# Investigation of the Optimal Output Parameter Equation in a Small Ethanol-Fueled Engine

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## ABSTRACT

**Biofuels are increasingly recognized as an urgent solution to reducing engine emissions and achieving sustainable development goals. Among them, ethanol fuel stands out as a promising candidate due to its clean combustion properties and high energy regeneration potential. This study investigates the optimal equations for the engine output parameters to enhance power and improve the overall engine performance. The findings demonstrate that optimizing the ignition angle allows the engine to achieve a higher power output, significantly reduce the fuel consumption, and minimize the emissions of harmful pollutants, such as CO, NOx, and HC. This research provides a solid foundation for the application of ethanol as a viable alternative fuel in internal combustion engines, paving the way for cleaner and more environmentally friendly engine technologies that meet stringent emission standards. Furthermore, the derived equations and insights offer practical implications for improving the existing engine systems and guiding the development of advanced biofuel-powered engines for future applications.**

***Keywords-ethanol fuel; optimal pressure; ignition angle; engine emissions; engine torque***

## I. INTRODUCTION

Electric vehicles are becoming increasingly popular and favored globally, including in Vietnam. However, many people continue to prefer road vehicles equipped with internal combustion engines for various reasons. This preference contributes to the ongoing toxic emissions and the depletion of fossil fuels [1-3]. In response, alternative fuels have emerged as an effective and necessary solution to mitigate these issues. Among these, ethanol -a clean and renewable fuel- has been widely studied as a viable alternative to traditional fossil fuels [4-8].

Despite its potential, the use of ethanol in internal combustion engines presents several challenges, particularly in optimizing the combustion chamber pressure and combustion efficiency. Numerous studies worldwide have examined the ethanol fuel utilization and strategies to improve the internal combustion engine performance. Specifically, authors in [9] investigated the influence of the early ignition angle on the performance of a single cylinder Compressed Natural Gas (CNG) engine forming an external mixture. The simulation results revealed that increasing the ignition angle, at each engine speed, caused both thermal efficiency and torque to exhibit similar patterns of change. In [10], authors observed that an increase in the ignition advance angle correlates with rises in the pressure, temperature, and exhaust gas levels. The study also found that the maximum value of the indicated work, corresponding to the optimal ignition advance angle, depends on the fuel composition. Similarly, authors in [11] explored the impact of ignition timing on combustion by adding hydrogen to the fuel mix, resulting in an improved engine performance and reductions in the HC and CO emissions, though, the NOx emissions showed a slight increase. In [12], experiments were conducted at different ignition timings at 10°, 14°, 18°, 22°, 26°, 30°, and 34°, characteristic curves were presented for parameters, such as power, torque, and thermal efficiency. The study highlighted the critical role of ignition timing in determining the engine performance. Authors in [13] investigated the internal combustion engine emissions and performance optimization through fuel injection timing. The study emphasized various strategies, including adjustments to the injection pressure, shape ratio, timing, and split injection, to improve performance and reduce emissions.

While these studies provide valuable insights into the ignition timing and engine efficiency, very few have focused on developing optimal equations for quickly and accurately determining the output parameters in ethanol-fueled engines. Moreover, most approaches rely heavily on experimental methods, which are time-intensive, resource-demanding, and sensitive to variations in experimental conditions. This study aims to address these limitations by developing optimized equations to rapidly and accurately determine the engine output parameters. By doing so, it seeks to minimize the reliance on extensive experimental trials and reduce the associated time and material costs while ensuring consistency across varying operating conditions.

## II. METHODOLOGY

### A. *Experimental Setup and Engine Specifications*

Figure 1 illustrates the schematic diagram of the experimental setup and the engine test system. The system was designed to evaluate the performance of a two-cylinder Spark-Ignition (SI) engine fueled with ethanol, while reducing weight. These engines are commonly employed in applications requiring high power within a compact design. The engine features a two-cylinder configuration arranged in a V shape, enhancing its performance characteristics. Detailed engine specifications are provided in Table I. The engine was tested at full load across various engine speeds, with the ignition advance angle having been adjusted from 5° Crank Angle (CA) to 45° CA. This experimental system enables an in-depth evaluation of the performance of a small two-cylinder SI engine using ethanol fuel. Moreover, it contributes to the research and development efforts in creating sustainable solutions for the automotive industry. Transitioning to renewable fuels, such as ethanol, represents an important step toward reducing the greenhouse gas emissions and protecting the environment.

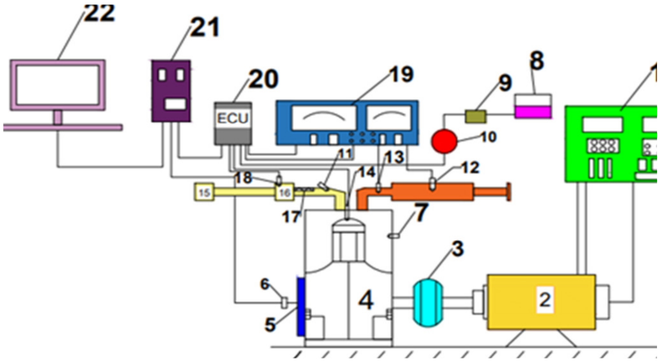


Fig. 1. Diagram of the small SI engine test system utilized: 1-the dynamo test system, 2-power meter (AVL MCA325MO2), 3-coupling, 4-engine, 5-flywheel, 6-autonics encoder, 7, 13-temperature sensors, 8-fuel tank, 9-fuel pump, 10-fuel filter, 11-injector, 12-oxygen sensor, 14-pressure sensor, 15-air filter, 16-intake manifold, 17-air heater, 18-air mass sensor, 19-gas analyzer, 20-ECU, 21-data acquisition unit, 22-computer.

TABLE I. ENGINE SPECIFICATIONS

| Parameter | Unit | Value |
|---|---|---|
| Engine Model | - | SI-engine |
| Number of Cylinders | - | 2 |
| Compression Ratio | - | 11.8:1 |
| Cylinder Diameter | mm | 57 |
| Stroke | mm | 53.5 |
| Connecting Rod | mm | 107.9 |
| Intake Valve | - | 2 |
| Exhaust Valve | - | 2 |

### B. *Optimal Equation Investigation Model*

To determine the optimal equation for the output parameters, consider $n$ data points of the form $(x_1, y_1)$, $(x_2, y_2)$,…, $(x_n, y_n)$. The equation that passes through all the $n$ points is given by:

$$P(x) = \sum_{i=1}^{n} y_i \times L_i(x) \quad (1)$$

where $L_i(x)$ is the basis polynomial for the i-th data point, calculated as:

$$L_i(x) = \prod_{\substack{j=1 \\ j\neq i}}^{n} \frac{x-x_j}{x_i-x_j} \quad (2)$$

where:

- $i$ is the index of the current data point being considered in the summation for constructing $P(x)$. It runs from 1 to $n$.
- $j$ is the index used in the product within $L_i(x)$. It iterates over all data points except $i$ $(j\neq i)$ to construct the basis polynomial for the $i$-$th$ point.

## III. RESULTS AND DISCUSSION

The ignition angle ($\theta_{ig}$) plays a crucial role in engine performance, directly affecting emissions, torque, engine power, and parameters such as BSFC, ISFC, IMEP, BMEP. In this study, the results were derived by comparing these parameters with the pressure characteristic curve to identify the optimal curve through ignition timing adjustments for ethanol-fueled engines. Figure 2 illustrates the relationship between maximum pressure ($P_{max}$), torque, and ignition angle ($\theta_{ig}$) of the engine.

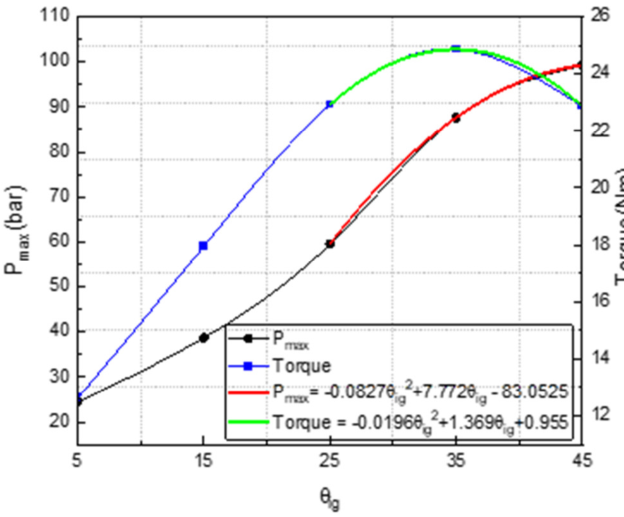


Fig. 2. Optimal pressure and torque curves versus ignition angle.

High torque is crucial for enhancing the engine performance. A higher torque value allows the engine to produce more power, improving acceleration and reducing fuel consumption. High torque is especially beneficial under heavy load conditions or in applications requiring significant traction and continuous power. Selecting the high-torque region optimizes the engine performance and ensures a stable operation. As the ignition angle increases from 5° to 25°, the torque rises gradually, reaching its maximum at 25°. Beyond this point, the torque decreases as the ignition angle continues to increase to 45°. This indicates that the optimal ignition angle for achieving maximum torque is approximately 25°.

The peak pressure also increases as the ignition angle rises, forming a parabolic trend in the pressure characteristic curve. The red line in Figure 2 represents the experimental data, where the optimal engine pressure corresponding to the maximum torque region is determined to be 90 bar. The equation of the optimal pressure characteristic curve is:

$$P_{max} = -0.827\theta_{ig}^2 + 7.772\theta_{ig} - 83.0525 \quad (3)$$

Similarly, the equation for the optimal torque characteristic is:

$$Torque = -0.0196\theta_{ig}^2 + 1.369\theta_{ig} + 0.955 \quad (4)$$

These equations clearly demonstrate the relationship between the ignition angle, torque, and pressure. From this analysis, it is evident that the optimum engine pressure lies within the ignition angle range of 25° to 45°, based on the strong correspondence between the torque and pressure.

The Brake Mean Effective Pressure (BMEP), another key performance parameter, exhibits a trend consistent with the engine torque, as displayed in Figure 3. They both increase continuously with the ignition angle from 5° to 35°, reaching their highest and most optimal value at 35°. Beyond this point, they tend to decline as the ignition angle increases to 45°. Given the strong similarity between these trends, the optimal pressure characteristic curve, derived from the relationship with BMEP through the ignition angle adjustment, matches exactly with the optimal pressure characteristic curve constructed from the relationship with torque. The optimal BMEP equation is:

$$BMEP = -0.00898\theta_{ig}^2 + 0.627763\theta_{ig} - 2.53132 \quad (5)$$

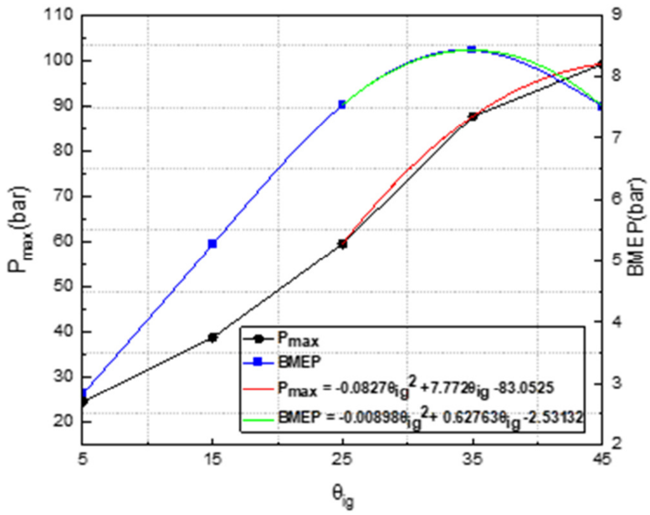


Fig. 3. Optimal BMEP curve versus ignition angle.

Figure 4 depicts the Indicate Specific Fuel Consumption (ISFC) curve along with the corresponding optimal pressure. As the ignition angle increases from 25° to approximately 45°, the ISFC gradually decreases, reaching its lowest value of 450 g/kWh at about 35°. Beyond this point, ISFC begins to rise again as the ignition angle increases slightly from 35° to 45°. At lower ignition angles, from 5° to approximately 25°, the fuel consumption decreases but remains relatively high, despite the continuous rise in the maximum pressure.

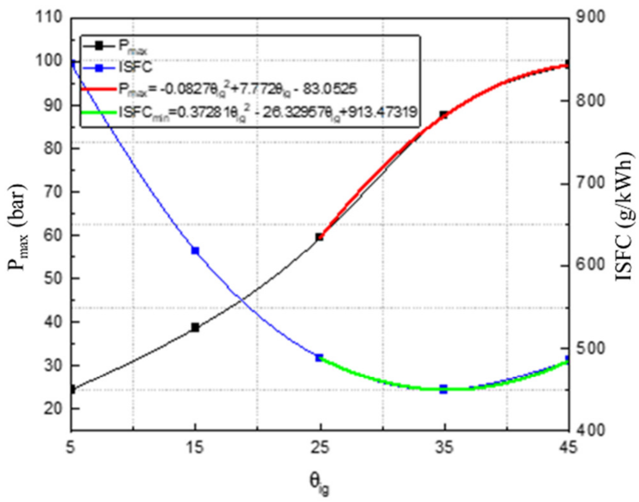


Fig. 4. Optimal ISFC versus ignition angle.

This indicates that an ignition angle within the low fuel consumption range is crucial for minimizing the operating costs, conserving the ethanol fuel, ensuring a cleaner engine operation, and reducing the environmental impact. The ignition angle of 35° is optimal, as it represents the point of minimum ISFC, balancing the engine performance and fuel economy. The equation of the optimal ISFC curve is:

$$ISFC = 0.37281\theta_{ig}^2 - 26.329957\theta_{ig} + 913.47319 \quad (6)$$

When comparing the ISFC trend to the pressure characteristic curve, as illustrated in Figure 4, it is evident that the optimal pressure also lies within the ignition angle range of 25° to 45°. This emphasizes the importance of calibrating the ignition angle to achieve a balance between the engine pressure and fuel consumption, ultimately improving efficiency and reducing the fuel costs.

Figure 5 portrays the optimal Brake Specific Fuel Consumption (BSFC) curve across different ignition angles. Comparing Figures 4 and 5, it is observed that the optimal pressure characteristic curve is also evidenced in the ignition angle range of 25° to 45°. The optimal BSFC equation is:

$$BSFC = 0.708110\theta_{ig}^2 - 49.760555\theta_{ig} + 1481.48426 \quad (7)$$

When the ignition angle falls between 25° and 45°, the optimal pressure characteristic curve is achieved, delivering both high torque and low fuel consumption.

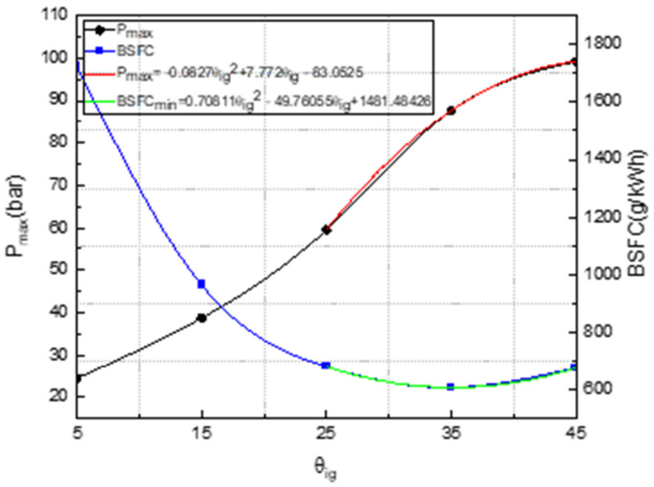


Fig. 5. Optimal BSFC versus ignition angle.

Reducing engine emissions is a critical objective to safeguard the environment and human health. Harmful emissions, such as NOx, CO, and HC, contribute significantly to air pollution, climate change, and a decline in the quality of life. One key goal is to determine the optimal pressure characteristic curve by analyzing the exhaust gas trends and adjusting the ignition angle to achieve the lowest emission levels. Figure 6 demonstrates the CO emission curve of the engine at various ignition timings. The engine achieves its minimum CO emissions (ranging from 120-150 g/kWh) at an ignition angle of 35° CA. Beyond this point, the CO emissions begin to rise as the ignition angle continues to increase. This indicates that at 35° CA, the combustion process is highly efficient, minimizing the generation of CO. The low-emission range is identified between 35° and 45° CA, where the combustion efficiency is maximized. The optimal CO characteristic equation for this range is:

$$CO = 0.366150\theta_{ig}^2 - 25.902243\theta_{ig} + 614.26738 \quad (8)$$

When the ignition is either too early or too late, the combustion process becomes inefficient, resulting in an incomplete combustion of the fuel mixture and higher CO emissions.

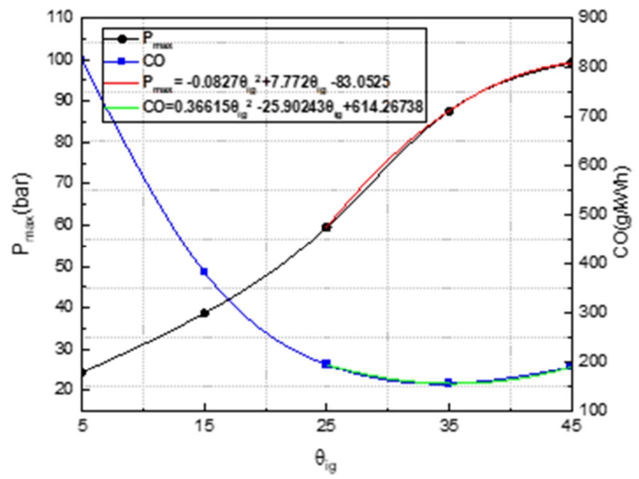


Fig. 6. Optimal CO emission versus ignition timing.

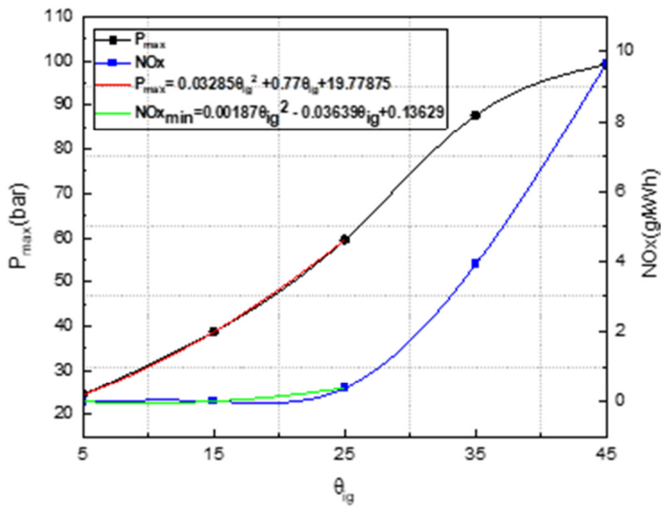


Fig. 7. Optimal NOx emmision versus ignition angle.

Figure 7 presents the optimal NOx emission curve at different ignition timings. The lowest NOx emissions are observed when the ignition angle is within the range of 5° and 25° CA. This can be explained by the fact that, during this stage, the combustion process has not yet reached the highest temperature, resulting in limited NOx formation. NOx is primarily formed at high temperatures, where the oxidation reaction of nitrogen in the air becomes more intense. Therefore, when the combustion temperature is not sufficiently high, the amount of NOx produced is reduced. Meanwhile, the pressure increases from approximately 25 bar to 60 bar, corresponding to the ignition angles of 5° and 25°. The optimal pressure equation, derived from the optimal equation graph of NOx emissions, can be also easily established.

$$NOx = 0.00187\theta_{ig}^2 - 0.03639\theta_{ig} + 0.13629 \qquad (9)$$

Additionally, Figure 8 represents the relationship between the HC emissions and different ignition angles. It is evident that the optimum HC characteristic curve is when the ignition angle ranges from 15° to 25°. At that time, HC emissions will be the lowest, and the optimum equation is (10) corresponding to a pressure range of 40 bar to 90 bar:

$$HC = 0.00561\theta_{ig}^2 - 0.284225\theta_{ig} + 10.14581 \qquad (10)$$

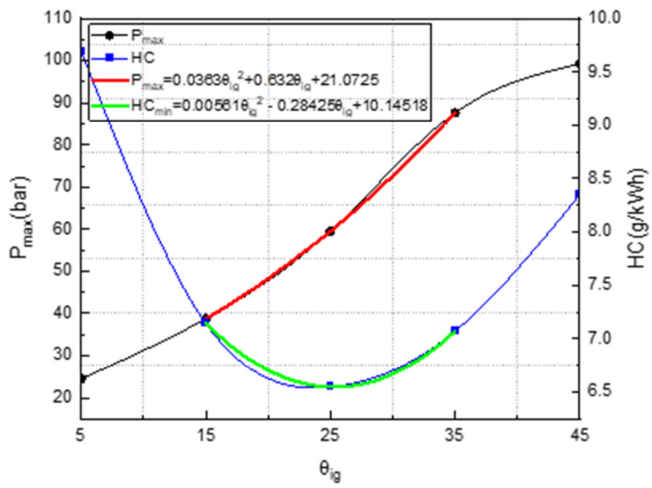


Fig. 8. Optimal HC emissions versus ignition timing.

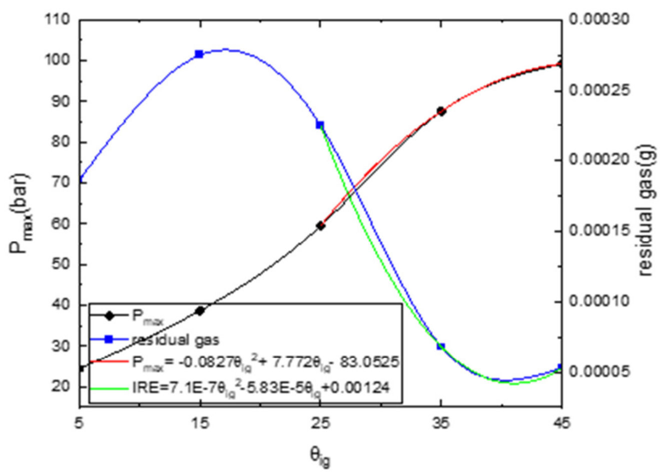


Fig. 9. Optimal residual gas emission versus ignition angles.

Residual gas refers to the remaining gas from the combustion process of the previous cycle. This residual gas negatively affects both the environment and engine performance by reducing efficiency and increasing emissions. Identifying the ignition angle range that minimizes the residual gas is therefore critical for optimizing the engine operation. As depicted in Figure 9, the lowest levels of residual gas are observed at ignition angles of approximately 25° and 45°. This indicates that within this range, the combustion process is more complete, reducing the impact of residual gas on the engine performance. The optimal residual gas characteristic curve is expressed as:

$$RE = 7.1E - 7\theta_{ig}^2 - 5.83E - 5\theta_{ig} + 0.00124 \qquad (11)$$

In this range, the peak pressure ($P_{max}$) lies from 60 bar to 100 bar, supporting an efficient combustion and engine operation. The corresponding optimal pressure characteristic curve is:

$$P_{max} = -0.827\theta_{ig}^2 + 7.772\theta_{ig} - 83.0525 \qquad (12)$$

## IV. CONCLUSIONS

This study presents a comprehensive investigation into the optimal output parameters of ethanol-fueled engines, focusing on the critical role of the ignition angle in enhancing the engine performance. By analyzing the results derived from the experimental data and characteristic equations, it was determined that an ignition angle between 25° and 35 delivers the most favorable balance between the maximum power output, minimal fuel consumption, and reduced emissions. The study's contribution lies in its development of precise mathematical models for the key performance metrics -torque, BMEP, ISFC, and emission characteristics. These models provide a clear framework for understanding how ethanol-fueled engines can be optimized to achieve a sustainable and efficient operation. Unlike previous studies, which often lacked detailed mathematical representations or focused on alternative fuels, this research bridges a critical gap by offering targeted insights into the ethanol combustion dynamics. Beyond its technical findings, this work underscores the potential of ethanol as a viable alternative fuel for internal combustion engines. By optimizing the ignition parameters, ethanol-fueled engines can achieve a performance comparable to or even surpassing that of traditional fossil-fueled engines, while significantly lowering the environmental impact.

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