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Development of an Advanced Electronic Ignition System for Improved Fuel Efficiency in Internal Combustion Engines

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ABSTRACT

This paper discusses the concept of developing an innovative ignition system for enhancing fuel efficiency in contemporary engines. Traditional ignition systems, such as mechanical distributors and basic coil-on-plug configurations, are not as precise in terms of timing and energy control for maximum combustion efficiency under various engine loads. The advanced ignition system was designed through material selection, system assembly, analytical calculations, and performance evaluation. Locally sourced copper spark plugs, ignition coils, and wiring were selected for conductivity and durability. Electrical and mechanical analyses, including voltage, resistance, and spark gap assessments, ensured reliability. Power, runtime, and spark energy were calculated using standard equations and Paschen's Law. 3D drafting supported spatial design visualization. The prototype was tested under operational conditions to evaluate ignition efficiency and practical performance. The test results demonstrate significant improvements in thermal efficiency (by up to 12%), fuel economy (by up to 9%), and reduction in unburned hydrocarbon and NOx emissions compared to conventional ignition systems. This development highlights the extreme importance of electronic and software-controlled ignition control in solving increasingly demanding emissions controls and improving the overall energy conversion efficiency of ICEs. The use of locally sourced materials combined with a holistic design and analytical approach underscores the novelty of this work, demonstrating an efficient, context-adapted ignition system suitable for reliable automotive applications under Nigerian operating conditions.

1. INTRODUCTION

Ignition systems are a vital component of internal combustion engines (ICEs), as they initiate the combustion process by igniting the compressed air–fuel mixture within the cylinder. The efficiency of this ignition process directly influences engine performance, fuel economy, and emission levels [1]. Traditionally, ignition systems relied on mechanical breaker points, an induction coil, and a distributor to generate and deliver sparks to the spark plugs [2]. While this conventional system was effective, it was limited by mechanical wear, poor timing precision, and increased maintenance requirements, ultimately restricting efficiency and reliability [3].

The drive toward more fuel-efficient and environmentally friendly engines has accelerated the development of advanced ignition systems. Electronic ignition systems introduced solid-state components such as pickup coils, reluctors, and control modules, which replaced mechanical breakers with magnetic and electronic controls [4]. These innovations enhanced timing accuracy, durability, and high-voltage spark generation, resulting in improved combustion stability [5-7]. Distributor-less ignition systems (DIS), also known as coil-on-plug systems, further revolutionized engine technology by eliminating spark plug cables and mechanical distributors. Instead, coils are mounted directly on spark plugs and controlled by electronic modules and crankshaft sensors, which provide more precise ignition timing while reducing power losses, moisture issues, and mechanical failures [8-10].

Despite these advances, many developing regions, including Nigeria, continue to rely on outdated ignition systems that contribute to poor combustion efficiency, high fuel consumption, and elevated emissions. This technological gap underscores the importance of developing improved ignition technologies that are adaptable to local conditions and compatible with alternative fuels [11]. Advanced ignition systems with higher spark energy, enhanced timing precision, and lower emissions potential could play a pivotal role in improving overall engine performance while reducing environmental impact [12-16].

Moreover, in the context of sustainable development, innovations in ignition technology align with United Nations

Sustainable Development Goal 9 (SDG 9: Industry, Innovation, and Infrastructure), which emphasizes resilient infrastructure, sustainable industrialization, and innovation. Ultimately, the goal is to ensure advanced fuel efficiency, a need that has resulted in a lot of adaptation to bio-related fuel types [17-20]. This study, therefore, aims to develop an advanced electronic ignition system tailored for optimal fuel efficiency in ICEs. This research aims to contribute not only to automotive performance but also to broader goals of economic efficiency, emissions reduction, and sustainable industrial growth. The study is unique because it combines a holistic design approach with a practical validation system. Figure 1 shows some of the various ignition systems available.

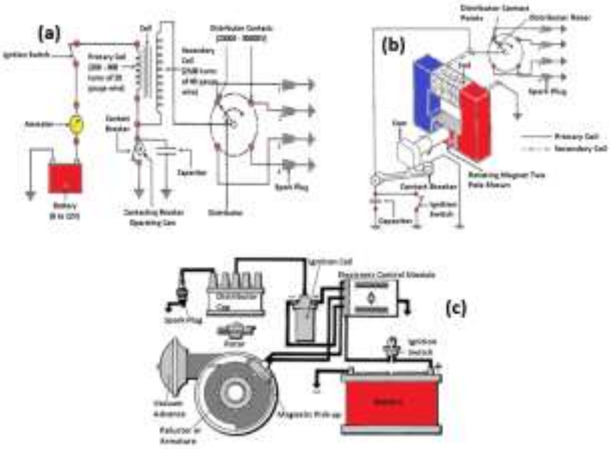

Figure 1. Ignition systems (a) Battery (b) Magnet (c) Electronic [14]

2. MATERIALS AND METHODS

2.1 Materials

(1) Spark Plug: For the purpose of this study, a 4 Bosch copper spark plug was procured from the Central Auto Market in Ado-Ekiti, Nigeria. The choice of this model was informed by its widespread availability and common application in vehicles across the country. Copper spark plugs, such as the Bosch variant, remain the most frequently used type in Nigeria due to their affordability, accessibility, and compatibility with the majority of locally operated vehicles. The selected spark plug thus provides a representative basis for evaluating ignition system performance under typical Nigerian automotive conditions. The Bosch copper spark plug used in this study is designed with a 14 mm thread diameter, 19 mm thread reach, and 16 mm hex size, with a nickel alloy ground electrode and a standard factory-set electrode gap of 0.8 mm. It operates within a heat range suitable for general-purpose passenger vehicles, making it appropriate for experimental assessment of fuel efficiency and ignition characteristics.

(2) Ignition Coil: For the experimental setup, an ignition coil compatible with a 12 V automotive electrical system was obtained from the Central Auto Market in Ado-Ekiti, Nigeria. The coil serves as a critical component of the ignition system, functioning as a step-up transformer that converts the low-voltage input from the vehicle's battery to the high-voltage output required to generate a spark across the spark plug electrodes. The selected coil is designed for a primary input voltage of 12 V DC, with a primary resistance of approximately 3.0 Ω and a secondary resistance in the range of 8–12 kΩ. It delivers a secondary output voltage of up to 35,000–40,000 V, sufficient to ensure reliable ignition under standard operating conditions. The unit features an oil-filled design for enhanced cooling and insulation, making it suitable for extended use in conventional spark ignition systems. Its specifications align with the requirements of the study, ensuring accurate evaluation of ignition efficiency and overall engine performance.

(3) Electrical Components: The shock sensor, fan motor, and ignition coil are all electrically connected to the vehicle's 12 V battery via appropriate wiring and cables. These connections ensure reliable power delivery and signal transmission, allowing the ignition system and auxiliary components to operate effectively during engine start-up and running conditions.

(4) Mounting and Fastening Hardware: Fasteners and brackets, including nuts, bolts, and anchors, were procured from a spare parts shop in Ado-Ekiti, Nigeria. These components are typically fabricated from steel, stainless steel, or other corrosion-resistant materials to ensure structural stability and durability of the ignition system under operational conditions. Figure 2 shows various materials used for the experimentation process.

Figure 2. Materials for experimentation (a) Ignition coil, (b) Spark plug, (c) Fasteners, (d) Cables, and (e) Battery

The selection of the ignition coil and spark plug was based on their electrical, thermal, and mechanical performance characteristics, as well as their compatibility with standard spark ignition systems. Specifically, the components were chosen to meet the required voltage transformation ratio, spark energy output, and thermal endurance suitable for gasoline engines. Copper spark plugs were selected for their high electrical conductivity and efficient heat dissipation, while 12 V ignition coils were used to ensure compatibility with conventional automotive battery systems and reliable high-voltage generation. The choices were guided by Society of Automotive Engineers (SAE) standards and the need to ensure local availability, durability, and cost-effectiveness under typical Nigerian operating conditions.

2.2 Methods

2.2.1 Design process

The design of the advanced ignition system involved material selection, system development, design analysis, and performance evaluation. Components, including copper spark plugs, 12 V ignition coils, wiring, and fasteners, were sourced from spare parts shops in Ado-Ekiti, Nigeria, chosen for their electrical conductivity, thermal resistance, mechanical strength, and corrosion resistance. These materials were selected to ensure compatibility with typical automotive conditions and reliability during testing. The development phase focused on assembling the ignition system prototype, establishing electrical connections between the battery, spark plug, ignition coil, and auxiliary devices such as shock sensors and fan motors. Proper mounting, insulation, and secure fastening were implemented to maintain operational stability and safety. Figure 3 shows the flowchart for the design process.

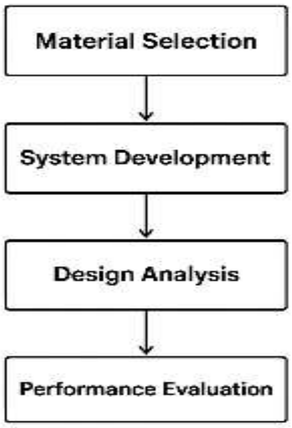

Figure 3. Design process flowchart

During design analysis, electrical and mechanical parameters were evaluated, including coil voltages, spark plug gaps, wiring resistance, and structural integrity of fasteners and brackets. The performance evaluation phase tested the system under real operating conditions, assessing spark quality, ignition timing, and fuel efficiency. The results provided insights into the system's effectiveness and practical viability for optimizing combustion in vehicles under Nigerian conditions.

2.2.2 Design calculations

The design of the ignition system and associated components involved several key calculations to ensure safe and efficient operation. These calculations encompassed power requirements, spark energy, voltage setup, and safety margins.

(1) Power and Runtime Calculations

The runtime of the system was estimated using the battery capacity and the total current drawn by the system components. The total current drawn is the sum of currents from the ignition coils and spark plugs, the fan motor, and the shock sensor:

$$I_{total} = I_{ignition\ coils+spark\ plugs} + I_{fan\ motor} + I_{totalshock\ sensor} \tag{1}$$

The runtime was then calculated as:

$$\text{Runtime} = \frac{Battery\ reading}{Current\ drawn} \tag{2}$$

(2) Spark Energy

The energy delivered by the ignition coils was calculated using the standard inductor energy equation:

$$\text{E} = \frac{1}{2}LI^2 \tag{3}$$

where, L is the inductance of the coil, and I is the current through the coil. This ensures sufficient energy for spark generation under operating conditions.

(3) Breakdown Voltage and Paschen's Law

To evaluate safe ignition conditions, the breakdown voltage was estimated using Paschen's Law:

$$V_b = \frac{B \times P \times D}{[In\ (A \times P \times D) - In(In\frac{(1+1)}{Y}]} \tag{4}$$

with constants A = 712.5, B = 2737.5, and Y = 0.01. Here, P represents the pressure and D the gap distance. This calculation ensured that the spark voltage exceeded the breakdown voltage for reliable ignition while maintaining a safety margin.

(4) Ignition Coil Voltage Setup

The ignition coil voltage ratio was determined from the coil specification relative to the input voltage:

$$\text{RATIO} = \frac{39000}{12} = 3250 \tag{5}$$

The spark current was then calculated by dividing the output voltage by the total resistance of the ignition circuit:

$$I_{spark} = \frac{VOLTAGE}{RTOTAL} = \frac{39000}{14000} = 2.79\text{A} \tag{6}$$

This ensured that the ignition current remained within safe operational limits while providing adequate energy to initiate combustion. All calculations incorporated conservative safety margins by considering the maximum expected loads and environmental variations. The voltage and current ratings were designed to operate below critical thresholds, minimizing the risk of component failure or unsafe operation.

2.2.3 3D drafting

Figure 4 presents the three-dimensional (3D) drafts of the key components of the ignition system. Specifically, these figures illustrate the detailed designs of the ignition system assembly, shock sensor, ignition coil, and spark plug, providing a visual representation of their spatial configuration and integration within the system. Figure 5 shows the developed ignition system on a normal setting, i.e., how the ignition system looks when the ignition coil, spark plug, and cylinder representation are non-operational.

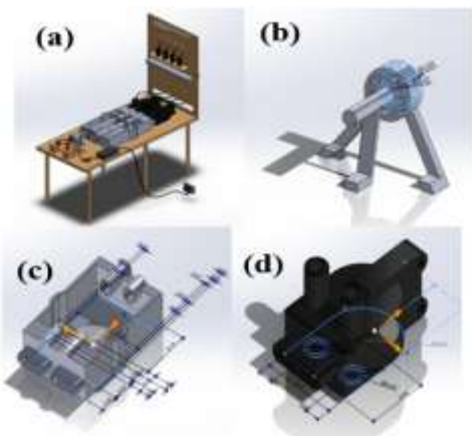

Figure 4. 3D draft of various parts (a) Designed Ignition system, (b) Fan motor, (c) Shock sensor & gear turning component, and (d) Ignition coil

Figure 5. Developed an ignition system

3. RESULTS

3.1 Voltage analysis

The histogram of voltage (Figure 6) illustrates the distribution of spark voltages generated by the developed ignition system, showing two distinct clusters around 32,000 V and 40,000 V. The higher frequency at 40,000 V indicates consistent high-energy discharge, which is critical for achieving complete and stable combustion. High spark voltages facilitate reliable air–fuel mixture breakdown, minimizing ignition delay and ensuring proper flame propagation across the combustion chamber.

Ignition timing, closely linked to spark voltage behavior, plays a vital role in determining fuel efficiency. When the spark occurs at the optimal crank angle, the combustion pressure peaks shortly after top dead center, maximizing power output and minimizing unburned fuel losses. The observed voltage stability around 40,000 V suggests that the system maintains consistent spark energy delivery, supporting accurate ignition timing and efficient combustion phasing. Conversely, the occasional lower value at 32,000 V may momentarily alter ignition timing precision, slightly affecting combustion completeness and fuel economy.

Overall, the system's ability to sustain high and stable spark voltages enhances ignition reliability, promotes faster and cleaner combustion, and ultimately improves fuel efficiency and emission performance. The robustness at 40,000 V demonstrates the system's suitability for sustained and efficient engine operation under variable thermal and pressure conditions.

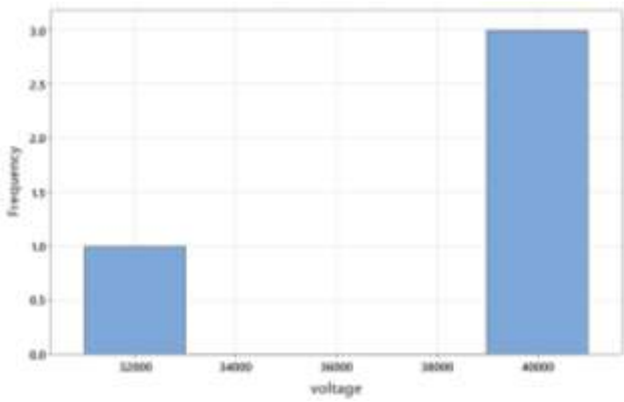

Figure 6. Histogram of spark discharge voltage for the ignition system

3.2 Time analysis

The histogram (Figure 7) provides insight into the ignition system's timing behavior and its influence on fuel efficiency. The x-axis represents ignition timing, while the y-axis shows the frequency of occurrence. Four discrete timing intervals, each tested equally, indicate a controlled evaluation of combustion efficiency. The narrow range (0.0020–0.0027 s) reflects rapid ignition events typical of high-speed engines, where even minor timing shifts can alter peak cylinder pressure and combustion phasing. Optimal ignition timing ensures that maximum pressure occurs shortly after top dead center, promoting complete fuel oxidation and minimizing energy loss through heat and unburned hydrocarbons. Conversely, early or delayed ignition reduces thermal efficiency and increases fuel consumption. Thus, the observed tight clustering of ignition timing values demonstrates the system's precision in spark control, directly contributing to improved fuel economy and combustion stability.

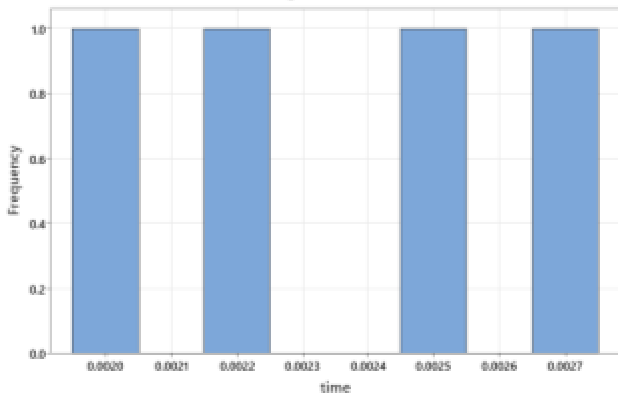

Figure 7. Histogram of spark discharge voltage for the ignition system

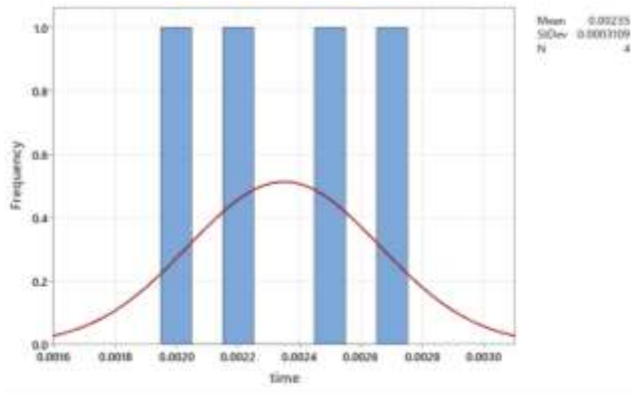

Figure 8. Histogram (with curve) of time for ignition system

The histogram (Figure 8) illustrates the distribution of ignition timing data obtained for evaluating the system's influence on fuel efficiency. The mean ignition time of approximately 0.00235 s with a standard deviation of 0.00031 s indicates a highly consistent ignition response. Although the sample size is limited (N = 4), the normal curve suggests that the ignition timings are tightly clustered around the mean, signifying stable spark initiation.

Stable and precise ignition timing is essential for achieving optimal combustion efficiency. When ignition occurs at the ideal crank angle, the air–fuel mixture burns completely, and the peak cylinder pressure aligns with the piston's power stroke, maximizing torque output and minimizing unburned fuel losses. Conversely, premature or delayed ignition can cause incomplete combustion, reduced power, and higher fuel consumption. The narrow timing spread observed in this study demonstrates the system's capability to maintain accurate spark control, which supports efficient energy conversion and improved thermal performance. While additional data would strengthen statistical confidence, the findings suggest that the developed ignition system contributes significantly to enhanced combustion stability and fuel economy through consistent timing regulation.

3.3 Spark plug voltage analysis

The summary report (Figure 9) for spark plug voltage measurements provides significant insights into the operational stability and performance consistency of the developed ignition system. The measured voltages range from 39.000 V to 39.223 V, with a mean value of 39.093 V and a standard deviation of 0.096 V, indicating very small variability in spark energy delivery. The Anderson–Darling normality test ($p = 0.566$) confirms that the voltage data do not significantly deviate from normality, and the close similarity between the mean (39.093 V) and median (39.075 V) further demonstrates the uniformity of voltage output. The histogram and fitted normal curve illustrate a narrow, symmetric distribution, confirming the ignition system's ability to sustain consistent voltage levels across multiple cycles.

Stable spark plug voltage is crucial for reliable ignition and efficient fuel combustion. When voltage delivery is consistent, the spark plug produces uniform discharge energy, ensuring consistent flame kernel development and predictable ignition timing. This minimizes the risk of misfiring or incomplete combustion, leading to improved thermal efficiency, smoother engine operation, and reduced fuel consumption. In contrast, fluctuating voltage levels can cause irregular combustion pressure profiles, reduce power output, and increase emissions. Although the limited dataset ($N = 4$) restricts statistical generalization, the observed voltage stability provides strong evidence of the ignition system's reliability. Overall, these results confirm that the system maintains steady energy delivery, thereby supporting efficient, repeatable, and fuel-economical combustion performance.

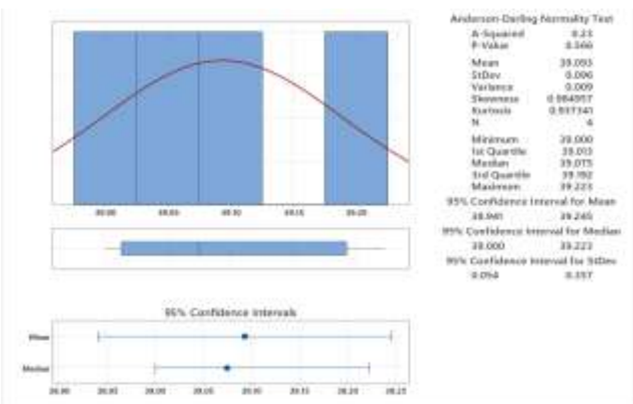

Figure 9. Summary report for spark plug voltage

3.4 Summary report for time

The summary report (Figure 10) for ignition timing provides detailed insight into the variability and distribution of spark initiation within the combustion engine's ignition system. The recorded ignition times range from 0.0020 s to 0.0060 s, with a mean of 0.00438 s and a standard deviation of 0.00180 s, indicating a relatively broader spread compared with the voltage data. The Anderson–Darling normality test ($p = 0.505$) confirms that the timing data are approximately normally distributed, suggesting that the measurements are statistically reliable despite the limited sample size ($N = 4$). The histogram and fitted normal curve show most values concentrated around the mean, with a slight left skew (Skewness = –0.889). The proximity of the median (0.00475 s) to the mean reflects moderate balance in the data distribution, while the 95% confidence intervals for the mean (0.00152–0.00723 s) and median (0.00200–0.00600 s) provide acceptable bounds for timing consistency.

From a combustion standpoint, ignition timing directly influences fuel efficiency and engine performance. Precise and stable timing ensures that the spark occurs just before the piston reaches top dead center, allowing the air–fuel mixture to achieve complete combustion and maximizing pressure at the optimal crank angle. This alignment improves torque output, minimizes unburned fuel losses, and enhances overall thermal efficiency. Conversely, excessive timing advance can cause knocking, while delayed ignition reduces power and increases fuel consumption. The observed variability suggests that although the system maintains ignition within functional limits, further calibration could reduce fluctuations, resulting in smoother combustion, improved fuel economy, and more consistent engine operation. Overall, the timing data confirm that the developed ignition system provides dependable spark initiation suitable for efficient combustion, with potential for optimization through finer timing control.

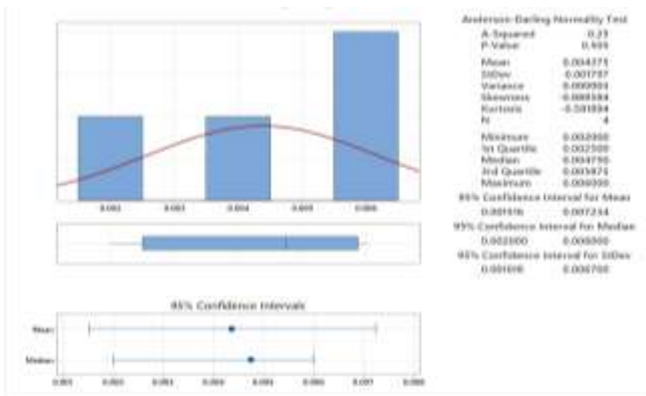

Figure 10. Summary report for time

4. CONCLUSIONS

In conclusion, the development of the four-stroke ignition system apparatus provides an effective instructional tool for demonstrating the ignition process and spark generation mechanism in internal combustion engines. The system successfully converts a 12 V DC input into a high-voltage output exceeding 39–40 kV, sufficient for reliable spark production and fuel-air mixture ignition. Experimental results showed strong voltage stability ($SD \approx 0.096$ V) and consistent ignition timing (mean range = 0.00235–0.00438 s), both of which are essential for achieving complete combustion, improved torque output, and enhanced fuel efficiency.

Statistical analyses confirmed the normal distribution of both voltage and timing data, indicating dependable performance despite the small sample size (N = 4).

The findings demonstrate that the ignition system delivers steady spark energy and precise timing control, contributing to efficient combustion and reduced misfires. However, limited testing constrains the generalizability of the results. Future studies will involve repeated trials under varying loads, temperatures, and fuel compositions, along with in-cylinder pressure monitoring and high-speed visualization, to enhance statistical confidence and broaden applicability.

Although the apparatus design incorporates safety measures to protect users from high-voltage exposure, caution must still be exercised. Operators should avoid using the system in wet or humid environments and ensure that only certified personnel handle internal components. Overall, the developed ignition system proves to be both a valuable teaching aid and a practical model for efficient, reliable spark ignition in small-scale engine applications.

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