An Investigation of the Optimal Combustion Duration in Turbocharged Gasoline Engines

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ABSTRACT

This study analyzed the influence of combustion duration on the output power, fuel efficiency, and emission levels of a turbocharged gasoline engine with the aim of identifying the optimal duration for enhancing engine performance while minimizing environmental impact. The simulation was conducted using the AVL-Boost software, where various combustion durations were tested to evaluate their effects on key engine parameters, including torque, power output, Indicated Mean Effective Pressure (IMEP), Brake Mean Effective Pressure (BMEP), and pollutant emissions such as CO, NO_x, and hydrocarbons. The results indicated that a combustion duration between 50° and 60° Crank Angle (CA) yielded optimal performance. Within this range, the torque values varied from 52.4 to 54.19 Nm, the power output reached 6.81 kW, and the IMEP and BMEP were recorded at 3.5137–3.5131 bar and 3.4137–3.4131 bar, respectively. Moreover, both fuel consumption and residual gas fraction were significantly reduced. Specifically, the lowest fuel consumption was observed at 50° CA (33.9577 g/Wh) and 60° CA (33.909 g/Wh), whereas the residual gas fraction decreased progressively from 0.3761 at 50° CA to 0.3743 at 70° CA. Regarding emissions, the lowest concentrations of hydrocarbons and NO_x were achieved at 50° CA recorded at 1.7212 and 4.0987 g/kWh, respectively. However, CO emissions peaked at the same CA, reaching 0.003725 g/kWh. Despite the slight increase in CO, 50° CA is still considered the optimal combustion duration, as it delivers the highest engine performance while maintaining the lowest total emission levels.

Keywords-turbocharged gasoline engine; combustion duration; engine performance; emissions

I. INTRODUCTION

Turbocharged engines are gradually becoming the preferred choice in fields that utilize internal combustion engines, such as transportation, industry, and energy. These engines not only enhance operational efficiency but also contribute to fuel savings compared to conventional engines. However, in the context of increasingly complex climate change and stricter environmental regulations, reducing harmful emissions and optimizing performance have become urgent requirements in the research and development of turbocharged engines.

Many technical solutions have been applied to simultaneously increase the power output and reduce emissions, including the use of alternative fuels [1], optimization of engine structure [2], and adjustment of ignition timing and fuel injection processes [3]. Among these, combustion duration, defined as the time required for the fuel to burn completely, has been identified as one of the most influential factors affecting both engine performance and emission levels and has been examined from various research perspectives.

Previous studies [4] demonstrated that combustion duration significantly impacts the operational characteristics of naturally aspirated gasoline engines. Subsequent research extended this analysis to alternative fuels, such as ethanol-blended gasoline engines, revealing similar sensitivities and performance implications [5]. Authors in [6] proposed a method to improve the combustion efficiency of diesel engines by combining a dual-swirl combustion system with a split injection strategy. This combination influences the combustion duration, thereby enhancing performance and reducing emissions. Another approach is the use of Exhaust Gas Recirculation (EGR) systems. Authors in [7] investigated the effects of EGR combined with enhanced intake swirl flow on combustion duration, knock tendency, and cycle-to-cycle combustion variability in a commercial turbocharged gasoline direct injection engine. This study highlighted the potential of optimizing EGR and intake swirl to improve fuel economy and emission characteristics. To gain a more comprehensive understanding of combustion optimization, the relationships among factors such as injection process, fuel–air mixing, ignition, soot formation, and ambient density under conditions of colliding flame ignition were examined [8]. This study provides valuable insights into improving the combustion chamber and turbocharging system designs, thereby enhancing the thermal efficiency of diesel engines.

Although numerous studies have investigated the combustion process in internal combustion engines, most previous works have primarily focused on improving performance or reducing emissions by enhancing combustion efficiency. These studies often examine individual factors in isolation, such as thermal efficiency or emission levels. In particular, most research has been conducted on diesel engines, naturally aspirated gasoline engines, or engines using alternative fuels, whereas turbocharged gasoline engines have not yet been comprehensively analyzed in terms of how combustion duration affects both performance and emission characteristics. This study aims to fill this gap in literature. The results identified the relationship between combustion duration, engine performance, and emission levels, thereby providing a scientific basis for optimizing the combustion duration in turbocharged gasoline engines.

II. METHODOLOGY

A. Simulation Model Setup and Model Validation

The AVL-Boost is a widely used simulation software in internal combustion engine research, thanks to its capability to model various engine types, including Spark-Ignition (SI) and Compression-Ignition (CI) engines [9], as well as turbocharged gasoline engines and engines running on alternative fuels [10]. Figure 1 shows the simulation model of the turbocharged gasoline engine used in this study.

The engine investigated in this study is a turbocharged gasoline engine with four cylinders. It features a piston stroke of 125 mm and a cylinder bore of 110 mm. The intake valve opens 20 degrees Before Top Dead Center (BTDC), while the exhaust valve closes 14 degrees After Bottom Dead Center (ABDC). The diameters of the intake and exhaust valve heads were 48 and 42 mm, respectively.

The simulation was performed under full-load conditions with an ignition timing of 25° BTDC and an air-fuel ratio of 12.8. The temperature of the lubricating oil was maintained at 80 °C.

Figure 2 presents a comparison between the simulation results and experimental data for engine torque, brake specific fuel consumption, and NO_x emissions. The results show a high degree of agreement between the two methods, with discrepancies not exceeding 5% across all compared parameters. This indicates the reliability of the simulation model, confirming its suitability for investigating the effects of combustion duration on engine performance and emissions.

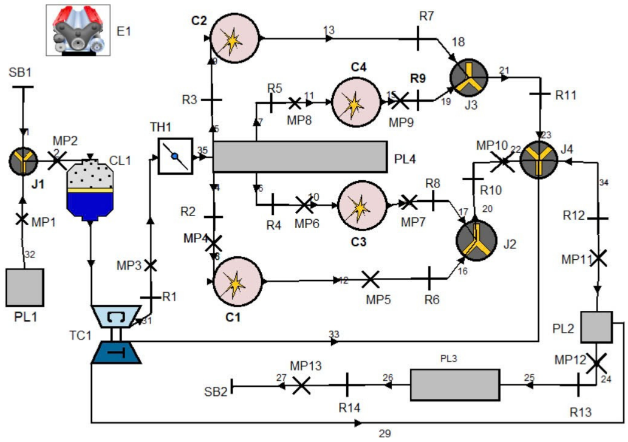

Fig. 1. Schematic of the turbocharged gasoline engine. Engine (E1), dynamo test system (SB1-2), air cleaner (CL1), plenum (PL1-2), restriction elements (R1-2-3-4), injector (I1), cylinder (C1), measurement elements (MP1-2-3-4), junction elements (J1-2-3), and turbocharger (TC1).

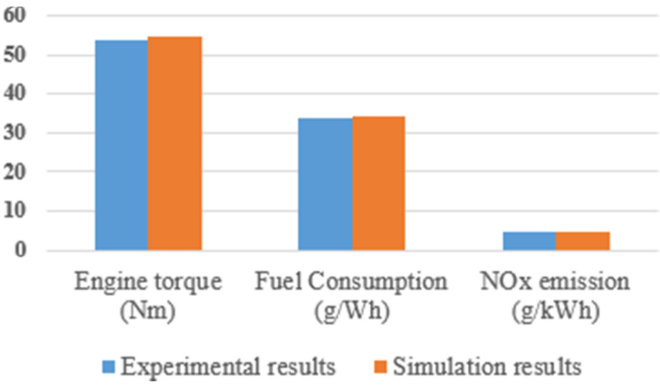

Fig. 2. Model validation.

III. RESULTS AND DISCUSSION

Figure 3 illustrates the variation of engine torque with respect to combustion duration, measured in degrees of crank angle (°CA). The results show that torque increases as the combustion duration extends from 30° to around 50–55° CA, reaching a peak value of approximately 54.3 Nm. Beyond 60° CA, the torque begins to decline. This indicates that the range between 50° and 60° CA is the optimal combustion window, where the combustion process occurs most efficiently and maximum torque is generated. Within this range, fuel combustion occurs near the Top Dead Center (TDC), producing a peak in-cylinder pressure at the ideal moment to effectively transfer force to the crankshaft. When the combustion duration is too long, the piston has already moved away from the TDC, reducing the effective pressure and resulting in a loss of torque. This chart clearly highlights the importance of controlling the combustion timing to optimize engine performance.

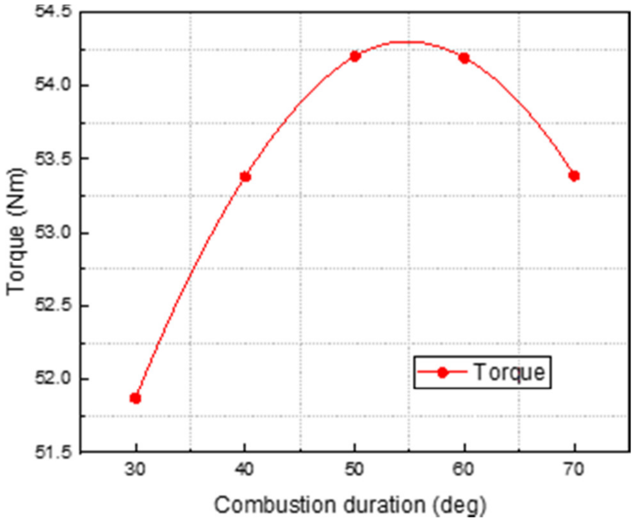

Fig. 3. The influence of combustion duration on torque.

From Figure 4, it is evident that the combustion duration has a significant impact on the Brake Mean Effective Pressure (BMEP). As the combustion duration increases from 30 to around 55° CA, BMEP gradually rises, reaching its peak at approximately 55 degrees. This indicates that within this range, the combustion process occurs more efficiently, resulting in a greater power output per cycle. However, when the combustion duration continues to increase beyond 55 degrees, BMEP begins to decline. This may be due to excessively prolonged combustion causing the peak pressure to occur at a less optimal CA, thereby reducing the work output. Therefore, it can be concluded that there is an optimal combustion duration that yields the highest BMEP, and optimizing this parameter is crucial for improving engine performance.

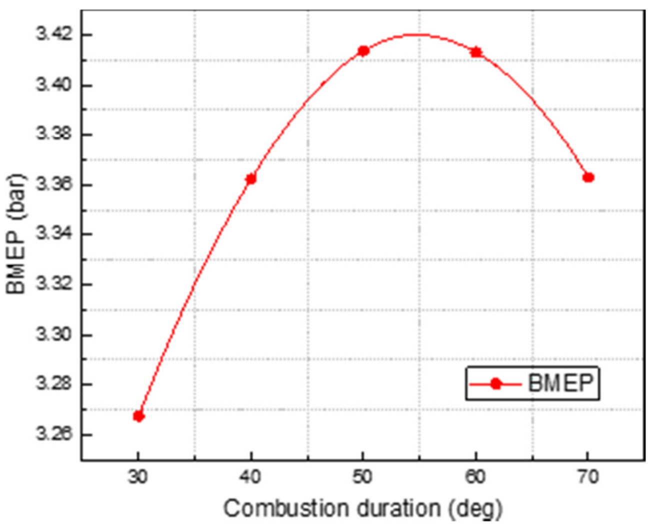

Fig. 4. The influence of combustion duration on BMEP.

Figure 5 illustrates the variation in Brake Specific Fuel Consumption (BSFC). The results show that BSFC gradually decreases as the combustion duration increases from 30° to around 55–60° CA, reaching its lowest value within this range, and then begins to rise again when the duration exceeds 60° CA. This trend can be explained by the fact that, in the 50–60° CA range, the combustion process is most efficient, allowing for maximum conversion of the fuel's chemical energy into mechanical work. When the combustion was completed near the TDC, the in-cylinder pressure peaked at the ideal time, just as the piston began its downward stroke. This resulted in higher thermal efficiency and lower fuel consumption, as reflected in the reduced BSFC values. However, when the combustion duration was too short (below 40° CA), the combustion process was incomplete, leading to inefficient fuel use and increased BSFC. Similarly, if the combustion duration is too long (above 60° CA), combustion continues while the piston has already moved far past TDC, reducing the effective pressure and combustion efficiency, which again leads to a rise in BSFC. The results indicate the existence of an optimal combustion duration range (50–60° CA), within which BSFC reaches its minimum, signifying the highest fuel efficiency of the engine. This finding is crucial for optimizing both the performance and fuel economy in engine design and control.

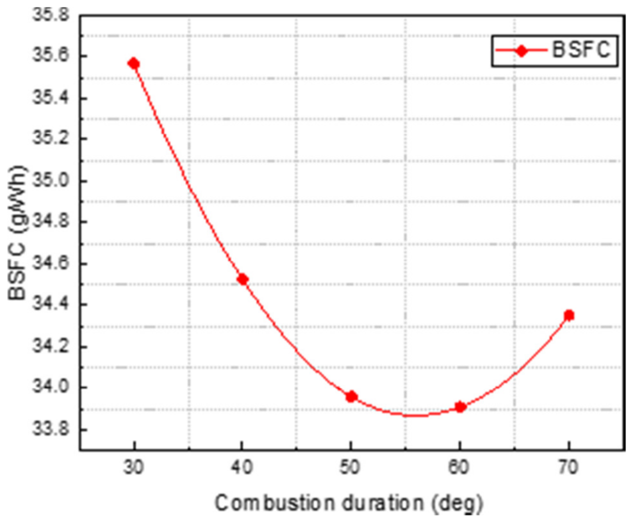

Fig. 5. The influence of combustion duration on BSFC.

Figure 6 illustrates the variation of residual gas content in the combustion chamber with respect to combustion duration. The results show a decreasing trend in residual gas content as the combustion duration increases from 30° to 70° CA. This phenomenon can be explained by the fact that a longer combustion duration allows the combustion process to occur more gradually and uniformly throughout the chamber, enabling more complete fuel oxidation. As a result, fewer unburned fuel particles and partially reacted gases remain in the chamber, leading to a reduction in the residual gas content. Additionally, extended combustion maintains high temperatures in the combustion chamber for a longer period, promoting the breakdown of intermediate combustion products and unburned hydrocarbons.

Residual gas plays an important role in engine performance and emissions. A moderate amount of residual gas can help reduce peak combustion temperatures, thereby lowering NO_x (nitrogen oxides) emissions, which are major pollutants in engine exhaust. However, excessive residual gas dilutes the air-fuel mixture and impedes the combustion process, resulting in decreased power output and increased fuel consumption. Therefore, controlling residual gas levels is essential for optimizing engine efficiency, reducing emissions, and ensuring stable combustion. Reducing the residual gas content by appropriately adjusting the combustion duration is an effective strategy for enhancing the overall engine performance.

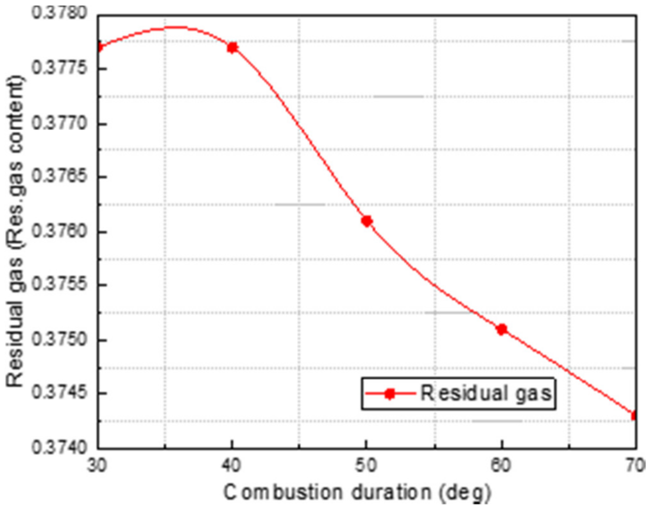

Fig. 6. The influence of combustion duration on residual gas.

Figure 7 illustrates the variation of carbon monoxide (CO) emissions with respect to the combustion duration. It can be observed that CO emissions increase as the combustion duration increases from 30° to around 50°, reaching a peak at approximately 50°, and then gradually decrease as the duration continues to extend up to 70°. At shorter combustion durations (below 50°), the combustion process occurs too rapidly, potentially leading to incomplete combustion due to insufficient time for thorough air-fuel mixing and oxidation, which results in relatively low CO emissions. As the combustion duration increases, the combustion becomes more progressive and allows better oxidation of the fuel, but it also creates conditions for richer local mixtures and incomplete combustion zones, thereby increasing CO formation.

However, when the combustion duration extends beyond 50°, the in-cylinder temperature may decrease due to prolonged expansion and heat loss, which promotes further oxidation of CO into CO_2 and thus reduces CO emissions. In addition, overly long combustion durations may lead to less efficient combustion, where part of the fuel burns under suboptimal conditions, also contributing to lower CO emissions. Therefore, it can be concluded that the combustion duration that results in the highest CO emissions is around 50°, while shorter or longer durations help reduce CO formation due to either rapid combustion or improved oxidation conditions.

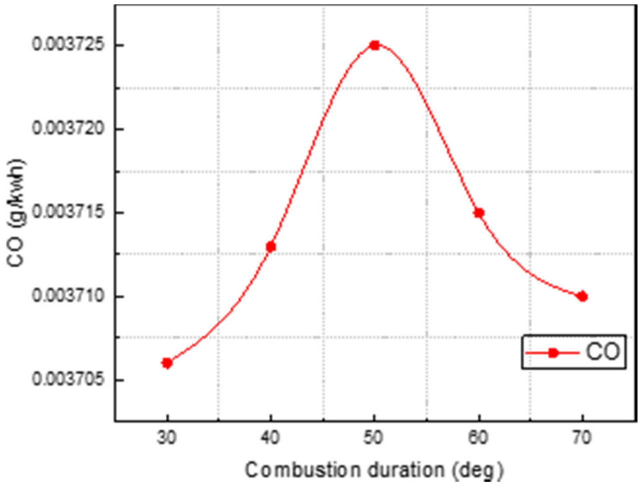

Fig. 7. The influence of combustion duration on CO emissions.

Figure 8 illustrates the relationship between hydrocarbon (HC) emissions and combustion duration. As combustion duration increases from 30° to just under 50°, HC emissions gradually decrease, reaching a minimum due to improved combustion completeness. With combustion durations of less than 50°, the process is too rapid, limiting the time available for full oxidation, especially in rich or quenching zones, leading to higher HC emissions. Around 50°, the combustion process becomes more stable and thorough, allowing better oxidation of the air-fuel mixture and minimizing unburned HCs. However, when the combustion duration exceeds 50°, in-cylinder temperatures drop due to extended combustion and heat loss, which reduces oxidation efficiency and causes HC emissions to rise again.

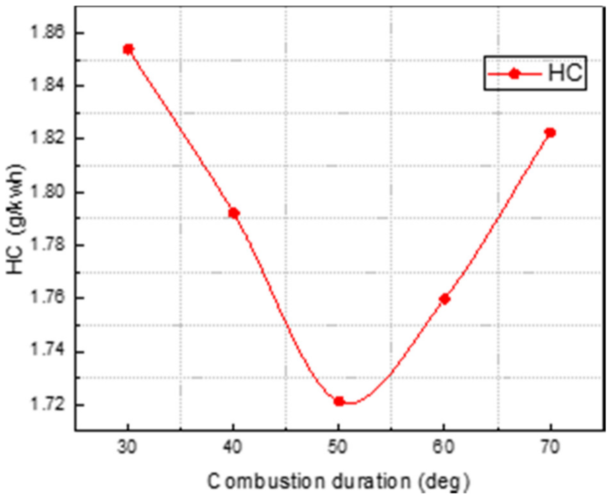

Fig. 8. The influence of combustion duration on HC emissions.

Figure 9 illustrates the variation of nitrogen oxide (NO_x) emissions with respect to combustion duration. It is evident that NO_x emissions decrease gradually as the combustion duration increases from 30° to 50°, reaching a minimum at 50°. However, beyond 50°, as the combustion duration continues to lengthen, NO_x emissions begin to rise again. This trend can be attributed to the strong relationship between NO_x formation, in-cylinder temperature, and combustion timing. When the combustion duration is shorter than 50°, the combustion process is fast and concentrated, resulting in high peak temperatures that promote NO_x formation. As the duration increases to 50°, the combustion process becomes more distributed, which reduces peak temperatures and lowers NO_x emissions. However, beyond 50°, the combustion process extends too long, and while peak temperatures may still be moderate, the extended residence time at elevated temperatures contributes to higher thermal NO_x production. Therefore, to minimize NO_x emissions, the optimal combustion duration is 50°, where the combination of lower peak temperatures and shorter high-temperature residence time leads to the lowest NO_x emissions.

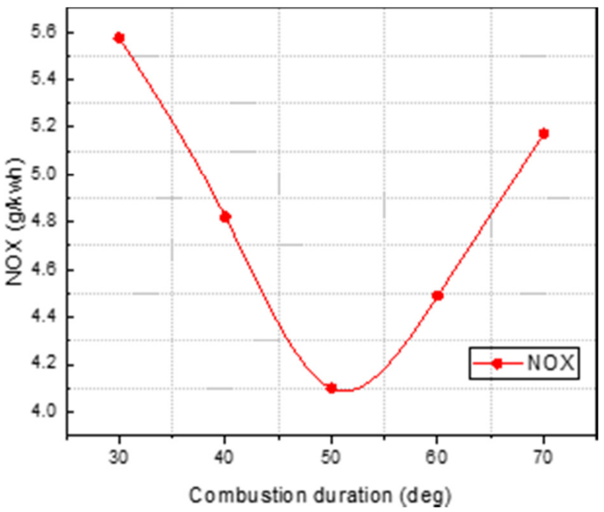

Fig. 9. The influence of combustion duration on NO_x emissions.

IV. CONCLUSIONS

The results of this study demonstrate that the combustion duration significantly influences both power output and emissions of a turbocharged gasoline engine. Specifically, peak power is achieved when the combustion duration falls between 50° and 55° Crank Angle (CA), with a torque value of approximately 54.3 Nm. However, if the combustion duration exceeds 60° CA, power decreases, as the prolonged combustion process prevents the pressure in the combustion chamber from reaching its optimal value at Top Dead Center (TDC).

With regard to emissions, the study reveals that combustion duration directly affects the emissions of CO, HC, and NO_x:

The CO emissions increase as combustion duration extends from 30° to around 50° CA, reaching a peak at 50°. As the duration increases further, CO emissions decrease, indicating that shorter combustion durations result in incomplete combustion, leading to higher CO production, whereas longer durations improve the oxidation of CO.

The hydrocarbon (HC) emissions decrease as combustion duration progresses from 30° to near 50° CA, reaching a minimum at 50°. However, beyond this point, a decrease in the combustion chamber temperature reduces the oxidation efficiency, causing HC emissions to increase again.

The NO_x emissions decrease as combustion duration increases from 30° to 50°, reaching a minimum at 50°. Beyond this range, the NO_x emissions rise due to the extended residence time of hot gases in the combustion chamber, which contributes to the formation of thermal NO_x.

In conclusion, the optimal combustion duration for achieving the highest efficiency and lowest emissions in a turbocharged gasoline engine is between 50° and 60° CA. Within this range, power output is maximized, and CO, HC, and NO_x emissions are minimized, demonstrating the successful optimization of both engine performance and emission control.

This study offers a novel contribution by exploring the impact of combustion duration on turbocharged gasoline engine performance and emissions, addressing a gap in existing literature. It should be noted that this study did not account for the knock tendency, which is crucial under high load and advanced ignition timing conditions. Additionally, the focus on steady-state conditions excludes transient engine behavior. Future work will incorporate knock prediction, simulate transient operating scenarios, and expand experimental validation across a wider range of conditions to further enhance the robustness and applicability of the findings.

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