.id

1. Introduction

Modern engines must meet increasingly stringent requirements for reduced emission levels and increased performance, especially thermal efficiency [1]. The increasing use of motorized vehicles, massive consumption of the problem of increasing pollution globally, and fossil energy, to overcome these problems by exploring alternative fuels that are more optimal for everyday use. Biofuels have attracted much attention because of their technological prowess—very abundant and optimal raw materials for the combustion process [2][3]. SI-Engine will remain the primary power source for energy-generating machines and vehicles due to their maneuverability, reliability, and durability requirements. However, Fuel was rapidly depleting due to the high absorption of fossil fuels towards the growth of motorization and industrialization in developing countries today [4]–[6].

The ABE fermentation method is used to produce bio-butanol, and the typical ratio of acetone, butanol, and ethanol in the ABE fuel mixture is 3:6:1. The bio-butanol extraction process requires large amounts of energy in the ABE fermentation solution [7][8]. These conditions have identified that in terms of price, biobutanol has a less good reputation. For this reason, many researchers have directly explored ABE as an alternative fuel mixture in SI engines. In recent years, much research has described the impact of adding ABE on SI engine performance [9][10][11]. Fuel additives are a straightforward technique for changing the properties of the base fuel to minimize emissions and improve performance. Alcohol is a renewable alternative fuel that can be derived from bio-energy-based resources. Alcohol, ether, and acetone are viable fuel candidates for SI engines due to their characteristics and optimal oxygenated content compared to others. Bio-based waste is abundantly available in developing countries, where agriculture is a significant economic resource. It can be usefully used for alcohol production [12]–[14].

ABE is a biofuel as an alternative fuel, has relatively superior characteristics, and is optimal for SI engines. ABE can be produced as biofuel from the biobutanol reaction. However, the high cost and extra energy consumption in recovering biobutanol from intermediate fermentation solvents (i.e., ABE mixtures) have hindered its application on a large scale. There is increasing attention to investigating ABE as a potential alternative biofuel. The production and combustion of ABE in ICE engines has been studied extensively. ABE fermentation can be produced from three methods. The first step is to determine the appropriate fermentation strain of biobutanol. The second step is to determine precisely the optimal substrate; the third step is the innovation of efficient fermentation methods. ABE becomes liquid energy to replace fossil fuels because the ABE production process is environmentally friendly, has optimal efficiency, and reduces pollutant capacity [15]. Exploration of the performance of SI engines using a mixture of standard fuel with ABE is used to increase oxygen and hydrogen levels in the combustion process. The percentage of the ABE mixture at an engine speed of 1500 rpm with a portion of 5.4% ethanol can reduce CO levels by up to 0.58% and HC levels by 211 ppm. In line with engine performance, BTE increased by 28%. The same conditions at an engine speed of 2264rpm in the ABE variant with a 5% ethanol portion experienced a reduction in NOx of 1029 ppm. In contrast, the BTE that occurred experienced a significant increase of 30% [13], [16], [17]. ABE can be used to overcome the high costs of producing bio-butanol. The research was carried out with several ABE variations, including 25% -100% and an air ratio of 0.9 to 1.2. The increase in IMEP occurs in the 75% ABE variant, so it is directly proportional to IMEP and BTE, which increase at $\lambda = 0.9$ and decrease when the air ratio is 1.0 to 1.2. HC exhaust emissions have been reduced in the ABE variant by 50%. This research shows that the ABE variant is very suitable for SI engines as an alternative fuel for daily use. The high ABE variant is more significant than 50%, so it can effectively improve combustion [5].

Butanol is an alternative energy for SI engines, but its production requires many costs. Acetone-butanol-ethanol (ABE) is a product of the bio-butanol fermentation process, and ABE is an alternative fuel to replace fossil energy and power with high oxygen levels. ABE fermentation is developing rapidly so that control of the bio-solvent capacity contained in ABE can be more optimal. In this proposal, ABE fuel with varying volumetric ratios is used, namely (A:B: E from 12:8:1, 15:10:1, and 18:12:1)v/v with a Port Fuel Injection fuel supply system on automatic engines-SI capacity 155cc. Engine testing with non-constant speed, namely 3000-9000 rpm. Test engine performance using a dyno test-chassis type Super-Dyno 50L. The test result data is in the form of engine performance indices: torque, power, specific fuel consumption, average adequate pressure, and thermal efficiency. The exhaust gas emissions produced are HC, CO, and NOx.

2. Method

2.1. The Diversity of Fuel Capacity Used.

The alternative fuels used in this research are acetone-butanol and ethanol (ABE). The level of oxygen contained in the power will influence the combustion process to be more environmentally friendly. This time, the butanol content in the fuel will improve engine performance, so it can be used daily. The fuel variants compared in this study were ABE1 (12%-Acetone, 8%-Butanol and 1%-Ethanol)v/v, ABE2 (15%-Acetone, 10%-Butanol and 1%-Ethanol)v/v, ABE3 (18%-Acetone, 12%-Butanol and 1%-Ethanol)v/v. Table 1 shows that an increase in engine performance can be determined based on the characteristics of calorific value and the octane number. Meanwhile, viscosity affects and fuel density the injection characteristics of the combustion chamber. The greater the viscosity value, the smaller the spray angle. Table 2 shows the ABE comparison and the RON-90 fuel capacity used. The fuel capacity will affect the SI engine's emission characteristics and performance.

2.2. The Engine Matic-SI Performance Test

Fuel variations will be used to test engine performance. Table 3 shows the characteristics of the SI engine used with a compression ratio of 11.6:1; the engine's maximum torque occurs at 13.9Nm at a speed of 6500 rpm. The maximum engine power that occurs at a speed of 8000 rpm is 11.3kW.

The dimensions of the combustion chamber have a diameter of 58 mm and a stroke length of 58.7 mm. The BRT-50L Chassis Dyno test determines the engine performance level, namely torque and power. EPSG4 Gas Analyzer determines the level of exhaust gas emissions, namely HC, CO, and NOx. In this engine performance test, it produces torque, power, and fuel consumption. The test results will further analyze average adequate pressure (Mep), thermal efficiency, and specific fuel consumption (Sfc). So, these results will describe the resulting engine performance.

Table 1. Diversity Of Fuel Capacity [2], [6], [13], [15], [17].

Properties	RON-90	Ethanol	Butanol	Acetone
Octane Number	90	100	96	117
Flash Point (°C)	20	13	35	-20
Stoichiometric AFR	14.7	9	11.2	9.5
Density (kg/m^3) at 20 °C	715	795	813	791
Chemical Formula	C_8H_{18}	C_2H_5OH	C_4H_9OH	C_3H_6O
LHV (MJ/kg)	45.2	26.8	33.1	29.6
Cetane Number	5-20	5-8	25	-
Oxygen Content (wt%)	-	34.8	21.6	27.6
Auto-Ignition Temp. (K)	753	434	343	465

Table 2. Distribution Of Fuel Capacity.

Index Mixture	RON-90	Acetone	Butanol	Ethanol
ABE1	790 ml	120 ml	80 ml	10 ml
ABE2	740 ml	150 ml	100 ml	10 ml
ABE3	690 ml	180 ml	120 ml	10 ml

Table 3. Specifications of the SI-Matic engine used.

Detail	Specification
Number of Cylinders.	: 1pc.
Engine Capacity.	: 155 cc.
Stroke x Diameter.	: 58.7 mm x 58,0 mm.
Maximum Power.	: 11.3 kW / 8000 rpm.
CR.	: 11.6 : 1.
Maximum Torque.	: 13.9 Nm / 6500 rpm.
Fuel System.	: FI (Fuel Injection).
Transmission Type.	: V-belt Automatic.
Machine Type.	: Liquid-cooled 4-stroke, SOHC.
Clutch Type.	: Dry, Centrifugal Automatic.

Figure 1 shows the engine performance test using ABE1, ABE2, and ABE3 fuel comparisons. The SI engine used has a capacity of 155cc and runs at speeds between 4000 to 10000 rpm; the fuel consumption used can be determined while the vehicle is running so that when the engine is connected to a chassis dyno test, the CPU display will describe the torque and power output of the engine. At the same time, an emissions test is carried out on the vehicle exhaust, describing CO, HC, and NOx emissions.

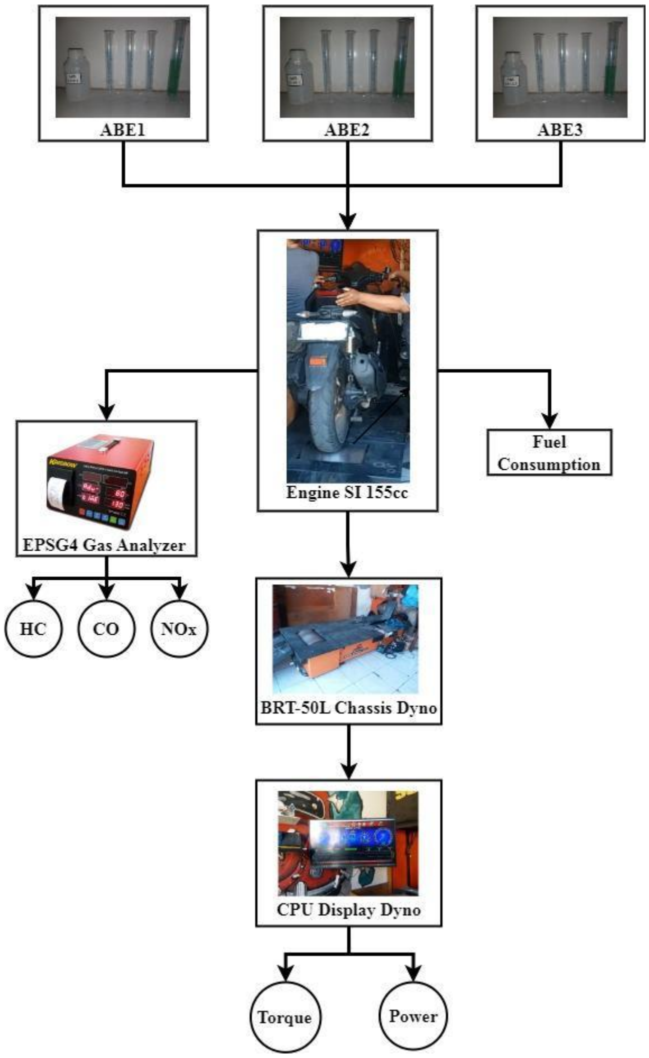

Figure 1. SI-Matic Engine Performance Test Scheme

2.3. Research Flowchart

This research uses alternative energy in the form of liquid fuel, which is environmentally friendly. Engine performance test using a mixture of RON-90 fuel with ABE1, ABE2, and ABE3. Figure 2 shows that performance tests and emissions tests are carried out simultaneously so that the test results produce engine performance and emissions that are interrelated. It means that when exploring SI engine performance levels, the sustainability of emission levels can be described, these conditions will be more optimal for monitoring exhaust emissions and engine performance. From the relationship between engine performance and emissions, data analysis can be carried out and produce a conclusion that can explain the aim of this research. The variables in this study are the independent variables, which are conditions that influence a symptom in this study. The independent variables include fuel variations ABE1, ABE2 and ABE3. The dependent variable is all events or symptoms that arise in connection with the implementation of this research. In this research, the dependent variables are the composition of exhaust emissions, engine speed, fuel consumption, and fuel usage time. Control variables are factors whose influence is controlled or neutralized by researchers because if they are not neutralized, it affects the other two variables; the control variables are exhaust gas temperature and engine operating temperature.

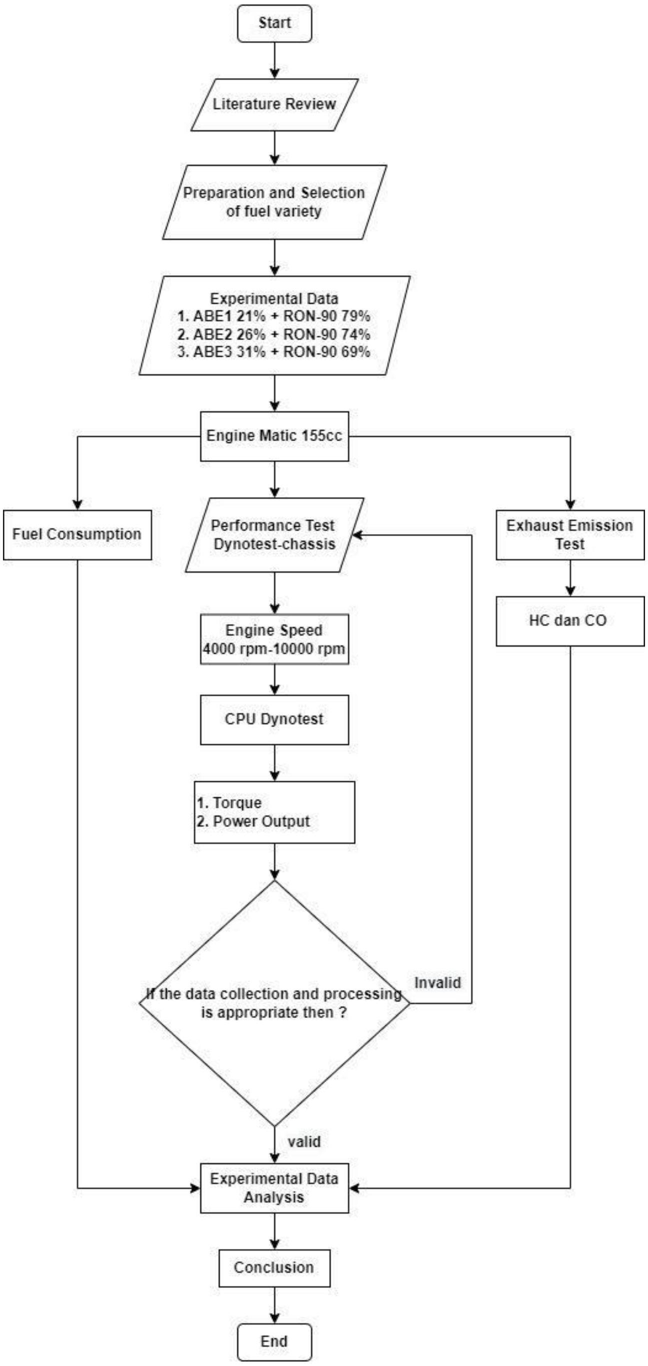

Figure 2. Process of Research.

3. Result And Discussion

The most essential SI engine parameter indication is torque; Figure 3 shows the phenomenon of torque versus engine speed gap 4000-10000 rpm at a compression ratio of 11.6:1. The picture below shows that the torque with the ABE3 variant has increased quite significantly compared to the other three different variants. The largest torque values in the ABE3 variant are 7%, 15%, and 22.2% more optimal than Pertalite (RON-90). Meanwhile, the torque of the ABE1 variant is the lowest, meaning that the accumulated ABE can only optimally increase the SI engine power by adding this variant. These symptoms can be described as follows. The lower stoichiometric fuel ratio of the ABE variant compared to RON-90 results in the ABE injection quantity being around one and a half times that of RON-90. When the ABE variant is added to the port, the higher addition capacity and lower injection pressure will result in some of the ABE adhering to the inlet valve and manifold walls. Apart from that, the influence of the latent heat evaporation rate of the ABE variant is too high, resulting in an inhomogeneous mixture and a high evaporation process of latent heat. Therefore, this phenomenon results in the torque of the ABE3 variant being greater than that of the ABE1. However, the direct addition of ABE can overcome this problem because the ABE variant is spontaneously introduced into the combustion chamber under high-pressure conditions, which can reduce the atomization characteristics and the comparison of evaporation properties between RON-90 and ABE. Therefore, LFS ABE and very significant oxygen capacity create a perfect and faster quality combustion process. So, it produces optimal torque for the ABE3 variant compared to RON-90 and ABE1.

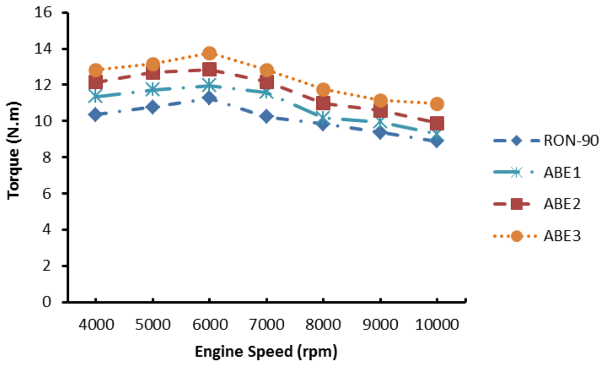

Figure 3. Comparison of torque to engine speed

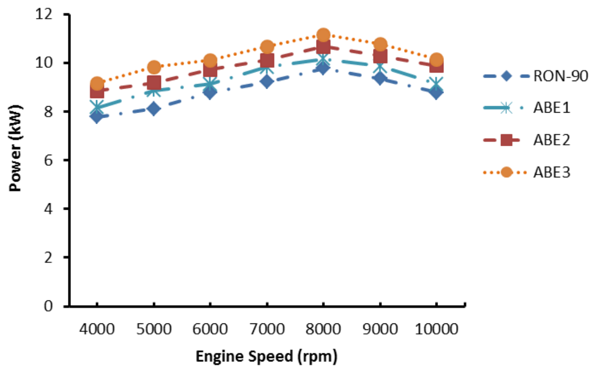

Figure 4. Comparison of power to engine speed

Figure 4 describes the power phenomenon of the SI engine with three ABE and RON-90 fuel variants. Following the illustration in Figure 4, SI engine power describes a phenomenon similar to torque for all fuel variants tested. SI engine power experiences a significant increase with throttle opening due to intensified intake air efficiency for all ABE variants. The engine power that experienced an optimal increase between the three ABE variants included 4.5%, 9.7%, and 14.1%. The phenomenon of increasing power occurs due to the allocation of fuel vapor in the combustion chamber. Therefore, the ignition process tempo at small throttle openings will be more optimal than at larger openings. Therefore, the SI engine power performance is escalated precisely and optimally. Apart from that, in the conditions of the ABE3 fuel variant, the engine power decreases coincident with the increase in the quantity of ABE addition fraction due to the heat evaporation of ABE fuel, which is more dominant compared to RON-90. The phenomenon is because the saturated vapor pressure and latent heat value of RON-90 fuel are higher compared to ABE [1], [2], [13]. For example, according to the description in Table 1, the LHV values for the fuel variants are 26.8, 33.1, and 29.6, respectively. Therefore, the evaporation time for RON-90 fuel after spraying is shorter compared to the ABE-RON-90 variant. The dominant ABE mixture capacity in the fuel causes the mixture to be non-homogeneous, causing the phenomenon of an incomplete combustion process. Therefore, engine power will decrease as engine speed increases and combustion chamber heat increases.

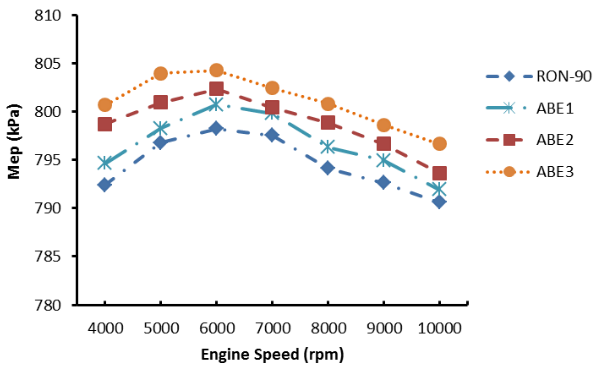

Figure 5. Comparison of MEP to engine speed

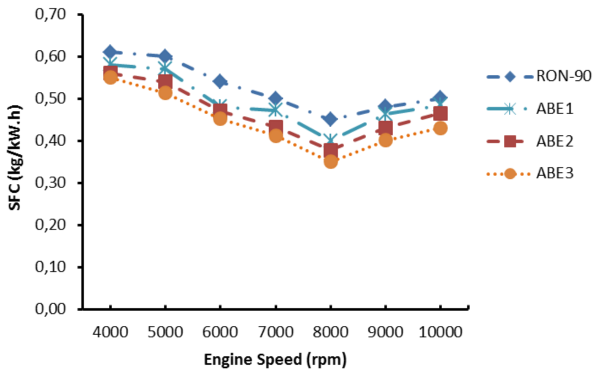

Figure 6. Comparison of SFC to engine speed

Figure 5 shows the MEP results for the three fuel variants, showing that ABE produces the highest. It's extraordinary that the Mep for the ABE3 variant is more optimal than the ABE1 variant. This phenomenon occurs because as MEP increases, the cylinder and intake temperature will increase, thereby forcing the ABE mixing and evaporation process in the manifold. The optimal mixing and evaporation process results in reducing the injection level at the ABE port and dominates the ABE quality in the combustion process, which causes MEP to be greater in the ABE3 variant compared to ABE1, namely 804.26 kPa. Along with the increase in engine speed, MEP experienced an increase at an engine speed of 6000 rpm, then decreased to 796.63kPa at a speed of 10000 rpm. Increasing engine speed causes heat losses to decrease, and this phenomenon is directly proportional to the speed of flame propagation in the cylinder. When the flame propagation and engine speed are too large, and the change in heat losses decreases, this results in a decrease in SI engine performance. Pumping losses experienced a significant decrease due to relatively large throttle openings and increased speed, so the engine speed continues to increase beyond 6000rpm.

Figure 6 shows the comparison between specific fuel consumption and engine speed. According to the illustration described in Figure 6, the SI engine is operated in the rotation range of 4000-10000 rpm with ABE1, ABE2, and ABE3 fuel variants. The SFC graph shows that the smallest gap occurs in the ABE3 variant with an engine speed of 8000rpm, and the SFC gap occurs in the three variants operating at a speed of 8000 rpm of 7.7%, 14.3%, and 28.6%. This phenomenon shows that the high speed of the SI engine can realize more optimal power by using a larger ABE ratio. In addition, the lean-burn limitation of high-speed SI engines is also developed by increasing the Pertalite-ABE mixture ratio. Two components cause this phenomenon. First, in collaboration with standard fuel, the ignition limitation of the increased ABE-RON 90 fuel mixing ratio in SI engines results in the development and formation of an initial spark nucleus in the combustion chamber. Second, the laminar flame capacity of ABE is greater than RON 90. So, a high ABE ratio can increase the laminar flame ratio, optimize the combustion rate, and cut the fire extinguishing distance that occurs on cold walls, thereby widening the ignition limitation.

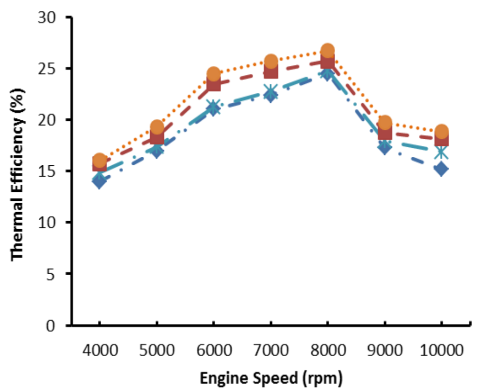

Figure 7. Comparison of thermal efficiency to engine speed

Because there is an average change in energy of 4.8% between the three fuel variants ABE1, ABE2, and ABE3, this research explores thermal efficiency to compare the three fuel variants. Figure 7 describes the phenomenon of thermal efficiency on SI engine speed. This phenomenon causes the impact of isentropic efficiency to increase in direct proportion to the increase in excess air ratio. The ABE1 fuel variant also produces the lowest thermal efficiency value, while the ABE3 variant has the highest thermal efficiency value. The ABE3 fuel variant has the highest average thermal efficiency value of 3.9%, 8%, and 9% higher compared to the ABE1 and ABE2 variants at a speed of 8000rpm. The rise influences the increase in thermal efficiency in total energy and the superior characteristics of ABE fuel and accurate injection methods [2], [11], [12]. Therefore, ABE3 fuel can increase thermal efficiency, which is the right choice as an alternative to liquid fuel energy.

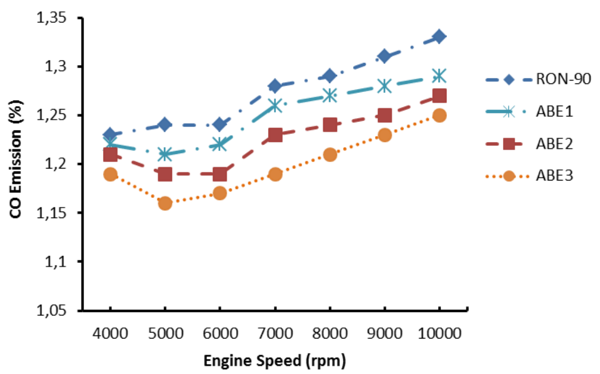

Figure 8. Comparison of CO emissions to engine speed

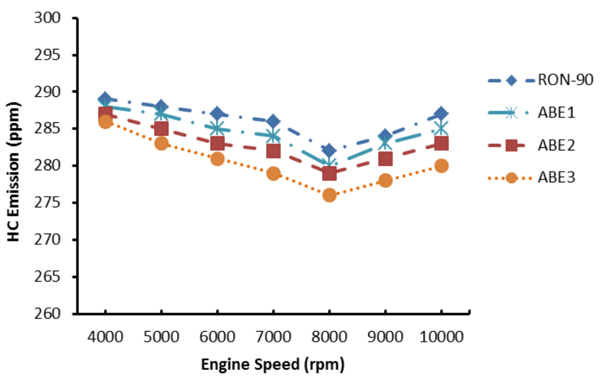

Figure 9. Comparison of HC emissions to engine speed

Carbon monoxide (CO) is a colorless, odorless gas at temperatures above its boiling point and dissolves easily in water. Carbon monoxide gas is the main component in polluted air because the reactivity of carbon monoxide gas towards hemoglobin in the blood causes the blood to lack oxygen and disorders nerves. Normal combustion will burn all the hydrogen and oxygen contained in the air and fuel mixture. CO emissions arising from flue gas are a phenomenon of an incomplete combustion process. Too little air supply in the combustion chamber will result in the combustion process being less than optimal, so this condition can reduce performance. In the CO emission graph, the engine speed function has a graphic trend that tends to decrease from low engine speed until it reaches the optimum point. At this optimum point, the supply of air is mixed in the appropriate composition, then CO will tend to rise again with higher engine speed. Figure 8 shows that the highest CO emissions occur when the engine uses RON-90 fuel. Meanwhile, the lowest emissions are produced by engines that use a mixture of RON-90 and ABE3 fuel. On average, the amount of reduction when using ABE3 addition is 10.5% compared to RON-90. The average reduction of the three ABE variants on SI engine speed is 8.2%.

Hydrocarbon (HC) exhaust emissions are the amount of fuel not burned during combustion. In general, HC emission levels will decrease with increasing engine speed because the air and fuel mixture's homogeneity will improve when the speed increases. However, this only happens up to a certain round. If the rotation becomes faster, the combustion time will become narrower so that the level of unburned fuel will be even greater. Figure 9 shows that the ABE1, ABE2, and ABE3 mixture of HC emissions produced by exhaust gas tends to decrease. This reduction is caused by the addition of ABE, which will have better combustion in the combustion chamber so that fewer unburned hydrocarbons are wasted in the exhaust. With this addition, HC emissions at high revs, which tend to be increased when using RON-90, will decrease by 276ppm at an engine speed of 8000rpm. It could also be caused by adding ethanol, resulting in better fuel misting, so fuel atomization becomes better and results in better combustion.

4. Conclusion

Acetone-butanol-ethanol (ABE) is an alternative energy that can be favored for SI engines. Its main advantages are ABE's higher oxygen capacity and characteristics than standard fuel. This research exploration shows the superiority of ABE compared to RON-90. Engine performance, such as torque, power, MEP, and thermal efficiency, experienced a significant increase after using ABE3 as fuel. Torque experienced an average percentage increase with a consecutive value of 14.7% at a speed of 6000rpm. Power increased significantly with an average percentage value of 9.5% at an engine speed of 8000rpm, MEP increased with an increase in torque with a value of 0.5%, and thermal efficiency was directly proportional to the power produced, so the percentage value is 7%. SFC experienced a quite optimal reduction phenomenon at an engine speed of 8000 rpm with a percentage value of 15.6%. The exhaust gas emissions produced are HC and CO. The decrease in HC and CO occurred in the ABE3 variant with percentage values of 8.2% and 1.6%, respectively. ABE is suitable for alternative energy so further research will explore and seek collaboration on fuel capacity, compression ratio, and SI engine capacity.

Acknowledgments

Researchers appreciate Wijaya Putra University, especially LPPM-UWP, which funds it through internal research with agreement letter number 03.21/KP/LPPM-UWP/K-I/V/2023 as well as the Faculty of Engineering and the UWP-Mechanical Engineering Study Program which has supported this research.

References

[1] W. Guillin-Estrada, D. Maestre-Cambronel, A. Bula-Silvera, A. Gonzalez-Quiroga, and J. Duarte-Forero, “Combustion and Performance Evaluation of a Spark Ignition Engine Operating with Acetone–Butanol–Ethanol and Hydroxy,” *Appl. Sci. 2021, Vol. 11, Page 5282*, vol. 11, no. 11, p. 5282, Jun. 2021, doi: 10.3390/APP11115282.
[2] Z. Guo, X. Yu, Y. Du, and T. Wang, “Comparative study on

combustion and emissions of SI engine with gasoline port injection plus acetone-butanol-ethanol (ABE), isopropanol-butanol-ethanol (IBE) or butanol direct injection," *Fuel*, vol. 316, p. 123363, May 2022, doi: 10.1016/J.FUEL.2022.123363.

[3] D. Li, H. Wang, X. Yu, and H. Yang, "Combustion and emission characteristics of an Acetone-Butanol-Ethanol (ABE) spark ignition engine with hydrogen direct injection," *Int. J. Hydrogen Energy*, vol. 46, no. 58, pp. 30145–30157, Aug. 2021, doi: 10.1016/J.IJHYDENE.2021.06.144.

[4] U. Kesieme, K. Pazouki, A. Murphy, and A. Chrysanthou, "Biofuel as an alternative shipping fuel: technological, environmental and economic assessment," *Sustain. Energy Fuels*, vol. 3, no. 4, pp. 899–909, Mar. 2019, doi: 10.1039/C8SE00466H.

[5] Z. Guo *et al.*, "Research on the combustion and emissions of an SI engine with acetone-butanol-ethanol (ABE) port injection plus gasoline direct injection," *Fuel*, vol. 267, p. 117311, May 2020, doi: 10.1016/J.FUEL.2020.117311.

[6] I. Veza, M. F. M. Said, and Z. A. Latiff, "Progress of acetone-butanol-ethanol (ABE) as biofuel in gasoline and diesel engine: A review," *Fuel Process. Technol.*, vol. 196, p. 106179, Dec. 2019, doi: 10.1016/J.FUPROC.2019.106179.

[7] I. Veza, M. F. Muhamad Said, and Z. A. Latiff, "Recent advances in butanol production by acetone-butanol-ethanol (ABE) fermentation," *Biomass and Bioenergy*, vol. 144, p. 105919, Jan. 2021, doi: 10.1016/J.BIOMBIOE.2020.105919.

[8] H. González-Peñas, T. A. Lu-Chau, G. Eibes, and J. M. Lema, "Energy requirements and economics of acetone–butanol–ethanol (ABE) extractive fermentation: a solvent-based comparative assessment," *Bioprocess Biosyst. Eng. 2020 4312*, vol. 43, no. 12, pp. 2269–2281, Jul. 2020, doi: 10.1007/S00449-020-02412-7.

[9] Q. Tang, P. Jiang, C. Peng, X. Duan, and Z. Zhao, "Impact of acetone–butanol–ethanol (ABE) and gasoline blends on the energy balance of a high-speed spark-ignition engine," *Appl. Therm. Eng.*, vol. 184, p. 116267, Feb. 2021, doi: 10.1016/J.APPLTHERMALENG.2020.116267.

[10] G. Wu, D. Wu, Y. Li, L. Meng, and D. Zhou, "Effect of Acetone- n -Butanol-Ethanol (ABE) as an Oxygenate on Combustion, Performance, and Emission Characteristics of a Spark Ignition Engine," *J. Chem.*, vol. 2020, 2020, doi: 10.1155/2020/7468651.

[11] S. M. N. Rahaju *et al.*, "Acetone-Butanol-Ethanol as the Next Green Biofuel - A Review," *Automot. Exp.*, vol. 5, no. 3, pp. 251–260, Jun. 2022, doi: 10.31603/AE.6335.

[12] J. Benajes, R. Novella, J. Gomez-Soriano, P. J. Martinez-Hernandiz, C. Libert, and M. Dabiri, "Evaluation of the passive pre-chamber ignition concept for future high compression ratio turbocharged spark-ignition engines," *Appl. Energy*, vol. 248, pp. 576–588, Aug. 2019, doi: 10.1016/J.APENERGY.2019.04.131.

[13] P. Dinesha, S. Mohan, and S. Kumar, "Experimental investigation of SI engine characteristics using Acetone-Butanol-Ethanol (ABE) – Gasoline blends and optimization using Particle Swarm Optimization," *Int. J. Hydrogen Energy*, vol. 47, no. 8, pp. 5692–5708, Jan. 2022, doi: 10.1016/J.IJHYDENE.2021.11.119.

[14] Q. Tang, K. Ren, X. Xie, T. Chen, P. Jiang, and D. Zhang, "The effect of acetone-butanol-ethanol and gasoline blends on the knocking performance of spark-ignition engine," *Therm. Sci. Eng. Prog.*, vol. 46, p. 102175, Dec. 2023, doi: 10.1016/J.TSEP.2023.102175.

[15] Y. Li, W. Tang, Y. Chen, J. Liu, and C. fon F. Lee, "Potential of acetone-butanol-ethanol (ABE) as a biofuel," *Fuel*, vol. 242, pp. 673–686, Apr. 2019, doi: 10.1016/J.FUEL.2019.01.063.

[16] Y. Li, Z. Ning, C. fon F. Lee, J. Yan, and T. H. Lee, "Effect of acetone-butanol-ethanol (ABE)–gasoline blends on regulated and unregulated emissions in spark-ignition engine," *Energy*, vol. 168, pp. 1157–1167, Feb. 2019, doi: 10.1016/J.ENERGY.2018.12.022.

[17] Z. Guo, X. Yu, G. Li, Y. Sun, Z. Zhao, and D. Li, "Comparative study of different injection modes on combustion and particle emission of acetone-butanol-ethanol (ABE) and gasoline in a dual-injection SI engine," *Fuel*, vol. 281, p. 118786, Dec. 2020, doi: 10.1016/J.FUEL.2020.118786.