A SIMULATION STUDY ON COMBUSTION CHARACTERISTICS OF A SPARK IGNITION ENGINE WITH DIFFERENT FUELS: GASOLINE, LPG, CNG, AND BIOGAS

NGHIÊN CỨU MÔ PHỎNG DIỄN BIẾN QUÁ TRÌNH CHÁY ĐỘNG CƠ ĐÁNH LỬA CƯỠNG BỨC KHI SỬ DỤNG NHIÊN LIỆU XĂNG, LPG, CNG VÀ BIOGAS

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ABSTRACT

This paper presents a simulation investigation of the combustion characteristics, performance, and emission of a spark ignition engine fueled with gasoline, liquified petroleum gas (LPG), compressed natural gas (CNG), and biogas. The simulation was conducted on the advanced software AVL Boost. The engine model was customed with different fuels in the simulation, but the air excess ratio (λ) was kept the same at 1.0. The difference in fuel properties contributed to a later combustion process for LPG, CNG, and biogas-fueled engines. The peak in-cylinder pressure was 77.7; 62.9; 68.9 and 32.2bar for gasoline, LPG, CNG, and biogas. The study's results indicated that the test engine's brake power decreased by up to 22.63; 17.22; and 39.10% on average for LPG, CNG, and biogas. However, the brake-specific energy consumption (BSEC) increased by 5.50 and 8.12% when fueled by LPG and CNG; and reduced by 27.4% for the bioag-fueled engine. Nevertheless, the exhaust emissions of the test engine that is powered by gaseous fuels significantly decreased. NO_x emissions decrease by 45.04; 56.75 and 66.75% on average for LPG, CNG, and biogas fuel. The average CO level of the engine when fueling with LPG, CNG, and biogas was reduced by 91.44; 90.51 and 93.01%. The HC emission of the engine that LPG and CNG powered is considerably lower than that of the original engine, in turn, 73.72% and 69.29% on average, while a reduction of 39.22% was observed for biogas-fueled engines on average.

Keywords: *LPG, CNG, biogas, gasoline.*

TÓM TẮT

Bài báo trình bày kết quả nghiên cứu mô phỏng quá trình cháy và tính năng kinh tế, kỹ thuật của động cơ đánh lửa cưỡng bức sử dụng nhiên liệu xăng, khí hóa lỏng LPG, khí thiên nhiên nén CNG và khí sinh học biogas. Quá trình nghiên cứu thực hiện trên công cụ mô phỏng AVL Boost. Động cơ được mô phỏng ở chế độ toàn tải sử dụng các nhiên liệu khác nhau với tỷ lệ hòa trộn được duy trì ở hệ số dư lượng không khí bằng 1,0. Kết quả cho thấy, sự khác biệt về tính chất của nhiên liệu làm quá trình cháy có xu hướng muộn hơn khi sử dụng LPG, CNG và biogas so với xăng. Áp suất cực đại bên trong xylanh lần lượt đạt 77,7; 62,9; 68,9 và 32,2bar đối với xăng, LPG, CNG và biogas. Công suất có ích của động cơ ở đặc tính ngoài giảm trung bình 22,63; 17,22 và 39,10% khi động cơ sử dụng LPG, CNG và biogas. Suất tiêu hao năng lượng BSEC có xu hướng tăng trung bình 5,5% và 8,12% khi sử dụng LPG và CNG. Tuy nhiên đối với trường hợp sử dụng biogas, BSEC lại có xu hướng giảm 27,4% so với trường hợp sử dụng nhiên liệu xăng. Các thành phần phát thải của động cơ có xu hướng giảm khi sử dụng nhiên liệu khí so với nhiên liệu xăng truyền thống. Phát thải NO_x giảm 45,04%, 56,75% và 66,75%; CO giảm 91,44; 90,51 và 93,01%; HC giảm 73,72; 69,29 và 39,22% khi sử dụng LPG, CNG và biogas.

Từ khóa: *LPG, CNG, khí sinh học, nhiên liệu xăng.*

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1. INTRODUCTION

Numerous studies show that developing nations' top priority is reducing air pollution from motorized transportation. Researchers have increasingly focused on replacing fossil fuels like petrol and diesel oil with other energy sources. Alternative fuels have been tested in new and old automobiles in Vietnam. Biodiesel [1], liquefied petroleum gas [2], natural gas (NG) [3], and biogas [4] have advanced in the country due to significant research on their use in vehicles.

Alternative fuels for internal combustion engines, such as NG, with its main component of CH_4, may replace traditional energy sources. These gaseous fuels may minimize diesel engine NO_x, soot, and greenhouse gas emissions [5]. Since CH_4 has a higher H/C ratio than gasoline [6], CO and CO_2 pollutants are minimized. Biogas improves engine combustion due to uniform air quality. This may improve combustion and lower HC emissions. Gas engines produce less HC than petrol engines due to limited fuel absorption/desorption from lubricating oil and cylinder walls, especially in cold starts [7]. Besides, LPG (Liquefied Petroleum Gas), which consists of butane (C_4H_{10}) and propane (C_3H_8) has been used as a fuel or duel fuel in engines. P.R. Chitragar et al. conducted an experimental investigation to investigate the combustion and emission of a 4-stroke gasoline engine that operates on LPG. It was discovered that the toxic emissions of CO, HC, and NO_x were reduced in LPG at stationary compared to gasoline [8]. Gaseous fuel can work without knocking due to its wide combustion limit and high RON. Hosmath observed that CH_4's higher RON index than petrol allows the engine to run at a higher compression ratio without detonation and enhance thermal efficiency. Biogas is also used as fuel in both S.I. engines and dual fuel in diesel engines. Biogas contains almost CH_4 (around 65% and CO_2 (around 33%) and other gas). A high RON index and slow combustion rate prolong combustion and lower thermal efficiency of a biogas-fueled engine [9].

Researchers found that natural gas-fueled engines converted from petrol engines function badly, notwithstanding emission reduction. Adding natural gas reduces charged air at the end of the intake stroke, lowering engine power. Yontar & Doğu (2018) found that using pure CH_4 fuel in dual-fuel CNG-gasoline spark ignition (S.I) engines reduced volumetric efficiency by 10%, resulting in inferior engine performance compared to petrol engines [10]. Even with improved ignition timing, mixing CH_4 with external gasoline lowered brake mean effective pressure by 16% [11]. Due to its high CO_2 content, biogas fuel has a lower heating value of 23,400kJ/m^3 [9], reducing engine power.

A simulation study was done to determine the affected engine performance and emissions of an S.I. engine fueled with different kinds of fuels, including conventional gasoline, CNG, LPG, and biogas (65% CH_4 and 35% CO_2). Advanced modeling software AVL-Boost evaluates in-cylinder pressure and temperature, as well as the rate of heat release (RHR) of the engine with fuels.

2. MATERIAL AND METHOD

2.1. Studying procedure

The engine was selected and then converted to run on either gasoline or gas fuel. In addition, a water electrolysis distillation was equipped to supply HHO to the test engine.

2.2. Fuel and engine specification

This study simulated a 4-cylinder, inline, multi-port injection engine. The first fuel was conventional gasoline. Table 1 lists the test engine's primary parameters. Table 2 presents the main characteristics of fuels obtained from the literature.

Table 1. The main parameters of the test engine

Parameters	Symbol	Value
Branch and model (-)	1NZ-FE	-
Bore x Stroke (mm)	SxD	84.7x75
Cylinder (-)	I	4
Max power output (kW) at 6000rpm	Ne	80
Max torque output (Nm) at 4200rpm	Me max	140
Minimum fuel consumption (g/kWh)	ge	220
Compression ratio (-)	ε	10.5:1

Table 2. The main characteristics of fuels [12-14]

Characteristics	Gasoline	LPG	CNG	Biogas
Composition	$C_{85}H_{15}$	50% C_3H_8 and 50%C_4H_{10}	95% CH_4 and other impurified components	65% CH_4, 34% CO_2, and other impurified components
Octane number	92.4	106	120	130
Latent heat of vaporization (kJ/kg)	270	795	508	244
Density (kg/m^3)	730	550		1.21

LHV (MJ/kg)	44	46	50	23,600
Combustion rate (m/s)	0.43	0.40	0.38	0.25
Combustion temperature (K)	2266	2240	2227	
H/C Ratio	1/5.7	1/2.0	1/3	-
A/F Ratio	14.7	15.6	17.0	6.05
Physical State	Liquid	Pressurized Liquid	Compressed gas	Gas

2.3. Model development

The use of AVL Boost commercial software created the simulation model, as shown in Fig. 1. Model-building includes model construction, governing equation selection, and initialization data. Engine pressure cycles are estimated using the first thermodynamic rule. This problem requires a combustion model, wall heat transfer model, and gas characteristics as a function of pressure, temperature, and mixture composition [15].

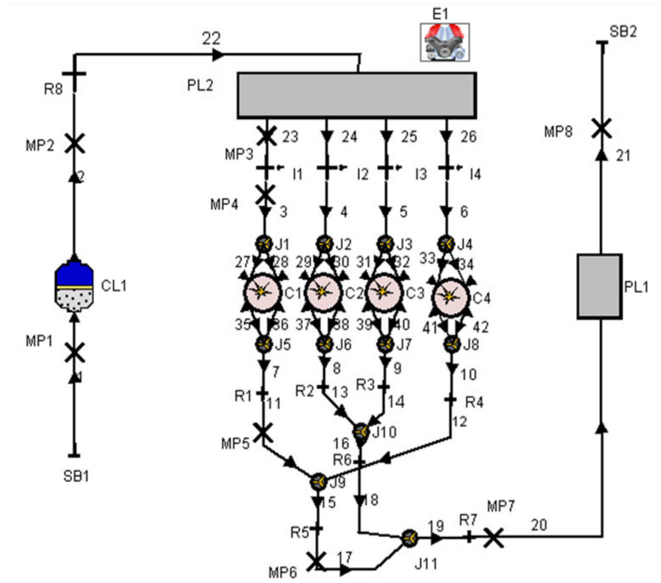

Figure 1. Simulation model of the 1NZFE engine

SB: System boundary; CL: Air cleaner; I: Injectors; C: Cylinder; PF: Plenum; MP: Measurement points; R: Restrictor; J: Conjuntions

2.4. Simulation procedure

The developed model first ran a fully open throttle with speeds ranging from 1500 to 4500rpm at 500rpm intervals. The simulated results of brake power and fuel consumption of an engine fueled with gasoline were used to validate the developed model. Then, the developed model was used to simulate another kind of fuel. In the simulation process, the air excess ratio was maintained at 1.0 for any kind of fuel.

3. RESULTS AND DISCUSSION

3.1. Model validation

Fig. 2a shows the variation of brake mean effective pressure (BMEP) as a function of simulated cycles at a constant speed of 4200rpm and fully opened throttle with conventional gasoline fuel. Over the initial cycles before coverage at simulation cycle 60, BMEP fluctuates by less than 0.01%. Fig. 2b validates the full-load model by comparing actual and simulated data. The output power (N_e), torque (M_e), and brake-specific fuel consumption (BSFC) modeling data match the actual. The simulated N_e and BSFC curves deviated by 2.23% and 3.41% on average from experimental values, confirming that the experiment and simulation agree well.

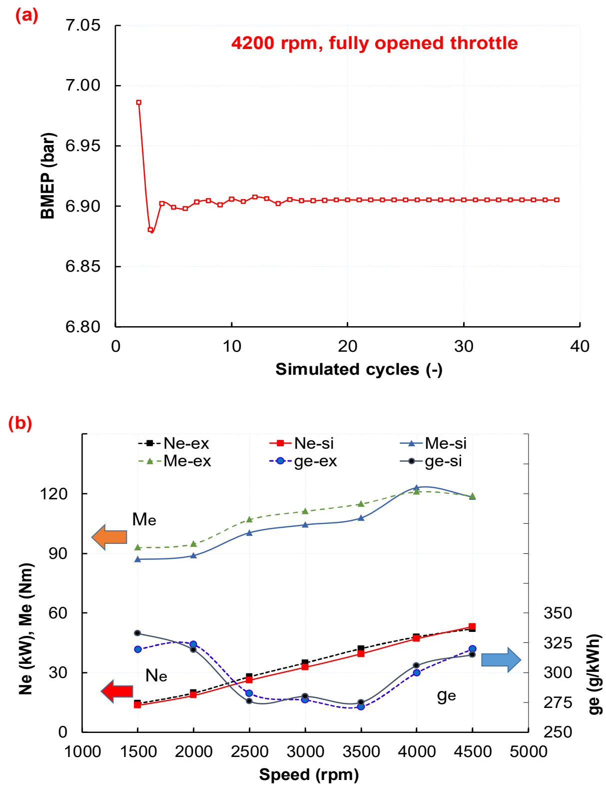

Figure 2. Comparison of engine performance obtained from simulation and vendor

3.2. In-cylinder pressure

For gasoline and gaseous fuel simulations, the lambda ratio was kept constant at 1.0, and the ignition time changed to maximize brake torque (MBT). Fig. 3 compares in-cylinder pressure profiles at maximum power and 4200rpm. Due to its higher RON, lower heating value, and flame speed of gaseous fuel, gas-fueled engines have lower peak in-cylinder pressure than the original gasoline engine. The peak pressure was 77.7bar at a crank angle (CA) of 370, 62.9 bar at CA of 372, 68.9bar at CA of 372, and 32.2bar at CA of 374 for gasoline, LPG, CNG, and biogas.

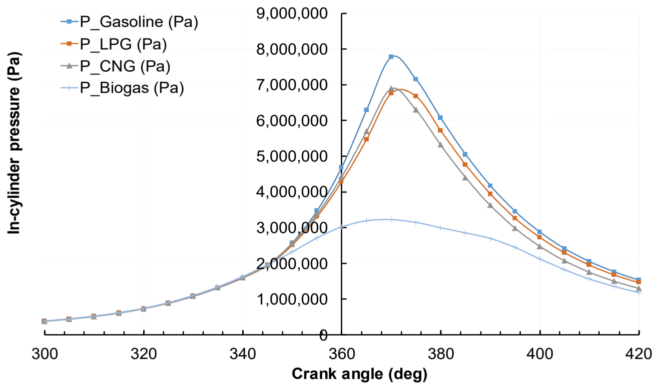

Figure 3. Simulation comparison of in-cylinder pressure with different fuels

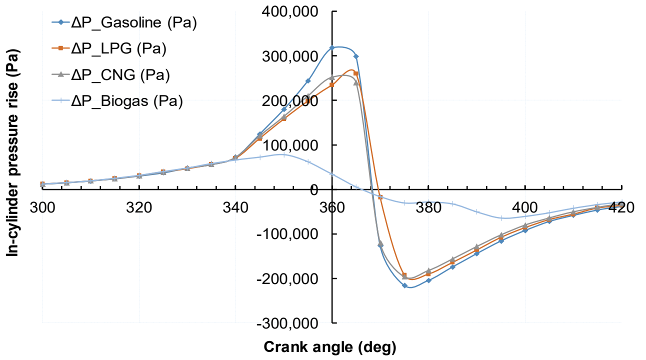

Figure 4. Simulation comparison of pressure rise with different fuels

AVL Boost predicts pressure rise as a function of crank angle based on heat release. Conventional gasoline fuel increases engine pressure by 2.98bar/deg, while peak pressure increases it by 2.67bar/deg, 2.45bar/deg, and 0.78bar/deg for LPG, CNG, and biogas.

3.3. In-cylinder temperature

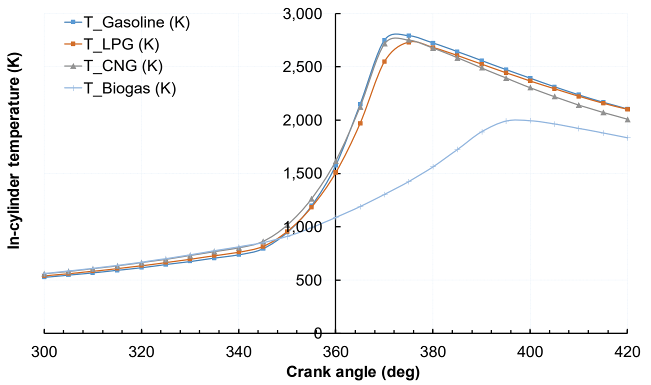

Figure 5. Simulation comparison of in-cylinder temperature with different fuels

As illustrated in Fig. 5, the combustion process is inclined to migrate to the right, indicating that it is more delayed when the engine is operated with gaseous fuel than a conventional engine, especially for biogas-fueled engines. The peak temperature of the original gasoline was 2791K at a CA of 373, while for LPG, CNG, and biogas engines, peak temperatures were approximately 2752K at CA 375, 2788K at CA 373, and 1994K at CA 400. This suggests that the biogas engine's expansion stroke was substantially delayed, resulting in an increase in heat loss through the cylinder wall.

3.4. Combustion characteristics

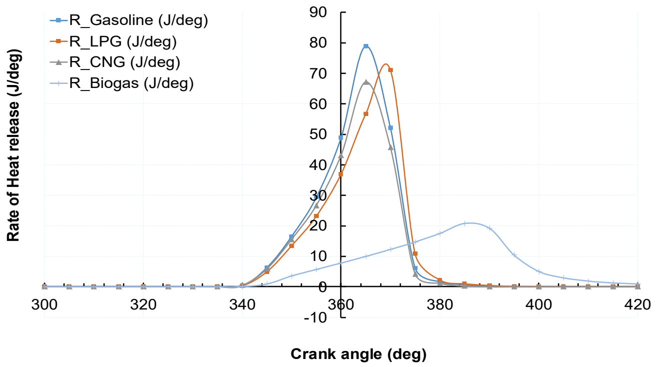

Figure 6. Simulation comparison of RHR with different fuels

For maximum torque condition, Fig. 6 compares combustion parameters RHR in the cylinders for different fuels. It is clear that the use of gaseous fuel results in a longer combustion process. The RHR patterns differ dramatically around the top dead center. RHR peaks at 78.8J/deg at CA 366, 72.1J/deg at CA 368, 67.1J/deg at CA 365, and 20.9J/deg at CA 386 for gasoline, LPG, CNG, and biogas engines.

3.5. Engine brake power and energy consumption

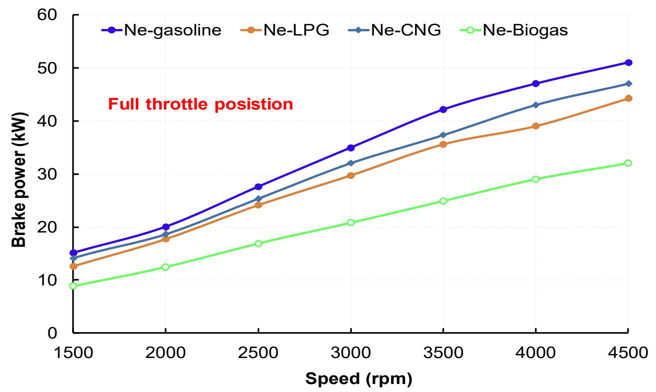

Figure 7. Simulation comparison of brake power with different fuels

The experimental comparison of the engine performance curves as a function of the engine speeds when the engine is operating at maximum load on either gasoline or gaseous fuels is illustrated in Fig. 7. The brake power of the test engine decreased by an average of 22.63%, 17.22%, and 39.10% when LPG, CNG, and biogas were used. This is a result of the lower heating value and reduction of the intake mixture caused by gas in the intake manifold. Moreover, as discussed above, the engine efficiency may be reduced because of an extended expansion stroke in gaseous-fueled engines that contributes to high heat loss through the cylinder wall.

This study employs brake-specific energy consumption (BSEC) instead of BSFC since energy input differs. The BSEC is calculated using the following equation (1).

$$\mathrm{BSEC} = \frac{\mathrm{m} * \mathrm{LHV}}{\mathrm{Ne}} = \mathrm{BSFC} * \mathrm{LHV} \qquad (1)$$

Where: m is the mass flow of fuel (kg/h), LHV is the lower heating value of fuel, and Ne is the brake power (kW).

Compared to gasoline, the average specific energy consumption (BSEC) of the test engine operating on LPG and CNG increased by 5.50% and 8.12%, as illustrated in Fig. 8. However, for biogas-fueled engines, the BSEC was reduced by 27.4% despite a remarkable brake power degradation.

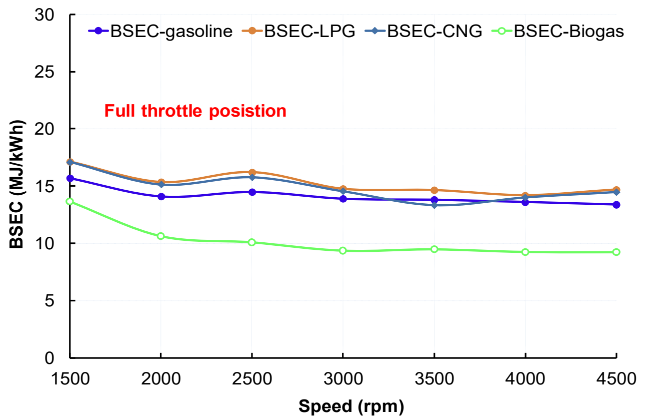

Figure 8. Simulation comparison of BSEC with different fuels

3.6. Engine emission

CO, NO_x and HC are among the pollutants that emanate from S.I. engines. The used fuel is not burned completely, resulting in the formation of CO emissions. NO_x, are the outcome of the reactions between nitrogen and oxygen atoms in high-pressure and high-temperature environments. HC emissions are the result of incomplete fuel combustion, unburned hydrocarbons from crevices, and the absorption and desorption of fuel by lubricating oil coatings and camshaft overlap duration. Fig. 9 shows the comparison of emissions of engines fueled with different fuels.

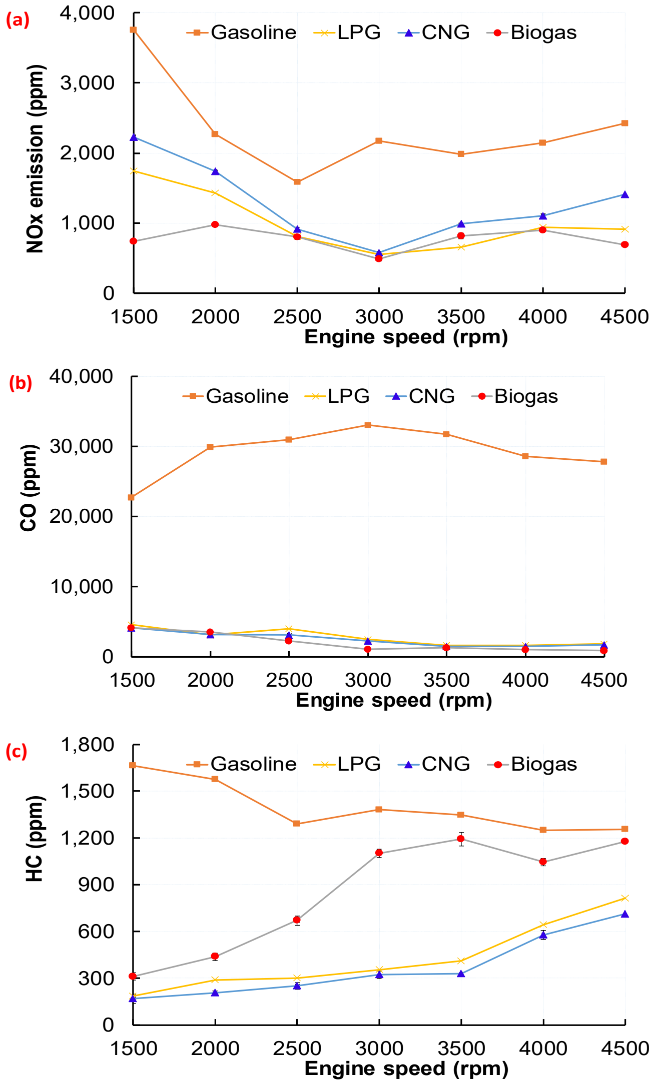

Figure 9. Simulation comparison of emissions with different fuels

The simulation was conducted at full load conditions as the throttle was in the fully opened position, and the air excess ratio was at the stoichiometric condition of 1.0 for all fuels. As shown in Fig. 9a, the formation of NO_x is contingent upon the combustion temperature, as evidenced by numerous studies that reported a significant reduction of approximately 45.04%, 56.75%, and 66.75% on average for LPG, CNG, and biogas fuel. This finding is consistent with Yujun's conclusion [16]. The most significant distinction between gaseous fuel and petroleum is the lower carbon content, which contributes to a remarkable CO level drop. The average CO level of the engine when fueling with LPG, CNG, and biogas was reduced by 91.44%, 90.51%, and 93.01%. The HC emission of the engine that is powered by LPG and CNG is considerably lower than that of the original engine, in turn 73.72% and 69.29% on average. Meanwhile, the HC level is reduced by 39.22% for biogas-fueled engines on average. The reduction in HC emissions is attributed to the improved formulation of the mixture when gaseous fuel is introduced into the intake manifold. Furthermore, the gaseous use reduced the formation of HC emissions from the mechanism of fuel absorption and desorption by lubricating oil coatings, as noted in the study conducted by Kato [17].

4. CONCLUSION

This study investigates the combustion, performance characteristics, and exhaust emissions of an S.I. engine powered by conventional petroleum and gaseous fuels, including LPG, CNG, and biogas. The study results indicate that using alternative gaseous fuel effectively reduces HC, CO, and NO_x emissions. This solution applies to the S.I. engines presently in use in Vietnam, as they emit a significant amount of pollutants. Nevertheless, the test engine's energy consumption and performance experienced a significant decline for LPG and CNG-fueled engines compared to the original gasoline-fueled engine. Therefore, future research should focus on resolving this issue in order to implement this solution on a global scale.

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THÔNG TIN TÁC GIẢ

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