A STUDY ON THE IMPACT OF IGNITION TIMING ON THE PERFORMANCE AND COMBUSTION CHARACTERISTICS OF HYDROGEN-FUELED ENGINES AT VARIOUS ENGINE SPEEDS

Pham Van Trong[1], **Nguyen Duy Vinh**[1,*],
Dinh Xuan Thanh[2]

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ABSTRACT

This study examines the impact of ignition timing on the performance, in-cylinder thermodynamic characteristics, and NO_x emissions of a hydrogen-fueled spark-ignition engine, utilizing AVL-BOOST simulation software. A single-cylinder engine model was developed with fixed geometric and operating parameters, while the ignition timing was varied to account for the fast-burning characteristics of hydrogen. Simulations were conducted at engine speeds of 2,500rpm; 3,000rpm, and 3,500rpm under stoichiometric conditions. The results indicate that advancing the ignition timing increases brake power up to an optimal range of approximately $(8\div10)^0$ BTDC, at which the minimum brake specific fuel consumption is also observed, reflecting improved combustion phasing and fuel conversion efficiency. Further ignition advance leads to a deterioration in performance due to increased negative work and heat losses. The maximum in-cylinder pressure and temperature increase with advancing ignition timing and engine speed, consistent with earlier combustion phasing and enhanced heat release. NO_x emissions exhibit a strong dependence on ignition timing and engine speed, reaching peak values near the operating conditions corresponding to the highest in-cylinder pressure and temperature, confirming the dominant role of thermal NO_x formation. Overall, the predicted trends are physically consistent with the combustion characteristics of hydrogen-fueled spark-ignition engines and provide useful insights for ignition timing optimization.

Keywords: *Hydrogen engine, Ignition timing, Emission reduction.*

[1]Phenikaa School of Engineering, Phenikaa University, Vietnam
[2]Hanoi University of Industry, Vietnam
[*]Email: vinh.nguyenduy@phenikaa-uni.edu.vn

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NOMENCLATURE

ATDC	After top dead center
A/F	Air-fuel ratio
BSFC	Brake-specific fuel consumption
BTDC	Before bottom dead center
CR	Compression ratio
CO	Cacbon oxit
CO_2	Cacbon dioxit
HC	Hydrocacbon
H_2	Hydrogen
HRR	Heat release rate
PM	Particulate matter
P_{max}	Pressure maximum
PPM/C	Parts per million
NO_x	Nitrogen oxit
N_e	Effective power
SI	Spark ignition
SB	System boundary
T_{max}	Temperature maximum

1. INTRODUCTION

Today, minimizing environmental pollution caused by the use of fossil fuels in internal combustion engines is an urgent need. The Vietnamese government has shown a strong commitment and determination to achieve the goal of net-zero emissions by 2050. To realize this commitment, there have been policies on state management of gasoline and diesel fuel use in cars and motorbikes, and increased use of electricity and renewable energy. The use of green energy and renewable energy is being researched and realized. In particular, hydrogen stands out among the fuel sources used for engines with almost zero CO_x and HC emissions. Hydrogen contains no carbon, so its combustion process does not produce CO_2, CO or PM, which significantly reduces greenhouse gas emissions [1]. Therefore, research, design, and improvement of conventional gasoline and diesel fuel engines are increasingly receiving attention. Among alternative fuels, hydrogen is a renewable fuel source that can be produced from an inexhaustible source of water, making it a potential fuel for internal combustion engines. Compared with other alternative fuels, hydrogen has outstanding characteristics such as: Hydrogen can diffuse in air faster than other gases, the diffusion coefficient of hydrogen is 0.61cm^2/s; The flammability of hydrogen with air is much larger than that of methane and other fuels from (4 ÷ 75)%; Within the flammability limit, hydrogen can ignite with only a small energy of 0.02mJ; Hydrogen has a flame spread rate of 1.85m/s, much higher than other fuels [2]. The hydrogen fuel delivery system can be categorized into three main types: carbureted, port-injected, and direct-injected. With the port fuel injection (PFI) system, hydrogen is injected directly into the intake manifold, showing a structural improvement compared to indirect fuel injection engines, which are not much structurally different. Hydrogen can be injected into the intake manifold by continuous injection or timed injection. Constant injection of hydrogen into the intake manifold will cause unwanted combustion, less flexibility, and make it more difficult to control [3].

The intermittent injection method on the intake manifold shows outstanding advantages that can be exploited with this type of engine. Numerous studies worldwide have been conducted on indirect injection hydrogen engines utilizing the intake manifold, yielding promising results. Dhyani et al. studied the effects of knocking parameters such as spark timing, injection timing, and equivalence ratio on the multi-cylinder hydrogen-fueled SI engine at 1500rpm, it was observed that knock and backfire were related to each other at high equivalence ratios. The spark and injection timings of 12^0 BTDC and 40^0 ATDC, respectively, inhibited backfire [4]. Szwaja et al. studied and systematically compared knock-in hydrogen and gasoline engines, concluding that techniques developed for gasoline engines, with some adjustments, apply to hydrogen SI engines [5]. Additionally, Rrustemi D-N et al. used the maximum amplitude of pressure oscillation to define the knock intensity, and the result revealed that increasing CR increased the in-cylinder pressure and heat release rate (HRR), leading to earlier knock onset [6]. Yanfei Qiang et al. studied the effect of variable valve timing and spark timing on the performance of the hydrogen-fueled engine with passive pre-chamber ignition under partial load conditions, showing that delaying the SI could reduce NO_x emissions [7]. Yasin Karagz et al. studied the investigation of hydrogen usage on combustion characteristics and emissions of a spark ignition engine, showing that NO_x emissions were obtained when using hydrogen as fuel [8].

In Vietnam, Hoang Dinh Long studied and evaluated the performance of gasoline engines when switching to hydrogen fuel. The results show that at the same speed and pressure mode (shown through the average indicated pressure) decreased by about 11%, but the thermal efficiency of the engine was on average, the thermal efficiency of the hydrogen engine was 3,9 % higher than the thermal efficiency of the gasoline engine in terms of efficiency value and the relative increase was (8.8 ÷ 11.5)% of the original engine efficiency value [9].

In this research, the authors focused on studying the model of a small engine using hydrogen fuel on AVL-BOOST software. From there, they investigated the influence of technical parameters, such as ignition timing with hydrogen fuel, on the characteristics of hydrogen-fueled engines at different speeds when studying hydrogen engines injected into the intake manifold.

2. SIMULATION ENGINE MODEL

2.1. Theoretical basis of modeling

The calculation of the high-pressure cycle of an internal combustion engine is based on the first law of thermodynamics. Expressed by two formulas Eq. (1) and Eq. (2) [10].

$$\frac{d(m_c.u)}{d\alpha} = -p_C.\frac{dV}{d\alpha} + \frac{dQ_F}{d\alpha} - \sum\frac{dQ_W}{d\alpha} - h_{BB}.\frac{dm_{BB}}{d\alpha} \tag{1}$$

$$\frac{dm_c}{d\alpha} = \sum\frac{dm_i}{d\alpha} - \sum\frac{dm_e}{d\alpha} - \sum\frac{dm_{BB}}{d\alpha} + \sum\frac{dm_{ev}}{dt} \tag{2}$$

The process of converting energy in the cylinder depends on many factors, including the work of the piston, heat released by fuel combustion, heat loss and enthalpy flow caused by the blowing air. Eq. (1) applies to engines employing internal or external mixture preparation. Eq. (2) the combustion products mix uniformly with the cylinder charge, forming a homogeneous mixture. During this process, the air-fuel (A/F) ratio decreases progressively, starting from a high value at the beginning of combustion and stabilizing at a final value once combustion is complete. Based on these assumptions, Eq. (1) is modified accordingly to reflect the conditions of internal mixture preparation [10].

To solve this equation, it is necessary to combine the model of fuel mixing, combustion, heat transfer, and thermal state and medium composition. By establishing a relationship between pressure, temperature, and density, Eq. (3) can be solved for the in cylinder temperature using numerical methods such as the Runge-Kutta method.

$$\frac{\mathrm{d}T_c}{\mathrm{d}\alpha}=\frac{1}{m_c\cdot\left(\frac{\partial u}{\partial T}+\frac{\partial u}{\partial p}\cdot\frac{p_c}{T_c}\right)}\cdot\left[\begin{array}{l}\frac{\mathrm{d}Q_F}{\mathrm{d}\alpha}\cdot\left(1-\frac{u_c+\frac{\partial u}{\partial p}.p_c}{H_c}\right)-\frac{\mathrm{d}Q_W}{\mathrm{d}\alpha}\\ -\frac{\mathrm{d}m_{BB}}{\mathrm{d}\alpha}\cdot\left(h_{BB}-u_c-p_c\cdot\frac{\partial u}{\partial p}\right)\\ -m_c\cdot\frac{\partial u}{\partial\lambda}\frac{\partial\lambda}{\partial\alpha}-p_c\cdot\frac{\mathrm{d}V_c}{\mathrm{d}\alpha}\cdot\left(1-\frac{\partial u}{\partial p}\cdot\frac{m_c}{V_c}\right)\end{array}\right] \quad (3)$$

Once the in-cylinder temperature is determined, the corresponding cylinder pressure can be calculated using the ideal gas law or an appropriate gas equation of state. This approach accurately represents the thermodynamic behavior within the cylinder during the combustion process.

2.2. Hydrogen engine model

In this research, modelled a one-cylinder, four-strokes, naturally aspirated engine using AVL Boost software. The model was constructed based on the specifications outlined in Table 1, with simulation components placed within the working area on the screen. These components were then interconnected using pipes, as illustrated in Figure 1.

In this research, the authors built an engine model on AVL BOOST and used and hydrogen fuel. The combustion model chosen for setup is the AVL Vibe Two Zone [8] combustion model. However, because hydrogen exists in gas form and the combustion speed is much faster than gasoline. When setting combustion model, the author investigated the time of the hydrogen engine combustion process to be shorter than the combustion time of the gasoline engines [4, 8]. At the same time, the author simultaneously examined the change of ignition timing corresponding to each different type of fuel, from 18^0 BDCT to 6^0 BTDC. The parameters are set at SB1: pressure is 1 bar; temperature is 25°C; At the SB2: pressure is 1.1bar, temperature is 120°C. Corresponding to engine speeds of 2500, 3000, and 3500rpm, with an air surplus coefficient of 1, thereby evaluating the change in maximum temperature, maximum pressure in the cylinder, brake power, useful fuel consumption, and emission levels corresponding to each ignition timing on the same model.

Table 1. Engine specifications

No	Specifications	Value
1	Bore	6.8cm
2	Stroke	4.5cm
3	Cylinder capacity	163cm^3
4	Compression Ratio	8.5
5	Fuel	Hydrogen
6	Maximum power	4.0kW/ 4000rpm
7	Peak torque	10.3Nm/ 3600rpm

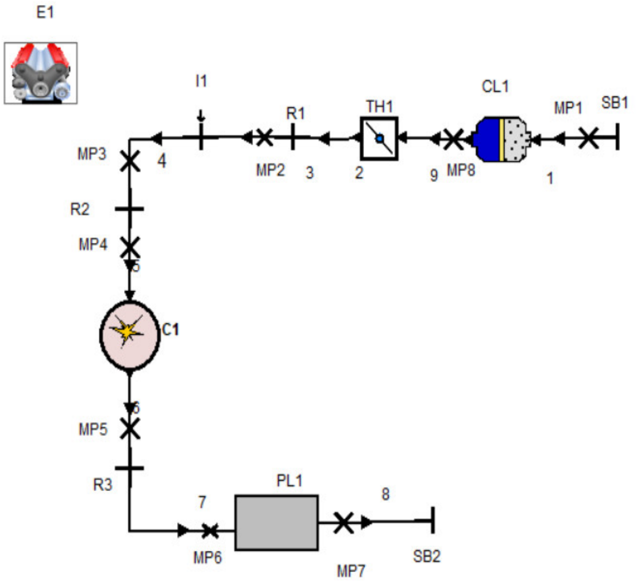

Figure 1. Hydrogen engine model in AVL-Boost software

2.3. Simulation model verification

The simulation model results show the logical fit and trend of a single-cylinder engine model using hydrogen fuel. These results can be referenced by research results [11]. However, research [11] is limited to the addition of hydrogen to the initial fuel. When using 100% hydrogen as fuel, the engine power decreases at a greater rate and there are no HC and CO emissions.

3. RESULT AND DISCUSSION

3.1. Effect of ignition timing on the brake power and brake-specific fuel consumption

Figure 2 illustrates that the simulation results indicate that the developed hydrogen-fueled spark-ignition engine model exhibits consistent and physically reasonable behavior over a wide range of ignition timings and engine speeds. For all operating speeds, the brake power increases when increases ignition timing , reaches a maximum at an optimal advance of approximately (8÷10) ⁰ BTDC, and subsequently decreases when the ignition timing is further advanced. This behavior is associated with improved combustion phasing, whereby the peak cylinder pressure occurs closer to top dead center.

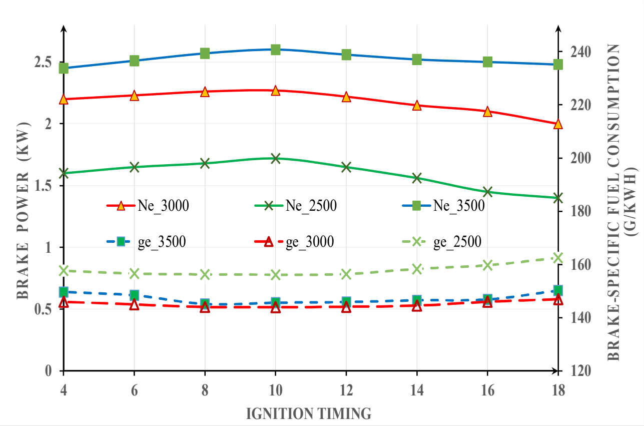

Figure 2. Effect of ignition timing on the brake power and brake-specific fuel consumption

The brake-specific fuel consumption exhibits a minimum near the same optimal ignition timing, indicating enhanced fuel conversion efficiency under these conditions. Retarded ignition results in incomplete utilization of the fuel energy, whereas excessively advanced ignition leads to increased negative work during the compression stroke and higher heat losses, thereby deteriorating fuel economy. As the engine speed increases from 2500 rpm to 3500 rpm, the model predicts a higher brake power accompanied by a slight increase in BSFC. This trend can be attributed to increased mechanical losses and reduced effective combustion duration at higher engine speeds.

3.2. Effect on the maximum pressure and temperature in the cylinder

In Figure 3, the results indicate that both the maximum in-cylinder pressure and temperature increase with advancing ignition timing at all investigated engine speeds. Higher engine speeds (3500rpm) consistently result in higher peak pressure and temperature compared to lower speeds, which can be attributed to enhanced in-cylinder turbulence and faster heat release. The monotonic increase of peak pressure and temperature with ignition advance reflects earlier combustion phasing and the high burning velocity of hydrogen. Overall, the predicted trends are physically reasonable and consistent with the combustion characteristics of hydrogen-fueled spark-ignition engines, indicating that the developed model adequately captures the effects of ignition timing and engine speed on in-cylinder thermodynamic conditions.

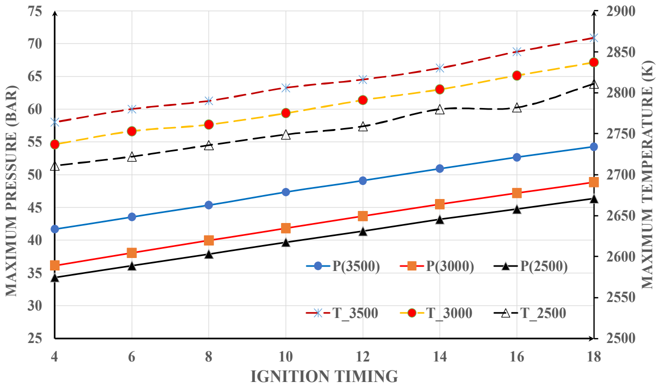

Figure 3. Effect of ignition timing on the max pressure and temperature in the cylinder

3.3. Effect of ignition timing on NO_x emission

In Figure 4, at all speeds, the results indicate that NO_x emissions increase with advancing ignition timing at all investigated engine speeds, reaching a maximum at approximately (8 ÷ 10)⁰ BTDC. Which corresponds to the ignition timing range where the maximum in-cylinder temperature (T_{max}) and pressure (P_{max}) are highest. Higher engine speeds consistently produce higher NO_x levels due to increased T_{max} and P_{max}, which promote thermal NO_x formation through temperature-dependent reaction mechanisms. At more advanced ignition timings, NO_x tends to decrease slightly or stabilize, despite further ignition advance, which can be attributed to changes in combustion phasing and reduced residence time at high temperatures. Overall, the predicted NO_x trends show a strong correlation with T_{max} and P_{max} and are consistent with the combustion characteristics of hydrogen-fueled spark-ignition engines

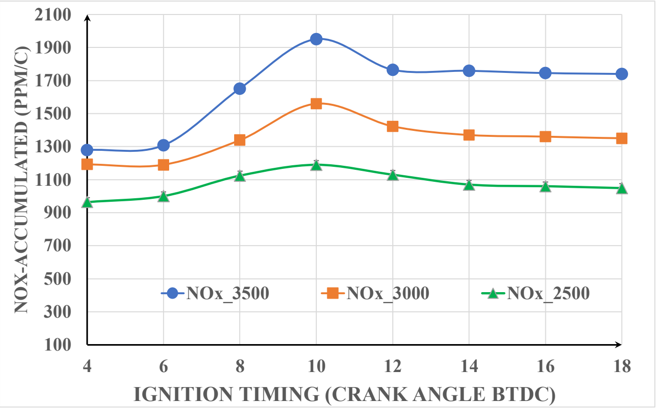

Figure 4. Effect of ignition timing on the NO_x emission

4. CONCLUSION

This study investigated the effects of ignition timing and engine speed on the performance, in-cylinder thermodynamic characteristics, and NO_x emissions of a hydrogen-fueled spark-ignition engine using a simulation model. The results show that brake power increases with advancing ignition timing up to an optimal range of approximately $(8 \div 10)^0$ BTDC for all investigated speeds, while the minimum brake specific fuel consumption is observed near the same ignition timing, indicating improved combustion phasing and fuel conversion efficiency. Advancing ignition timing and increasing engine speed led to higher maximum in-cylinder pressure and temperature, reflecting the fast-burning nature of hydrogen and enhanced in-cylinder turbulence at higher speeds. NO_x emissions increase with ignition advance and engine speed, reaching a maximum near the ignition timing corresponding to the highest pressure and temperature, confirming the dominant role of thermal NO_x formation. Overall, the predicted trends are physically consistent with the combustion characteristics of hydrogen-fueled spark-ignition engines, demonstrating that the proposed model is suitable for qualitative and parametric analysis of hydrogen engine performance and emissions.

REFERENCES

[1]. Jayashish Kumar Pandey, G.N. Kumar, "Effect of variable compression ratio and equivalence ratio on performance, combustion and emission of hydrogen port injection SI engine," *Energy,* 239, E, 122468, 2022. https://doi.org/10.1016/j.energy.2021.122468

[2]. Le Anh Tuan, Pham Huu Tuyen, Van Dinh Son Tho, *Alternative fuels for internal combustion engines.* Hanoi University of Science and Technology Publishing House, Page 145, 2017.

[3]. Karsten Wittek, Vitor Cogo, Geovane Prante, "Full load optimization of a hydrogen fuelled industrial engine," *International Journal of Hydrogen Energy*, 77, 230-243, 2024. https://doi.org/10.1016/j.ijhydene.2024.06.198.

[4]. Vipin Dhyani, K.A. Subramanian, "Experimental investigation on effects of knocking on backfire and its control in a hydrogen fueled spark ignition engine," *International Journal of Hydrogen Energy*, 43, 14, 7169-7178, 2018. https://doi.org/10.1016/j.ijhydene.2018.02.125.

[5]. S. Szwaja, K.R. Bhandary, J.D. Naber, "Comparisons of hydrogen and gasoline combustion knock in a spark ignition engine," *International Journal of Hydrogen Energy,* 32, 18, 5076-5087, 2007. https://doi.org/10.1016/j.ijhydene.2007.07.063.

[6]. D.N. Rrustemi, L.C. Ganippa, C.J. Axon, "Investigation of boost pressure and spark timing on combustion and NO emissions under lean mixture operation in hydrogen engines," *Fuel,* 353, 129192, 2023. https://doi.org/10.1016/j.fuel.2023.129192.

[7]. Yanfei Qiang, Changwei Ji, Shuofeng Wang, Gu Xin, Chen Hong, Zhe Wang, Jianpu Shen, "Study on the effect of variable valve timing and spark timing on the performance of the hydrogen-fueled engine with passive pre-chamber ignition under partial load conditions," *Energy Conversion and Management,* 302, 118104, 2024. https://doi.org/10.1016/j.enconman.2024.118104.

[8]. İlker Güler, Abdullah Kılıçaslan, Taha Küçük, Daniele Corsini, "Transient and altitude performance analysis of hydrogen fuelled internal combustion engines with different charging concepts," *International Journal of Hydrogen Energy,* 49, B, 1112-1122, 2024. https://doi.org/10.1016/j.ijhydene.2023.10.104

[9]. Hoang Dinh Long, "Research on evaluating the performance of automotive gasoline engines when switching to hydrogen fuel," *Hydraulic Engineering and Environment Science and Technology - Special issue (10/2019)- 12th Science and Technology Conference, Mechanical - Engineering club,* 2019.

[10]. Pham Van Trong, Nguyen Duy Vinh, Hoang Dinh Long, Pham Minh Thang, "A simulation study of the effect of ignition timing on the pressure and temperature profile of a 4-stroke gasoline engine," in *International Conference on Sustainability and Emerging Technologies for Smart Manufacturing* (SETSM 2025), *Proceedings in Technology Transfer*, 166-173. Springer, Singapore, 2025. https://doi.org/10.1007/978-981-95-1750-3_19.

[11]. Bui Van Ga, et al., *Ministry-level Science and Technology Project Report 2018, Research on the economic and technical performance and pollution emission levels of small-scale engines using biogas-hydrogen fuel mixtures*. Project code CTB2018-DNA.01.