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Effects of Fuel Injector Seat Angle on Power, Torque, and Exhaust Emissions of a Single-Cylinder Four-Stroke Engine

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Abstract: This study aims to examine the relationship and comparison of motor performance based on different fuel injector angles in a fuel injection system, and to identify the optimal injector angle for improved engine performance. Fuel injection is a control technology that regulates the air–fuel mixture entering the combustion chamber with speed, precision, and proportional balance. An experimental method was employed using a 2020 motorcycle with a 108 cc engine. The tests conducted included torque, power, and exhaust emission measurements. Torque and power were measured using a dynamometer, while exhaust emissions were analyzed with a gas analyzer. The study compared injector mounting angles of 60°, 70°, and 80°. Results showed that torque increased significantly from low engine speeds (around 3000 rpm) and peaked between 3500–3750 rpm before gradually declining. Among the tested angles, the 80° injector position produced the highest torque across most speed ranges, reaching approximately 15 Nm at 3500 rpm. The 70° angle yielded moderate performance, while the 60° angle demonstrated the lowest torque, especially at medium to high speeds. Overall, the study found that increasing the injector angle enhances torque and power output, with average increases of 6.1% in power and 6.4% in torque.

Keywords: Angle, fuel injector, power, torque and exhaust emissions

INTRODUCTION

The automotive industry focuses on producing cars with high performance and fuel economy. Vehicles, particularly those with fuel injection systems, utilize this new fuel treatment system. Some of the advantages of this newer fuel treatment system include improved fuel consumption. This electronically controlled fuel injection system is called an electronic fuel injection system, or EFI. Fuel is sprayed into the combustion chamber in a mist form according to the ratio of air entering the combustion chamber, ensuring the most efficient air-fuel mixture. The fuel tank, fuel filter, fuel pump, delivery pipe, injector, pressure regulator, fuel feed, return feed, and sensors are all components of the injection system.

The injector, the main component of an injection engine in an EFI system, is responsible for injecting fuel into the intake manifold, which is the passageway for air before entering the combustion chamber. The injector's crucial role lies in the fact that the fuel supply entering the combustion chamber is controlled by the injector located in the intake manifold. To maximize engine performance and meet engine needs, numerous experiments have been conducted on injectors to improve engine performance and reduce exhaust emissions. At the end of the compression stroke, when the piston is 18°–22° before TDC, the injector delivers fuel into the cylinder. During this stroke, the nozzle (part of the injector) sprays fuel in a precise mist, regularly and continuously. Supporting components assist the injector in its mechanism to maximize its performance when atomizing the fuel.

The use of racing injectors and high octane fuel improves performance, but must be balanced with appropriate ECU settings. Studies analyzing ECU remapping on injection motorcycles show that readjusting ECU parameters can increase engine power and torque output as well as fuel efficiency (Handriyanto, R., & Ponidi, P., 2024; Fatra, F., et al 2023; Fauzil, A. F. et al, 2023); Setiadi, B. et al, 2024; Hambali, H. et al, 2024). Racing or aftermarket ECUs provide improved performance compared to standard ECUs. Remapping and adjusting fuel injection and combustion timing also have an impact on reducing exhaust emissions such as CO, CO2, and HC (Purwanto, W. et al, 2024; Hadi, M. F. A., et al, 2024). Optimal settings on the ECU can balance performance and environmental friendliness. Various studies have developed and tested fuel injection systems in both gasoline and diesel engines using Electronic Control Unit (ECU) technology and various injector control methods (Deng, B. et al, 2020; Kim, J. B., & Lee, C. H., 2020; Syaka, D. R. B. et al, 2022). The design of the appropriate drive circuit and injector algorithm can improve the precision of fuel injection and combustion efficiency. Studies discussing split injection, common rail, multi-injector, and mass feedback injection control highlight the trend of improving injection technology to achieve better combustion efficiency and emission reduction (Ganesan, N. et al , 2022; Ferrari, A. et al, 2023).

Adaptive injector control to environmental conditions can improve the efficiency of the injection system. Research by Anugrah, A. (2024), shows that the number of injector holes and octane rating affect the performance of gasoline engines, including throttle response, combustion, and exhaust emissions. Research by Pratama, F. H., et al. (2024) and Diep, H. T., et al. (2023) highlights that ECU remapping, including Arduino-based ones, can be adjusted for various operating conditions to achieve maximum efficiency and performance of gasoline engines.

Studies by Francis, L. T., et al. (2022) and Yanoto, K., (2022) show how data-driven approaches and intelligent control systems (such as engine knock sensors or injector control devices) can improve the accuracy and safety of combustion systems. Research by Deepak, K., & Lakshmanan, T. (2020) and Stepanenko, D., & Kneba, Z. (2020), suggests that developing injection systems that support dual-fuel or multi-fuel injectors could be an innovative solution to increase flexibility and energy efficiency in combustion engines.

Combustion engine power is defined as the ability of an engine to convert chemical energy from fuel into mechanical energy used to produce rotation on the output shaft (Pham, V. C. et al, 2022). Torque is mentioned as one of the mechanical outputs produced by combustion in an engine, along with engine power. Implicitly, the torque refers to the rotational moment on the crankshaft, which is the product of the combustion force and the distance between the force and the center of rotation (Syaka, D. R. B., Mahir, I., & Muslim, G. M., 2023). Exhaust emissions are components of the remaining fuel combustion released from motorcycles with injection engines (FI). Carbon Monoxide (CO), a dangerous gas produced from incomplete combustion when there is not enough oxygen, resulting in CO molecules that can be harmful to health. Carbon Dioxide (CO_2), the result of perfect combustion; the CO_2 level indicates combustion efficiency. The higher the CO_2, the more efficient the combustion.

Hydrocarbons (HC), hydrocarbon compounds that have not been completely burned, increase when combustion is not optimal, as an indicator of fuel waste and potential pollution (Purwanto, W., et al, 2024). Questions arise about the discussion with different performance because of the description above, so the author conducted additional research to test different performance. For this study not to deviate from its initial objectives and to facilitate the collection of necessary data, the author sets limitations, how the relationship between the fuel injector angle of the fuel injection system and the performance of the combustion engine and how the comparison of the performance of the combustion engine on the variation of the fuel injector angle of the fuel injection system. The purpose of this study is to study the relationship and comparison of motor performance to the use of the fuel injector angle of the fuel injection system, as well as the fuel injector angle of the fuel injection system that produces better engine performance. This study has several benefits for the author and readers or observers of automotive technology, including contributing to knowledge about automotive technology, especially about vehicle modifications

RESEARCH METHOD

This study uses an experimental method approach, which aims to determine the effect of variations in the angle of the injector on the performance of a motorcycle engine, especially on the parameters of power, torque, and exhaust emissions. The experiment was carried out by providing certain treatments, namely variations in the angle of installation of the fuel injector, and then observing the changes that occur in the power output, torque, and exhaust gas composition. As explained by Gamal Thabroni, the experimental approach allows testing the direct impact of an independent variable on the dependent variable, by considering the controlled environmental conditions.

In carrying out this study, there are three types of variables used. First, the free variable or independent variable, namely the angle of the injector. The angles tested include 60°, 70°, and 80°, where each angle is considered to have a different effect on the combustion process in the engine combustion chamber.

Injector Angle 60º   Injector Angle 70º   Injector Angle 80º

Figure 1. Intake Manifold and injector

Second, dependent variables, namely the observed result parameters as a result of injector angle variations. In this case, the main focus is the power produced by the engine, the amount of torque, and the level of exhaust emissions, including hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), and oxygen (O_2). Third, control variables are elements that are kept constant during testing, in order to avoid external influences on the results. In this study, control variables include the tools and conditions of the engine temperature and the temperature of the room where the test was carried out. Controlling this variable is important to ensure that changes in the test results really come from changes in the injector angle, not from other factors.

In order for data collection to run accurately and validly, a number of instruments and testing materials have been prepared. The research instruments are divided into two groups, namely materials and testing tools. For testing materials, a motorcycle is used as the main object, with a modified injection system on the intake manifold and injector. The fuel used is Pertalite, because it is easy to obtain and represents medium octane fuel commonly used by the public.

Meanwhile, the tools used to support testing include, Tool box, which functions as basic equipment for the process of disassembling and reassembling the injector system. Dynotest, the main tool used to measure engine power and torque in real-time. This tool is very important for obtaining quantitative data on engine performance in various injector angle conditions. Gas analyzer, a tool that functions to measure exhaust emissions. With this tool, the concentration of each type of gas such as CO_2, O_2, HC, and CO can be determined precisely. The gas analyzer is a vital instrument for assessing combustion efficiency and the level of pollution produced.

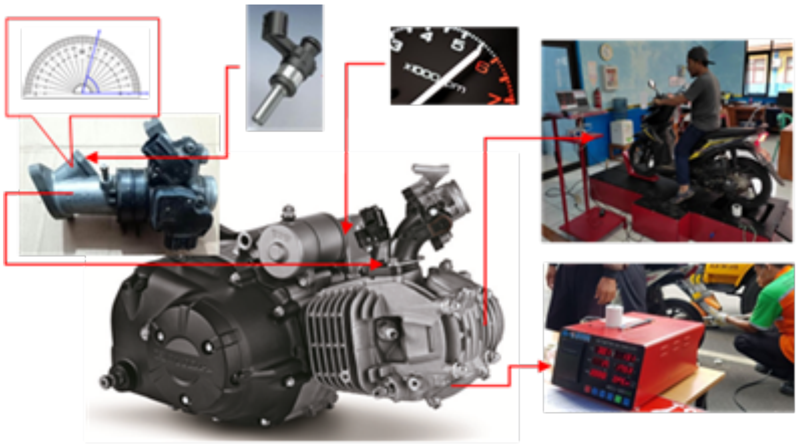


Figure 2. Research scheme

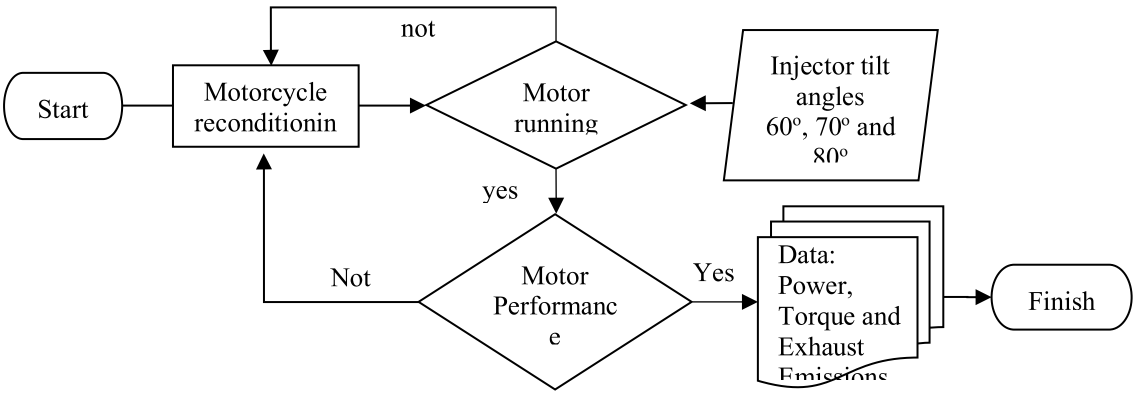


Figure 3. Testing flowchart

The research scheme is designed to describe the stages of the experiment as a whole. This scheme explains the relationship between variables, instruments, methods, and work steps taken by researchers from start to finish. The process begins with the preparation of tools and materials, followed by testing the motorcycle using variations in injector angles, then recording the results of power, torque, and exhaust emissions. The data obtained are then analyzed to determine the effect of injector angles on engine performance. This scheme is a systematic reference in the implementation and evaluation of research that is carried out in a structured and objective manner.

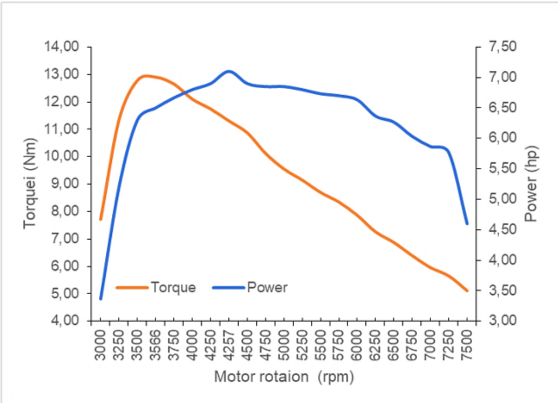
This research was conducted through three main stages, namely the preparation stage, the testing stage, and the data recording stage. In the Preparation Stage, the motorcycle as the test object was reconditioned to be in optimal condition. A thorough inspection included electrical, lubrication, and mechanical conditions of the engine. Furthermore, the measuring instruments dynotest for power and torque, and gas analyzer for emissions were prepared and calibrated. The motorcycle was positioned on the dynotest with the rear wheel directly on the roller. Additional safety was installed to prevent shifting or slipping during the test. After the installation was complete, a brief pre-test was carried out to ensure that all systems were connected and functioning properly. In the Testing Stage, the main testing process consisted of two sub-stages, which were repeated for three variations of injector angles (60°, 70°, and 80°). First, the engine performance test using a dynotest: the motorbike was run in a standard rotation range, while the dynotest recorded the power and torque values in real time. Second, exhaust emission testing: the gas analyzer captures gas samples from the exhaust pipe and measures the concentration of hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), and oxygen (O_2). By repeating these two sub-stages for each injector angle, a series of data is obtained that compares the effect of injector tilt on performance and emissions.

Data Recording Stage, all test results are recorded systematically. Power and torque data are downloaded directly from the dynotest and presented in a printed test result sheet. Meanwhile, the emission measurement results, HC, CO, CO_2, and O_2 values are recorded from the gas analyzer display. After the test is complete, this raw data is compiled in a table format to facilitate analysis. Further analysis will look at the correlation between injector angle and engine response, as well as the trend of changes in exhaust emissions. Thus, the study can answer the extent to which variations in injector angle affect combustion efficiency and the environmental impact of motorcycles.

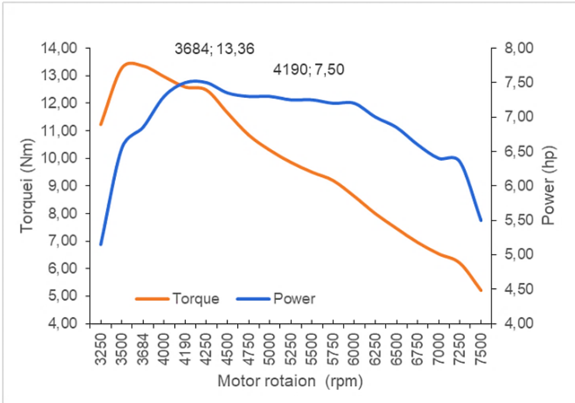
With a research design like this, it is hoped that a deeper understanding can be obtained regarding the effect of variations in injector angle on combustion efficiency and engine performance. The results can also provide technical recommendations in the development of more environmentally friendly and efficient fuel injection systems.

RESULT AND DISCUSSION

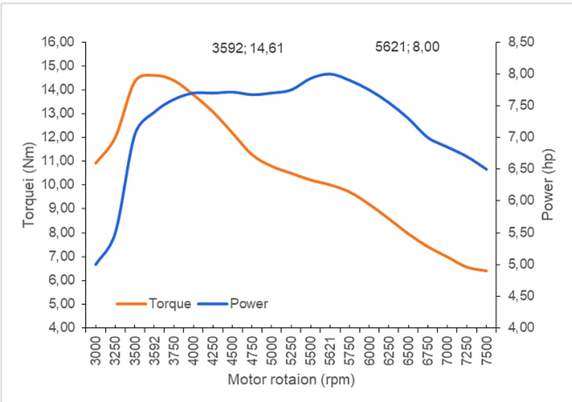
The results of engine performance testing using injectors with 60°, 70° and 80° seat angles, then the relationship between torque, power and rotation is obtained. The test results are transferred in the form of figure 1, figure 2 and figure 3 below:



(A)



(B)



(C)

Figure 4. Graph of the relationship between torque, power and rotation at (A) 60° injector seat (B) 70° injector seat and (C) 80° injector seat

Figure 4(A) shows the torque curve (orange line) and power (blue line) against engine speed (rpm). It can be seen that the torque increases sharply starting from 3000 rpm and reaches a peak of 12.90 Nm at 3566 rpm, then decreases gradually as engine speed increases. Conversely, power increases as engine speed increases, reaching a peak of 7.10 hp at 4257 rpm, then decreases slowly after that point. This pattern shows that the engine produces maximum torque at mid-range revs, while maximum power is achieved at higher revs. This reflects the general characteristics of internal combustion engines, where peak torque is achieved early, and power continues to increase until torque begins to decline. In Figure 4(B), Engine torque increases rapidly from 3250 rpm and peaks at 13.36 Nm at 3684 rpm. After reaching this maximum point, torque decreases gradually until the end of the rev range.

Meanwhile, engine power increases as engine revs increase, peaking at 7.50 hp at 4190 rpm, then begins to decline gradually after that point. This pattern shows the general characteristics of engines where maximum torque is achieved at mid-range revs, which is ideal for acceleration, while maximum power is achieved at higher revs, which is useful for peak speed or high loads. And in Figure 4©, Torque increases sharply from 3000 rpm and peaks at 14.61 Nm at 3592 rpm. After that, torque continues to decrease gradually until the end of the rev range at 7500 rpm. Meanwhile, the power continues to increase following the increase in engine speed, and reaches a maximum value of 8.00 hp at 5621 rpm, then decreases gradually after that point. This pattern indicates that the engine produces maximum torque at low to medium speeds, which greatly supports initial acceleration. While the maximum power is achieved at high speeds, which play an important role in maximum speed or heavy loads. In Figure 5 In general, the three curves show a similar pattern, namely an increase in power as the engine speed increases until it reaches a peak point, then followed by a decrease in power at high speeds.

The main difference is seen in the magnitude of the maximum power and the power distribution area between angles. The 80-degree angle shows the highest performance, with peak power approaching 8 HP in the range of 5000–5500 RPM. This indicates that a wider spray angle expands the fuel distribution area and improves combustion efficiency. This finding is in line with research by Pham, V. C et al. which states that a larger spray angle in a direct injection system provides better atomization efficiency, improves the mixing process, and increases engine power output. The optimal spray angle can accelerate the initial ignition and flame propagation, resulting in increased cylinder pressure and peak power (Pham, V. V., 2020). Meanwhile, a study by Fırat, concluded that a spray angle configuration between 120°–160° (equivalent to an injector inclination angle above 70° in the context of GDI) provides higher effective mean pressure and more stable power performance in the mid to high rpm range (Firat, M., & Varol, Y., 2019).

Torque in an internal combustion engine is closely related to the quantity and quality of the air-fuel mixture, as well as combustion efficiency in each work cycle. The more homogeneous the mixture and the more optimal the combustion time, the greater the torque produced. According to Pham, V. C et al (2022) in a study on a GDI engine, a wider spray angle (70º–80°) produces a more widespread and even fuel distribution, which increases cylinder filling efficiency and torque. Meanwhile, Fırat stated that increasing the spray angle is able to create a wider combustion zone and accelerate the increase in in-cylinder pressure, which is directly correlated with the increase in torque, especially at low to medium RPM. However, it should be noted that an angle that is too wide can cause wall-wetting if not followed by the right combustion chamber design, which will ultimately disrupt combustion stability at high RPM (Firat, M., & Varol, Y., 2019)

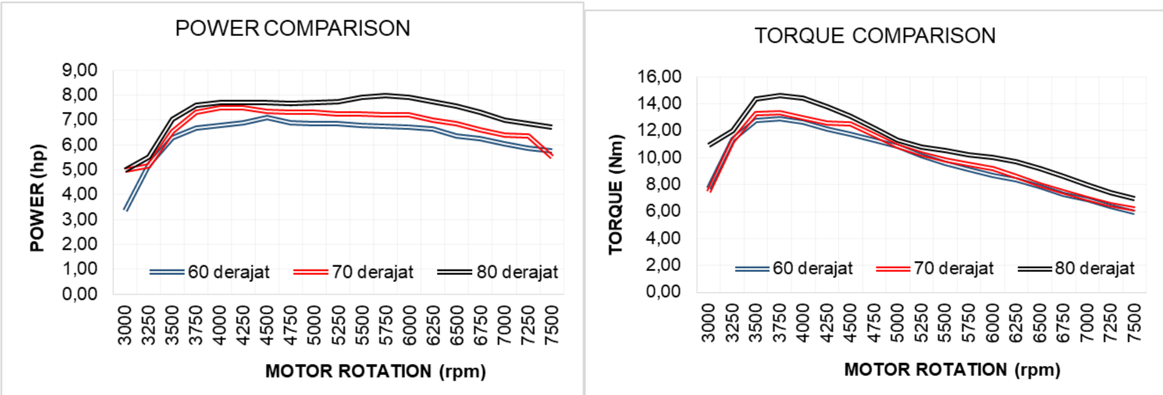


Figure 5. Power and torque comparison graph

Based on Figure 6, the exhaust emission graph displayed, there is a significant difference in the content of carbon monoxide (CO), hydrocarbons (HC), carbon dioxide (CO_2) produced from three variations of injector seat angles: 60°, 70°, and 80°. CO (Carbon Monoxide) Emissions, At an injector seat angle of 60°, the CO content produced is the lowest at 0.05%, increasing to 0.08% at an angle of 70°, and reaching 0.09% at an angle of 80°. Based on these findings, it can be concluded that the 60° injector seat produces combustion that tends to be "fat" or rich in fuel, but has low combustion efficiency. Isnanda (2007) in Marsius Ferdnian (2016) stated that a richer fuel mixture actually produces lower CO, because the imperfect combustion reaction is not yet able to form large amounts of CO.

On the other hand, in a more homogeneous mixture or approaching stoichiometry, the CO formation reaction is more dominant due to the increase in combustion temperature and limited oxygen availability to continue the CO oxidation process to CO_2. The results of the study stated that CO formation is greatly influenced by the local rich mixture area formed due to uneven spray distribution, especially in injection with a wide angle that has the potential to cause wall wetting or local fuel pooling (Pham, V. V., 2020).

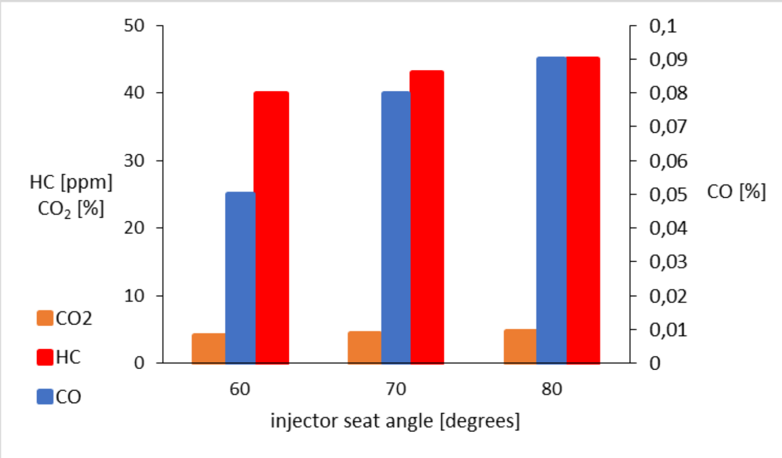


Figure 6. Comparison graph of exhaust emissions

HC (Unburned Hydrocarbon) Emissions, The highest HC emission concentration was also recorded at the 80° injector seat, which was 45 ppm, followed by 43 ppm at an angle of 70°, and the lowest at an angle of 60° (40 ppm). In line with M. Mofijur, a richer mixture tends to produce lower HC, because the combustion chamber temperature is not high enough to allow HC to evaporate significantly. In other words, fuel ignition is slower and most of it burns even at low temperatures (Mofijur, M. et al, 2019)

CO_2 (Carbon Dioxide) Emissions, The CO_2 emission pattern shows a gradual increase from 4.2% (60°) to 4.5% (70°), and 4.8% (80°). CO_2 is the end product of perfect combustion, so a higher CO_2 value indicates an increase in carbon oxidation efficiency. According to Yongjing Wang (2023), the carbon contained in the fuel will basically undergo an oxidation process to CO first, then to CO_2 through the subsequent reaction: $2CO + O_2 \rightarrow 2CO_2$, This means that if sufficient oxygen is available and the combustion temperature is high, the formation of CO can be suppressed and converted to CO_2. Thus, at the 80° injector seat which produces the highest CO_2, it can be assumed that most of the carbon has been successfully oxidized, although CO is still left due to the uneven distribution of the spray. The graphical analysis shows that the 60° injector angle produces the lowest CO and HC emissions, but is also associated with the lowest power as evidenced in the previous performance graphs. This confirms that a “rich” mixture results in slower combustion and lower combustion chamber temperatures, thus reducing pollutant emissions but with reduced power output. In contrast, the 80° injector angle produces the highest power performance but is accompanied by increased CO and HC, due to the incompletely homogeneous spray distribution and the formation of a fuel film on the walls (film formation), which hinders complete combustion. Taking into account the latest literature and empirical data, it can be concluded that the injector seat angle needs to be optimized as a compromise between engine performance and emission compliance. An intermediate angle (e.g. 70°) can be a balance point, especially when combined with injection control strategies such as swirl enhancement or the use of multi-hole injectors.

CONCLUSION

From the results of the study on the comparison of power and torque when using injectors with 60º, 70º and 80º mounting positions, the following conclusions were obtained:

1. In general, all torque curves experience a significant increase from low speed (3000 rpm) to reach a peak at around 3500–3750 rpm, then gradually decrease as the engine speed increases.
2. The 80o angle produces the highest torque in almost the entire rotation range, with a peak value approaching 15 Nm at around 3500 rpm. The 70º angle has medium performance, below the 80o angle but above the 60º angle. The 60º angle shows the lowest torque, especially at medium to high speeds, with a faster decrease than the other two angles.
3. The larger the angle used, the higher the torque produced, especially at low to medium speeds. The average power increase is 6.1% and torque is 6.4%

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