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Catalyst-Dependent Performance and Emission Trade-Offs in a Passive Hydrocarbon Cracking System for Gasoline Engines

Aji Bagus Ardiyanto, Sena Mahendra*, Bayu Ariwibowo, Fahmy Zuhda Bahtiar, and Fahmy Fatra
Mechanical Engineering and Vocational Education Study Program, Faculty of Sains and Technology, Universitas Ivet, Bendan Duwur, Semarang, Indonesia, 50235
E-mail: sena.mahendra1@gmail.com

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Abstract

Improving combustion efficiency and reducing exhaust emissions remain significant challenges for gasoline engines, particularly in developing countries experiencing rapid vehicle growth. This study investigated the effect of passive Hydrocarbon Cracking Systems (HCS) using various catalyst materials (steel, activated carbon, natural zeolite, and nickelin) on engine performance and exhaust emission characteristics without engine modification. Experiments were conducted on a 110cc single-cylinder, fuel-injected gasoline engine using commercially available RON 92 fuel. Engine performance was evaluated using a dynamometer to measure torque and power, while exhaust emissions (CO, HC, and CO_2) were analyzed using a calibrated gas analyzer at various engine speeds. The results indicate a clear trade-off between performance improvement and emission control depending on the catalyst material used in the HCS. . The zeolite-based catalyst provided the most significant performance improvements, increasing maximum torque by 5.61% and maximum power by 1.91%, while reducing HC by 9.48%, CO by 10%, and increase CO_2 by 1.4% . In contrast, the nickelin catalyst demonstrated superior emission control, achieving a 24.57% reduction in HC, 10.1% in CO and increase CO_2 4.17%, although the associated power gains were lower than those obtained with zeolite. However, most of the studies that have been conducted only focus solely on the effects on performance and exhaust emissions, without providing insight into the catalyst materials used for fuel cracking. To address this gap, this study aims to empirically provide insight into which media are best used as catalysts in HCS systems.

Keywords: *Catalytic cracking; Combustion enhancement; Exhaust emissions; Gasoline engine performance.*

Abstrak

Peningkatkan efisiensi pembakaran dan mengurangi emisi gas buang tetap menjadi tantangan signifikan bagi mesin bensin, khususnya di negara berkembang yang mengalami pertumbuhan kendaraan yang pesat. Studi ini meneliti pengaruh Sistem Perengkahan Hidrokarbon (HCS) pasif menggunakan berbagai material katalis (baja, karbon aktif, zeolit alami, dan nikelin) terhadap kinerja mesin dan karakteristik emisi gas buang tanpa modifikasi mesin. Eksperimen dilakukan pada mesin bensin satu silinder 110cc dengan injeksi bahan bakar menggunakan bahan bakar RON 92 yang tersedia secara komersial. Kinerja mesin dievaluasi menggunakan dinamometer untuk mengukur torsi dan daya, sementara emisi gas buang (CO, HC, dan CO_2) dianalisis menggunakan penganalisis gas yang telah dikalibrasi pada berbagai kecepatan mesin. Hasil menunjukkan adanya pertukaran yang jelas antara peningkatan kinerja dan pengendalian emisi tergantung pada material katalis yang digunakan dalam HCS Katalis berbasis zeolit memberikan peningkatan kinerja yang paling signifikan, meningkatkan torsi maksimum sebesar 5,61% dan daya maksimum sebesar 1,91%, sementara mengurangi HC sebesar 9,48%, CO sebesar 10%, dan meningkatkan CO_2 sebesar 1.14%. Sebaliknya, katalis nikelin menunjukkan pengendalian emisi yang lebih unggul, mencapai pengurangan THC sebesar 24,57% dan CO sebesar 10,1% dan meningkatkan CO_2 sebesar 4.17%, meskipun peningkatan daya yang terkait lebih rendah daripada yang diperoleh dengan zeolit. Namun, sebagian besar studi yang sudah dilakukan hanya berfokus pada efek terhadap kinerja dan emisi gas buang saja, tanpa memberikan wawasan tentang material katalis yang digunakan untuk perengkahan bahan bakar. Untuk mengatasi kesenjangan ini, studi ini secara empiris bertujuan untuk menjadi wawasan media apa yang bagus digunakan sebagai katalis pada sistem HCS.

Kata kunci: Perengkahan katalitik; Peningkatan pembakaran; Performa mesin bensin; Emisi gas buang.

1. Introduction

In 2024, the number of motorized vehicles in Indonesia reached approximately 153.4 million units, dominated by motorcycles, resulting in significant increases in fuel consumption and air pollution from gasoline engines [1]. To address this issue, innovations in the combustion process are needed, including the Hydrocarbon Crack System (HCS). HCS is a heating system that breaks down fuel molecules into hydrogen (H_2) and carbon (C) atoms using the hottest catalyst pipe, then injects the resulting H_2 gas into the combustion chamber to increase combustion efficiency.

Hydrocarbon Crack System (HCS) is a system that utilizes hydrocarbon compounds from fuel that are cracked (broken down) into hydrogen (H_2) and carbon (C) elements through a catalyst pipe by utilizing heat from the exhaust to trigger a reaction to separate the compounds [2]. This process operates specifically at the pre-combustion stage, before the fuel is injected or mixed with air and enters the engine's combustion chamber. The main advantage of the HCS design lies in its passive heating mechanism; it uses residual heat from the engine's exhaust gas to heat the catalyst or copper pipe that serves as the fuel flow path [3]. This utilization of exhaust thermal energy recovery is crucial because it significantly reduces the energy load on the engine, unlike electrolysis systems, which require active electrical power. This waste heat is then used to trigger chemical reactions aimed at increasing combustion efficiency, ultimately increasing the total thermal efficiency of the engine system thermodynamically.

The cracking process occurs through a combination of heating and catalysis. The initial step involves heating the fuel with copper pipes to completely vaporize it (in the gas phase), a crucial prerequisite for achieving a more homogeneous mixture with air, resulting in more complete combustion in the combustion chamber. Once vaporized, the fuel is passed through heated catalyst pipes. These catalysts facilitate the cracking of long-chain hydrocarbon molecules into hydrogen (H) and carbon (C) atom fragments. This molecular modification essentially increases the fuel's octane rating beyond that of the primary fuel. The primary product of this breakdown, hydrogen (H) atoms, is then transported to the combustion chamber along with oxygen. The presence of hydrogen and shorter hydrocarbon fragments fundamentally allows the engine to operate at a more optimal compression ratio or ignition timing, resulting in increased engine power and reduced CO and HC emissions [4].

Studies have been conducted on the Hydrocarbon Crack System (HCS). However, these studies were conducted using Thermal HCS (non-catalytic material). Research using catalytic materials has been very limited, including. One study used natural zeolite as a catalyst for the HCS system in a 4-stroke motorcycle. The use of the Hydrocarbon Crack System in gasoline engines reduces the levels of HC 20 percent and CO 4 percent exhaust emissions at rpm 5500 and above and the exhaust temperature is 215 degrees Celscius [5].

Research conducted using copper (Cu) catalysts obtained a torque increase of only 0.2 Nm from standard conditions (non-HCS) with the addition of a 7-winding HCS device using Pertamax turbo fuel. The power increase was only 0.03 kW from standard conditions (non-HCS) with the addition of a 7-winding HCS device using Pertamax turbo fuel. The largest decrease in specific fuel consumption was only 14.94% with the addition of a 7-winding HCS device fueled with methanol [6]. In another study, the use of HCS can increase the maximum torque of the standard Suzuki Satria FU150 using Pertamax fuel from 12.14 Nm to 12.41 Nm, an increase of 2.22% or 0.27 Nm, and increase the maximum power from 14.57 HP to 14.8 HP, an increase of 1.58% or 0.23 HP [7]. Other research shows thatthe use of HCS catalyst with a 2-pipe fuel system increases power by 57.2% at 4500 rpm [8]. Another study also showed that HCS is effective in reducing CO and HC emissions above 5500 rpm, with a 15% reduction in CO and 11% in HC at 5500 rpm, and even greater reductions at 6500 and 7500 rpm. HCS increased engine torque by 3.40% and reduced CO and HC emissions by 28.12% and 54.35%, respectively. However, CO_2 emissions increased by 12.48% [9].

However, most of these studies still focus on the effects on performance and exhaust emissions alone, without providing insight into the catalyst materials used for fuel cracking. To address this gap, this study empirically tests several catalyst materials, including nickel wire, steel, zeolite rock, and activated carbon, and uses commercially available gasoline (RON 92) in Indonesia, operating under standard engine conditions. These findings offer new insights into the potential of other catalysts as relatively inexpensive alternative media. By bridging the gap between experimental research and practical implementation, this study provides practical insights for readers to build prototypes and pursue broader innovations with catalyst materials that will be investigated in future studies.

2. Material and Method

This research was conducted at the automotive workshop of Ivet University, Semarang City from January 5 to February 25, 2026. The research was conducted with stable vehicle and load conditions so that the research data obtained remained constant. The research methods used included experimental and analytical methods. The experimental method used aims to test the cause-effect relationship between variables. The data analysis technique used was a 3 x 3 factorial DOE with 3 replications for each catalyst media condition and a baselie condition as the main control. Then, it was analyzed using two-way ANOVA to stimulate. The research flow is divided into 3 stages: (1) Selection of catalyst material, (2) Digital Catalyst Modeling, (3) Field testing.

2.1 Selection of catalyst materials

Nickel, steel, zeolite, and activated carbon have different thermal characteristics and thus contribute varyingly to engine performance, combustion quality, and exhaust emission profiles. Nickel wire has mechanical properties similar to carbon steel and its resistance to corrosion is very high, besides it can withstand operating temperatures of around 400°C [10] to 1000°C [11]. Low-carbon steel, with a dissolved carbon content of less than 0.2% in the iron, is commonly used for the manufacture of machine components because it is softer and easier to machine and form [12]. Zeolite is a non-metallic mining material and industrial mineral with unique physical and chemical properties, namely it can be used as an adsorbent, ion exchanger, molecular filter and catalyst [13]. Meanwhile, activated carbon contains a large carbon and porosity which has high absorption and high surface-area adsorptive material with a largely amorphous structure [14].

The base fuel used is RON 92 gasoline sourced from Pertamina gas stations. The catalyst material used is obtained from metal materials markets and online. The composition of the materials used is shown in Table 1.

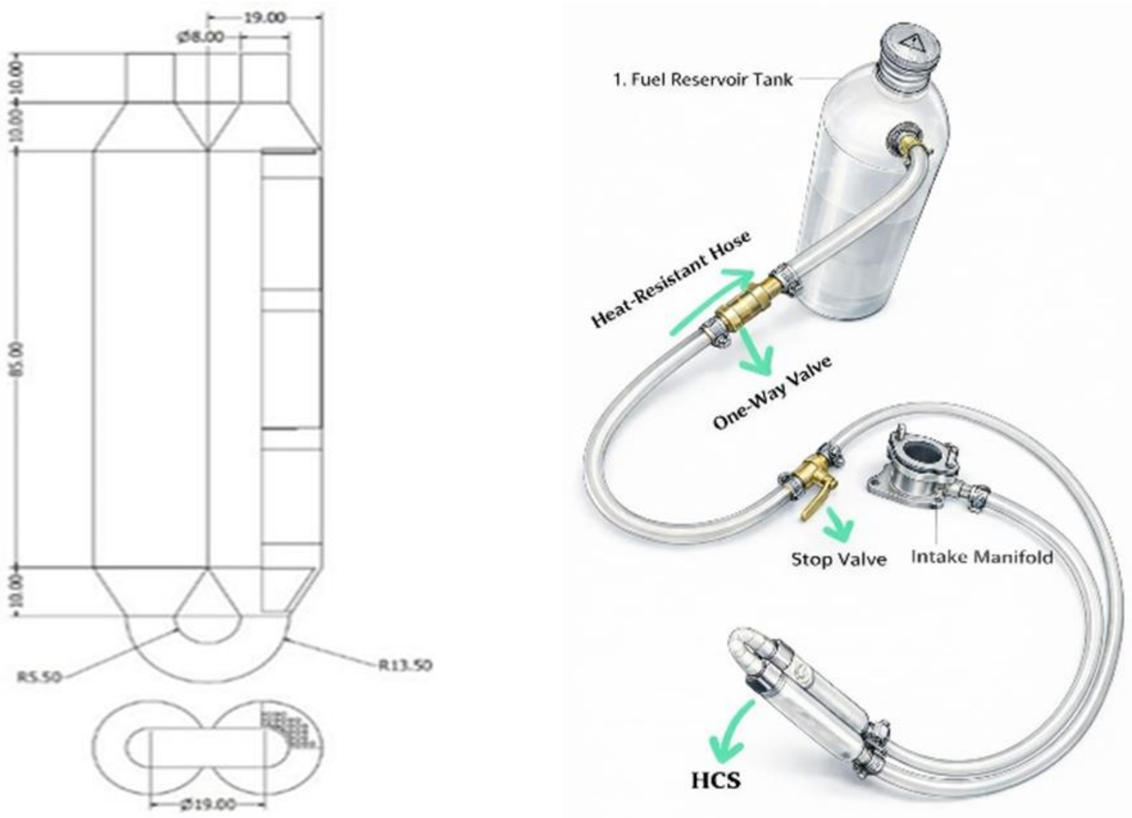
Table 1. Material Composition

Catalyst Material Composition		
Material	Heavy	Visual
NIKELIN Nickel wire has mechanical properties similar to carbon steel and its resistance to corrosion is very high, besides it can withstand operating temperatures of around 400°C [10] to 1000°C [11].	67 Gram	
STEEL Low-carbon steel, with a dissolved carbon content of less than 0.2% in the iron, is commonly used for the manufacture of machine components because it is softer and easier to machine and form.	252 Gram	
ZEOLITE Zeolite is a mineral that has an alumina silica structure or framework with the chemical formula Mx/n $[(AlO_2)x.(SiO_2)y.wH_2O]$ [13].	88 Gram	

Catalyst Material Composition		
ACTIVATED CARBON Activated carbon contains a large carbon and porosity which has high absorption and high surface-area adsorptive material with a largely amorphous structure [14]	102 Gram	

2.2 Digital catalyst modeling

This 3D digital model was created using Solidworks software. This catalyst was created based on actual field conditions, where fuel vapor is taken from a reservoir tank outside the tank and then enters the Hydrocarbon Crack System catalyst and hydrogen enters through an artificial hole in the vehicle's intake manifold.



(a) (b)

Figure 1. Construction of HCS, (a) Construct of catalytic system (b) Construction of HCS-based fuel saving device

2.3 Field testing

Field testing in this study used a normal motorcycle vehicle and without any modifications to either the engine or CVT. The equipment used to collect performance and exhaust emission data was facilitated by Ivet University, below are the specifications of the vehicle and the data collection equipment used. This study used a 110cc single-cylinder, SOHC Honda BEAT engine with an electronically controlled fuel injection system. The general specifications of the test engine are shown in Figure 2 [15].

2.4 Dynometer

A dynometer is a tool used to test a vehicle's engine to determine the torque and power generated by the rotation of the wheels connected to the dyno, below are the dyno specifications [16].

Specification Honda BeAT eSP	
Dimensions	
Length X Width X Height	1856 x 666 x 1068 mm
Wheelbase	1256 mm
Ground Clearance	146 mm
Fuel Tank Capacity	4 liters
Engine	
Engine Type	4-Stroke, SOHC with Air Cooling, eSP
Displacement	110 cc
Bore X Stroke	50 x 55.1 mm
Compression Ratio	9.5 : 1
Maximum Power	6.38 kW @7,500 rpm
Maximum Torque	9.01 Nm @6,500 rpm
Fuel Supply System	PGM-FI
Clutch	Dry, Automatic, Centrifugal
Transmission	Automatic, V-Matic
Engine Oil Capacity	0.7 L (Exchange)
Frame	
Frame Type	Back Bone
Front Suspension Type	Telescopic
Rear Suspension Type	Swing Arm Mono Suspension
Front Brake	Hydraulic Disc
Rear Brake	Drum
Front Tire Size	80/90-14M/C 40P- Tubeless
Rear Tire Size	90/90-14M/C 46P- Tubeless
Electrical	
Ignition Type	Full Transisterized, Battery
Spark Plug Type	NGK MR9C-9N

Figure 2. Machine Specifications [15]

Component	Specification	Description/Justification
Dynotest Type	**Inertia Chassis Dynamometer (Roller Dyno)**	Power & torque measurement based on roller acceleration and dyno moment of inertia (MOI).
Configuration	Roller 1 (RPM1)	SimpleDyno uses the main roller RPM reading for performance curve calculations.
Roller Diameter	**220 mm**	Main input data for dyno MOI calculation.
Roller Mass/Weight	**300 kg**	Main input data for dyno MOI calculation.
Roller Radius	110 mm (0.11 m)	Derived from diameter. Used to calculate MOI.
MOI Calculation	**$I = \frac{1}{2} m r^2 \rightarrow I \approx 1.815$ kg·m²**	With m=300 kg, r=0.11 m. MOI is the basis for inertia dyno torque & power calculations.
Software	**SimpleDyno (Windows)**	Processes roller RPM data to generate torque & power curves (*power run*) and data storage.
System Requirements	Windows + Microsoft .NET Framework	SimpleDyno requires .NET Framework to run.
RPM Data Acquisition Method	Audio-Only / Audio + COM / COM-Only	Choice of roller RPM reading methods.
Sampling Rate (Audio Mode)	11025 / 22050 / 44100 Hz	Higher sampling is generally more stable for RPM signals, depending on PC capability.
Test Mode	**Power Run (full acceleration/WOT)** + Coast Down	SimpleDyno calculates performance curves from roller acceleration and smoothes curves with curve fitting.

Figure 3. Dynometer Specifications

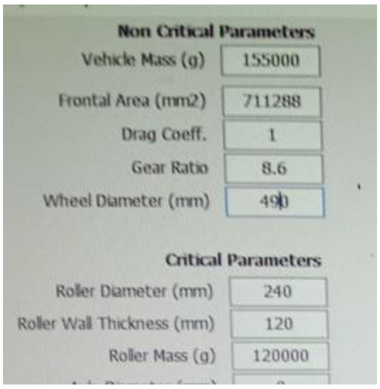


Figure 4. Dynometer Software Calibration

2.5 Gas Analyzer

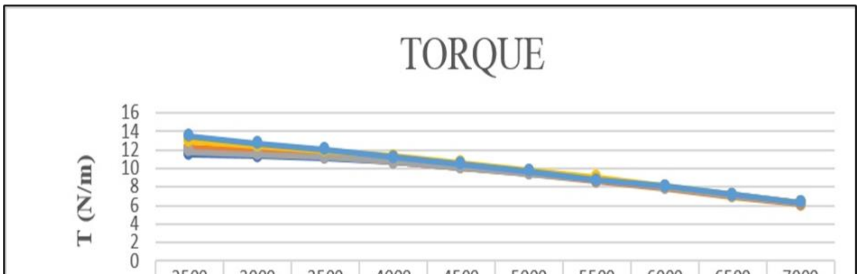
A gas analyzer is a device used to measure emission levels such as carbon dioxide (CO_2), carbon monoxide (CO), and hydrocarbons (HC). The gas analyzer used by the researchers was type 4020H 10076607. The gas analyzer is showing in figure 5.

Figure 5. Gas Analyzer Type 4020H 10076607

3. Results and Discussion

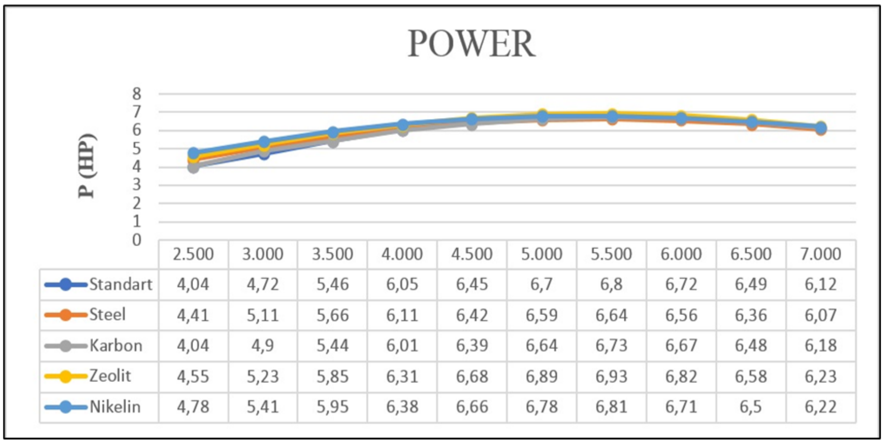
3.1 Result

To determine the effect of using several different catalyst materials on engine performance, the results of engine performance tests were analyzed. The main performance parameters include power, torque, and exhaust emissions as illustrated in Figure 6. These parameters provide valuable insights into how catalysts containing steel, activated carbon, zeolite, and nickel affect torque, power, and exhaust emissions.



	2500	3000	3500	4000	4500	5000	5500	6000	6500	7000
Standart	11,5	11,4	11,1	10,7	10,1	9,52	8,82	7,96	7,13	6,22
Steel	12,3	11,9	11,3	10,7	10,1	9,37	8,63	7,79	6,98	6,17
Karbon	11,8	11,5	11,2	10,7	10,1	9,42	8,72	7,93	7,11	6,29
Zeolit	12,93	12,4	11,9	11,3	10,6	9,75	9	8,07	7,21	6,33
Nikelin	13,4	12,7	12	11,2	10,4	9,7	8,78	8,07	7,13	6,33

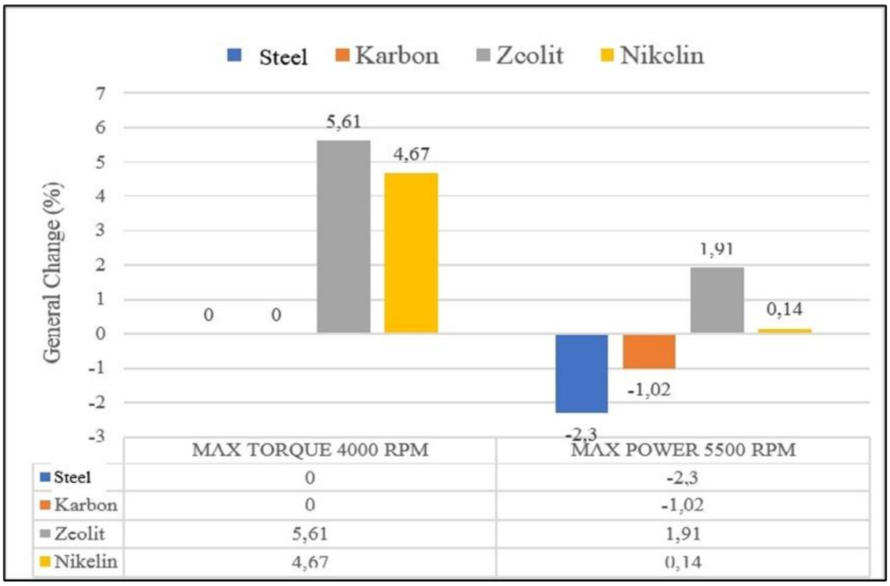
(a)



	2.500	3.000	3.500	4.000	4.500	5.000	5.500	6.000	6.500	7.000
Standart	4,04	4,72	5,46	6,05	6,45	6,7	6,8	6,72	6,49	6,12
Steel	4,41	5,11	5,66	6,11	6,42	6,59	6,64	6,56	6,36	6,07
Karbon	4,04	4,9	5,44	6,01	6,39	6,64	6,73	6,67	6,48	6,18
Zeolit	4,55	5,23	5,85	6,31	6,68	6,89	6,93	6,82	6,58	6,23
Nikelin	4,78	5,41	5,95	6,38	6,66	6,78	6,81	6,71	6,5	6,22

(b)

Figure 6. Peformance Test Result, (a) Torque test result with four materials and standart condition (b) Power test result with five materials



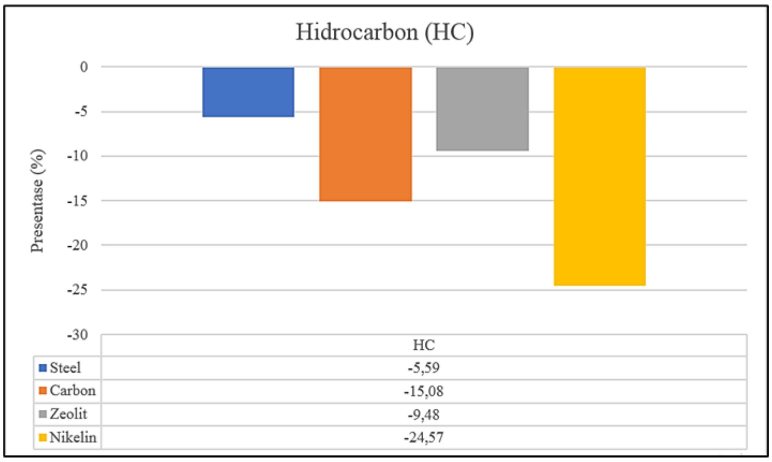
	MAX TORQUE 4000 RPM	MAX POWER 5500 RPM
Steel	0	-2,3
Karbon	0	-1,02
Zeolit	5,61	1,91
Nikelin	4,67	0,14

Figure 7. General changes in Torque and Power for catalyst materials containing steel, activated carbon, zeolite, and nickel.

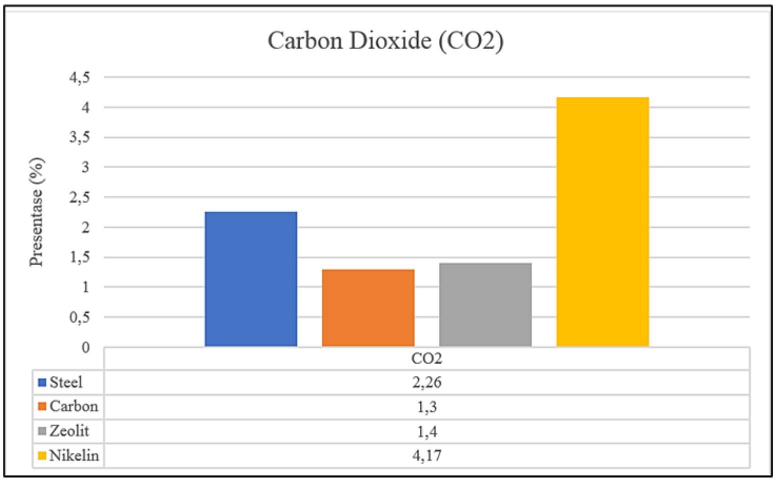
Figure 6 shows an increase in torque between 2500 and 4000 rpm for catalysts containing steel, activated carbon, zeolite, and nickelin. After the rpm exceeds 4000, the torque decreases for both the steel and activated carbon media. In contrast, for catalysts containing zeolite and nickel, torque increases steadily after the rpm exceeds 4000. Figure 7 illustrates the comparative performance of catalysts containing steel, activated carbon, zeolite, and nickel under standard conditions, showing changes in maximum torque (at 4000 rpm) and maximum power (at 5500 rpm). Torque and power measurements using the zeolite-containing catalyst showed increases of 5.61% in maximum torque and 1.91% in maximum power. In comparison, the use of the nickel-containing catalyst resulted in a 4.67% increase in maximum torque and a 0.14% increase in power.

3.2 Exhaust Gas Emission Measurement

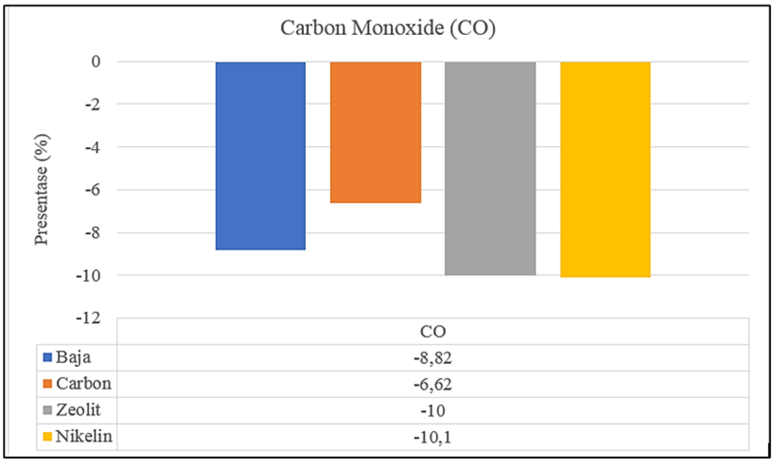
The next parameter measured in this test is exhaust emissions. Engine condition and the fuel used significantly influence emissions. Emissions indicate the quality of combustion occurring in the engine's combustion chamber. Emissions measured include CO (carbon monoxide), HC (hydrocarbon), and CO_2 (carbon dioxide).



(a)



(b)



(c)

Figure 8. Percentage of emission changes with Steel, Activated Carbon, Zeolite, Nickeline media, (a) HC (b) CO_2 (c) CO.

Figure 8 shows that the nickel-containing catalyst improves combustion, resulting in more complete fuel combustion and reduced emissions of these harmful pollutants. Furthermore, measurements indicate that carbon dioxide (CO_2) levels are higher when nickelin is used as the catalyst in the HCS system. Carbon monoxide (CO) emissions at high speeds show the largest reduction in CO emissions, up to 10.1%, with the nickel-containing catalyst. This indicates a more efficient combustion process, in which more carbon is converted to CO_2, reflecting increased oxidation during fuel combustion. Furthermore, measurements show that hydrocarbon (HC) levels are 24.57% lower when using the nickel-containing catalyst at high speeds. Using the nickel-containing catalyst results in lower emissions than using steel, activated carbon, or zeolite-containing catalysts. This provides insight into how the HCS system reduces harmful exhaust emissions.

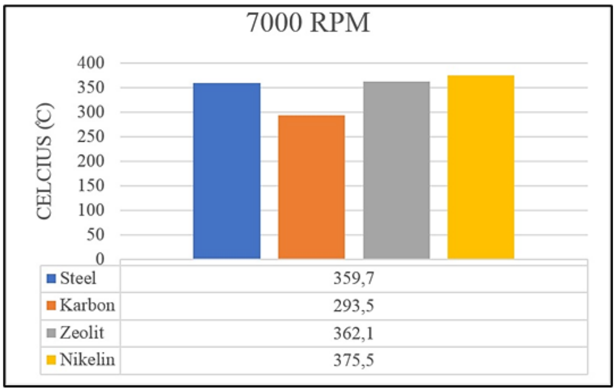


Figure 9. HCS catalyst temperature graph at 7000 RPM

3.3 Discussion

Engine performance metrics indicate that the contribution of a closed Hydrocarbon Crack System (HCS) toward enhancing power output and torque remains predominant during low- to mid-speed engine operation. Rather than representing an anomaly, this phenomenon stems directly from fundamental thermodynamic and combustion kinetic constraints operating within strict cyclic duration limits. Utilizing a 500 mL vaporized fuel capacity, the closed HCS operates with maximum efficiency at low speeds due to the extended time windows available for fuel atomization, mixture formation, flame propagation, and total combustion cycle duration [17]. Within this lower speed range, standard gasoline combustion possesses adequate time to attain near-optimal thermal efficiency. Because sufficient ignition delay is maintained, even the intrinsic burning velocity of standard fuel is capable of advancing peak cylinder pressure (Pmax) to a thermodynamically advantageous crank angle.

Conversely, high-speed engine operation severely compresses the mechanical cycle duration, drastically shortening the time allocated for complete heat release within the combustion chamber [18]. Under these high-frequency conditions, the vapor output from the fuel reservoir fails to keep pace with the rapid combustion cycle, thereby limiting peak performance gains at medium-to-high engine speeds.

In this regime, the introduction of HCS becomes critical. Catalytic cracking converts fuel vapor into gaseous hydrogen (H_2), a constituent possessing a laminar flame speed (LFS) substantially higher than that of conventional hydrocarbons. Injecting H_2 into the intake charge acts as a chemical kinetic accelerator, effectively boosting the overall turbulent flame propagation rate [4]. This elevated LFS compensates for high RPM combustion phase lag, ensuring that cumulative heat release is concentrated near the optimal early crank angle to produce higher cylinder gas pressures that drive the piston.

The exhaust emission test results provide strong empirical validation of the combustion acceleration mechanism caused by a closed hydrocarbon crack system. A significant decrease in carbon monoxide (CO) and hydrocarbon (HC) levels, accompanied by an increase in carbon dioxide (CO_2) concentration, is a standard indicator of increased completeness of combustion. CO and HC gases are byproducts of fuel-rich conditions, where the fuel is not completely oxidized to CO_2 and H_2O [19]. In addition, the optimal performance of the HCS system is highly dependent on the catalyst operating temperature because the catalytic cracking process is an endothermic and thermo-catalytic reaction.

The implementation of nickel wire and zeolite media demonstrates significant performance improvements due to their superior thermal stability. Nickel retains structural and functional integrity across extreme operational temperatures, ranging from 400°C [10]up to 1000°C [11]. Metallurgically, nickel's catalytic action is driven by its active nickel (Ni) and chromium (Cr) content, where nickel serves as the primary active site for hydrogenation and hydrocarbon cracking [20]. Concurrently, zeolite functions effectively as a cracking catalyst owing to the presence of Brønsted and Lewis acid sites within its aluminosilicate framework [21]. As gasoline vapor traverses the microscopic pores of thermal exhaust-activated zeolite, these acidic sites promote proton transfer or electron abstraction from hydrocarbon molecules.

Conversely, steel and activated carbon prove considerably less effective as HCS catalyst media. Steel exhibits low mechanical porosity and high density its thermally oxidized surface forms a thin iron oxide layer that reacts detrimentally with hydrocarbon vapors. Additionally, elemental iron (Fe) promotes excessive coking (carbon deposit buildup). Over-accumulation of coke severely degrades the material's capacity to cleave long-chain hydrocarbons into hydrogen (H) and carbon (C) radicals [22]. On the other hand, while activated carbon possesses high surface area and porosity, its predominantly amorphous carbon structure causes excessive adsorption rather than catalytic cracking , thereby impairing engine responsiveness and emission performance [14].

The findings regarding nickel, zeolite, steel, and activated carbon align closely with established literature. Studies on dual-pipe HCS architectures demonstrate power increases up to 57.2% at 4,500 RPM [8]. Other comparative evaluations confirm that HCS effectively mitigates CO and HC emissions beyond 5,500 RPM— achieving reductions of 15% for CO and 11% for HC at 5,500 RPM, alongside a 3.40% torque enhancement and overall reductions of 28.12% (CO) and 54.35% (HC), despite a 12.48% increase in CO_2 [9]. Steel media similarly elevates H_2 and CO_2 production [23]. whereas a 70:30 activated carbon formulation depresses engine output while reducing unburnt emissions [24].

4 Conclusion

Based on the results of tests conducted on a Beat Esp FI 110cc motorcycle engine, the use of a catalyst containing steel, activated carbon, zeolite, and nickelin offers several advantages and disadvantages in terms of engine performance and exhaust emissions. The use of steel and activated carbon media can reduce harmful gases in exhaust emissions. However, this can reduce power and not increase torque. Therefore, it is not recommended as a catalyst filling medium for HCS. The use of Zeolite media as a catalyst-filling medium for the HCS system can increase maximum torque by 5.61% and maximum power by 1.91%. In addition to increasing torque and power, using Zeolite media as a catalyst filling medium in the HCS system can reduce HC gas by 9.48%, CO gas by 10%, and increase CO_2 gas by 1.4%. The use of nickelin media as a catalyst-filling medium for the HCS system can increase maximum torque by 4.67% and maximum power by 0.19%. In addition to increasing torque and power, the use of nickelin media as a catalyst filling medium for the HCS system can reduce HC gas by 24.57%, CO gas by 10.1%, and increase CO_2 gas by 4.17%. The use of nickelin and zeolite as catalysts in the Hydrocarbon Crack System demonstrates that these two media reduce harmful combustion gases. In addition to reducing harmful gases, these two media also increase maximum performance and reduce harmful gases in vehicle exhaust emissions. These results indicate that the use of steel, activated carbon, zeolite, and nickelin media offers alternatives for use as HCS system feed media, especially if the goal is to reduce exhaust emissions and improve engine combustion. Further research can focus on variations in the fuels used as hydrocarbon cracking materials and on the durability of the catalyst media across these variations. The actual effectiveness of the Hydrocarbon Crack System is also influenced by the readiness of facilities and the availability of readily accessible raw materials.

Supplementary Information

Experimental testing was conducted on a 110cc single-cylinder gasoline engine with electronic fuel injection without mechanical modifications. A Hydrocarbon Crack System (HCS) was installed passively, utilizing exhaust gas heat as the energy source for the catalytic cracking process. Four types of catalyst materials were used: steel, activated carbon, natural zeolite, and nickelin, selected based on their thermal stability and commercial availability. The geometric configuration and catalyst mass were kept constant to ensure fair comparisons of material performance. Engine performance was evaluated using a dynamometer to obtain torque and power data, while exhaust emissions (CO, HC, and CO_2) were measured using a calibrated gas analyzer. The equipment was calibrated before each test session according to manufacturer procedures. Measurements were conducted at various engine speeds, from low to high, and each condition was tested repeatedly to ensure consistent data. Reported values are averages of stable measurements.

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