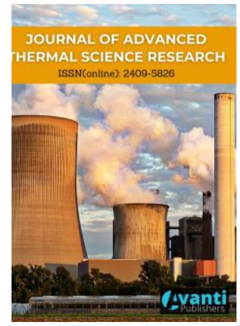
Publishers

Published by Avanti Publishers

Journal of Advanced Thermal Science Research

ISSN (online): 2409-5826



Combustion Performance of Hydrogen Direct Injection under Lean-burn Conditions for Power Generation

Meiqi Yu[1], Hongliang Luo[1,2,3,*], Chang Zhai[2], Yanzhao An[3] and Keiya Nishida[2]

[1]*School of Environmental and Chemical Engineering, Yanshan University, Qinhuangdao 066004, China*
[2]*Graduate School of Advanced Science and Engineering, Hiroshima University, Higashi-Hiroshima 7398527, Japan*
[3]*State Key Laboratory of Engines, Tianjin University, Tianjin 300072, China*

ARTICLE INFO

Article Type: Research Article

Keywords:
Spark ignition
Lean-burn combustion
Hydrogen direct injection
Combustion performance

Timeline:
Received: November 01, 2022
Accepted: December 15, 2022
Published: December 28, 2022

Citation: Yu M, Luo H, Zhai C, An Y, Nishida K. Combustion Performance of Hydrogen Direct Injection under Lean-burn Conditions for Power Generation. J Adv Therm Sci Res. 2022; 9: 84-94.

DOI: https://doi.org/10.15377/2409-5826.2022.09.7

ABSTRACT

This paper studies the combustion phenomenon of hydrogen (H_2) direct injection (DI) in a modified spark ignition (SI) engine. As we known, ignition timing strongly correlates with combustion performance, especially for power output and efficiency. Therefore, different ignition timing varying among -20, -15, -10, -5, 0, 5, 10, 15, and 20 deg top dead center (TDC) are tested in this research. Besides, different H_2 injection timings and injection pressures are also compared in this study. Moreover, as H_2 usually favors lean-burn combustion, λ at 3, 3.5, and 4 are tested to find the lean-burn limitation. In order to obtain the engine speed influences on power output, finally 1500, 2000, and 2500 revolutions per minute (rpm) are evaluated in this study. Finally, thermal brake efficiency (BTE) and power output are analyzed. Results showed that power output and efficiency increase with the delay of ignition timing from -20 to 5 deg TDC and then decrease with delaying timing from 5 to 20 deg TDC. However, injection timing has less effect on the H_2 combustion phenomenon. H_2 lean-burn limitation is found that when λ is larger than 3, the efficiency decreases sharply. Moreover, both power output and efficiency firstly increase then decrease with higher engine speed and 2000 rpm is the best option for this small engine. Finally, by evaluating the contribution index, ignition timing and engine speed should be optimized first to achieve higher efficiency.

*Corresponding Author
Email: arron2016@gmail.com
Tel: +(81) 08063419385.

1. Background

Climate change, energy security, and air pollution are key drivers of current research worldwide [1]. Much more efforts into new sustainable and renewable energy technologies should be conducted. Nowadays, reducing carbon emissions is a big issue in the world, not only for developed countries but also for developing countries [2, 3]. Therefore, to achieve the target of "carbon neutral" in the middle of the 21st century, many efforts should be made, including reducing the source of carbon production and absorption from emissions [4, 5]. In this study, as shown in Fig. (**1**), a regional system is designed to explore carbon recycling. In this system, animals can live and produce agricultural products.

Moreover, their excrements will be used to ferment gaseous fuels such as methane (CH_4), carbon dioxide (CO_2), and ammonia (NH_3) through hydrothermal pretreatment and high-temperature biogas fermentation. Then, these fuels can be applied for electric power generation. Besides, obtained through pyrolysis of NH_3, H_2 can be added for combustion as well, owing to the better performance of H_2 in lean-burn combustion. Finally, all the electric supplies in this system can be generated by themselves successfully, which is called the local self-circulating ecosystem in this study. Therefore, four parts can be involved in this project: biogas fermentation, hydrogen production, engine combustion for power output, and energy conversion.

Furthermore, the last one is the main work in our study. From our previous reports, biogas combustion with H_2 addition was widely analyzed under various conditions [6-8]. However, due to H_2 port fuel injection (PFI), BTE cannot increase significantly. Then, H_2 direct injection (DI) will be used here, and H_2-only combustion should be investigated to explore the H_2 lean-burn limit for this retrofit engine.

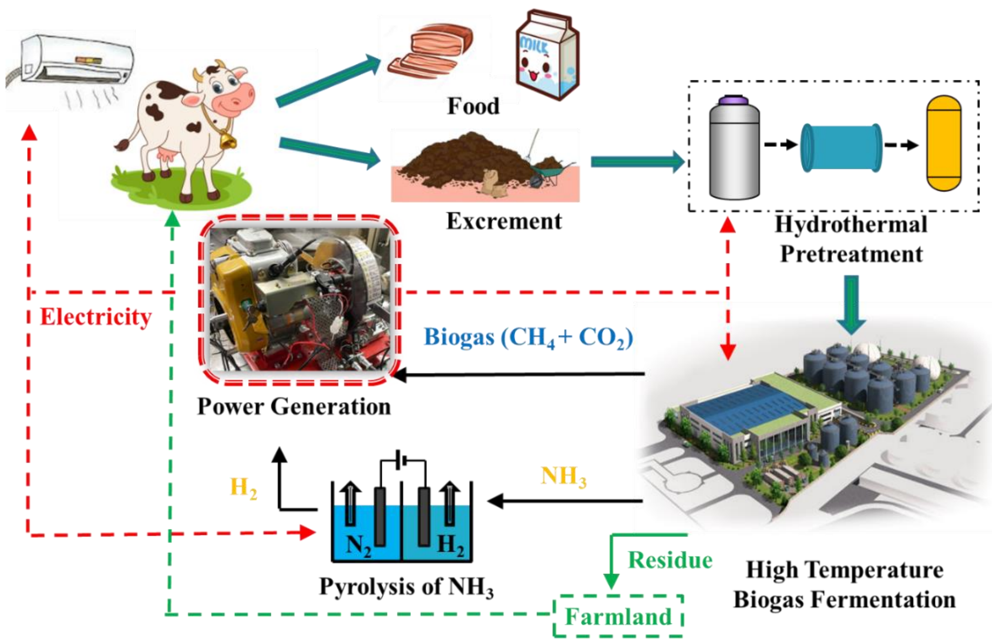


Figure 1: Schematic diagram of the regional energy system.

2. Introduction

Generally, H_2 is considered the ultimate fuel for internal combustion engines (ICEs) because of its beneficial combustion properties. More importantly, H_2 combustion enables mitigating pollutant emissions down to zero-impact levels because the wide hydrogen flammability limits allow the realization of lean burning [9]. However, H_2 injection in the intake manifold leads to power output loss and abnormal combustion [10, 11]. In contrast, the direct injection into the cylinder could avoid the above drawbacks with subsequent efficiency enhancement and emissions mitigation. Thus, in this study, H_2 (DI) is adopted by retrofitting a one-cylinder gasoline engine. Moreover, the main topic here is controlling different parameters to achieve higher efficiency and power output.

As the H_2 engine is an advanced engine with near-zero emissions and high efficiency [12], many scholars study it to improve its efficiency and decrease emissions. Yu *et al*. have studied the H_2 DI combustion engine [13-20]. They found that H_2 direct injection had the highest combustion temperature, the fastest combustion rate, and the highest efficiency in contrast to gasoline DI and port fuel injection (PFI) [13, 14]. Besides, it was reported that H_2 DI could reduce hydrocarbon (HC) and carbon monoxide (CO) emissions but increase NO_X emission [15], which is the main reason for our design and investigation on H_2 DI combustion. Furthermore, H_2 injection pressure and ignition time should be reconsidered because H_2 DI could form a stratified hydrogen distribution to enhance the stability of the ignition and reduce the coefficient of variation (COV), thus improving the engine combustion rate and efficiency [16, 17].

Moreover, H_2 DI can furtherly extend the lean-burn limit and achieve ultra-lean combustion [18-20], which should also be checked in this study. Recently, Fan *et al*. computationally studied the H_2 injection strategy on the combustion performance in a DI rotary engine fueled with natural gas/ hydrogen blends. The results showed that H_2 injection timing and angle could significantly change the flame propagation process by changing the fuel stratification pattern in the cylinder [21]. As a result, these parameters should also be reconsidered in our research here.

Furthermore, Fischer *et al*. modified a 3-cylinder turbocharged direct-injected gasoline engine to hydrogen operation. Results showed that hydrogen-fueled engines presented lower NO_x emissions and faster and more stable combustion than gasoline [22]. Then, Bao *et al*. conducted experiments for achieving near-zero nitrogen oxide (NO_x) emission at high power demand and high thermal efficiency in a 2L 4-cylinder turbocharged direct-injected engine. Results showed that higher injection pressure played an important role in obtaining high engine load at mid-high engine speed while maintaining low NO_x emission [23]. Moreover, many investigations were done on hydrogen stratification by Wang *et al*. and Huang *et al*. [24-27], which could favor the study in H_2 engine combustion. In addition to the above studies, recent papers reported a comprehensive review of H_2 in future internal combustion engines, highlighting the necessity of further contributions to future mobility [28, 29].

To the best of the author's knowledge, there are few studies on power generation for electricity. Besides, small engines for H_2 are limited until now. Therefore, the current work aims to investigate H_2 operating limits in a DI single-cylinder modified SI engine. At first, H_2 ignition and injection timing effects will be clarified. Then, the lean limit of H_2 combustion for high efficiency is tested. Afterward, H_2 injection pressure will be evaluated by engine performance with the consideration of safe usage. Finally, engine speed should be checked in the current status to obtain the highest brake thermal efficiency. The main objective is to understand H_2 DI combustion performance with various parameters, which also lays a significant foundation in the follow-up research for power generation. Furthermore, the most innovative in this paper is to seek the best condition for H_2 DI combustion by considering ignition timing, injection timing, injection pressure, λ, and Engine speed. Furthermore, through contribution index analysis, ignition timing and engine speed should be considered first to achieve higher efficiency.

3. Experimental Conditions and Setup

The specifications of the test engine are listed in Table **1**. The gas engine was modified from a Robin EH12-2DS gasoline engine with a displacement volume of 121 cc. The compression ratio (CR) of this engine was set at 8.5. The cylinder bore diameter is 60 mm, and the stroke is 43 mm, with connecting rod length of this engine being 110 mm. The 100% throttle opening was maintained in this study, also called the whole opening. Only H_2 was used as DI for combustion in this research. Generally, the engine runs for 30 minutes to warming-up before experiments at the beginning.

As shown in Fig. (**2**), H_2 was injected by a customized DI injector. A dynamometer coupled with this engine was applied to control the load and speed. A digital air/fuel ratio meter (LM-2) was used as the excess air ratio (λ) sensor to measure the λ value. One data acquisition system was utilized to collect λ, engine speed, H_2 flow rate, and torque. Then, parameters such as BTE and power output were calculated simultaneously in this system. More details about the calculation process can be found in our previous publication [6].

Table 1: Engine specifications.

Engine type	Robin EH12-2DS
Compression ratio	8.5
Displacement volume	121 cc
Bore & stroke	60 mm & 43 mm
Connecting rod length	73 mm
Fuel	H_2
Throttle opening	100%

Furthermore, the crankshaft position was measured by a crank angle encoder (OMRON E6B2-CWZ6C) with a resolution of 1000 P/R. Four thermocouples were applied to measure the temperatures of exhaust emission, intake air, main engine body, and engine oil. Moreover, a total of 200 cycles' results are recorded for analysis.

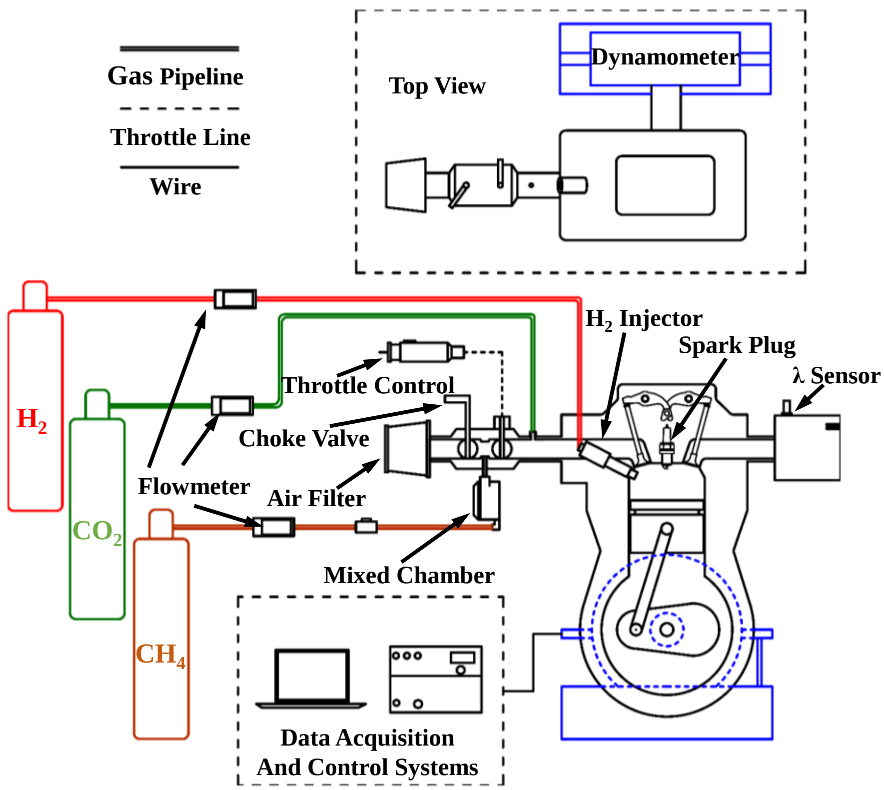


Figure 2: Experimental setup.

In order to obtain the various effect of H_2 direct injection combustion, different experimental cases are designed as listed in Table **2**. It changes from -20 to 20 deg TDC to check the effect of ignition timing. Then, H_2 injection timing varies among -300, -240, -180, -120, -60, and 0 deg TDC. The safety and limitations allow injection pressure to be used only at 5, 8, and 10MPa, respectively. For investigating the lean-burn combustion of H_2, λ at 3, 3.5, and 4 are selected. Finally, according to the performance of this modified gas engine, speed can increase from 1500 to 2500 rpm.

4. Results and Discussion

Fig. (**3**) shows the power output and thermal brake efficiency (BTE) at different ignition timings. The horizontal axis presents the ignition timing, with the left vertical axis describing power output and the right as efficiency. For

Table 2: Experimental cases.

Case No.	Objective	Parameter (Injection Duration)	Other Conditions
# 1	Ignition timing	-20, -15, -10, -5, 0, 5, 10, 15, 20 deg (0.82 ms)	λ=2.2; 1500 rpm; P_{inj}=8 MPa; Injection timing @ -20 deg ;
# 2	Injection timing	-300, -240, -180, -120, -60, 0 deg (0.82 ms)	λ=2.2; 1500 rpm; P_{inj} =8 MPa Ignition timing @ 5 deg;
# 3	Injection pressure	5, 8, 10 MPa (0.95, 0.54, 0.40 ms)	λ=2.9; 1500 rpm; Ignition timing @ 5 deg; Injection timing @ 0 deg ;
# 4	λ	3, 3.5, 4 (0.39, 0.34, 0.30 ms)	1500 rpm; P_{inj} =10 MPa; Ignition timing @ 5 deg; Injection timing @ 0 deg ;
# 5	Engine speed	1500, 2000, 2500 rpm (0.52, 0.71, 0.95 ms)	λ=2.5; P_{inj} =10 MPa; Ignition timing @ 5 deg; Injection timing @ 0 deg ;

this case, λ is set at 2.2 with engine speed at 1500 rpm. It is clear to see that power output and efficiency are greatly affected by different ignition timings. Moreover, both firstly increase and then decrease with retarding ignition timing. As we demonstrated before, for H_2 addition in CH_4 combustion, the maximum brake torque (MBT) ignition timing should be delayed owing to the high flame speed of H_2 [7]. Therefore, for only H_2 combustion, the ignition timing should be retarded to achieve higher efficiency. As a result, 5 deg TDC is the MBT ignition timing for H_2-only combustion in the current study. Moreover, in the following discussion, the gas engine will be operated at 5 deg TDC for all cases.

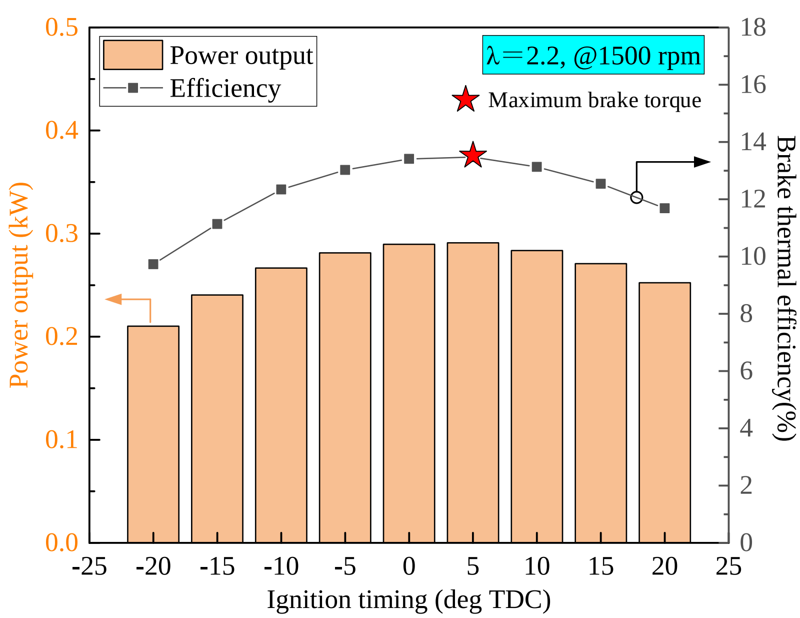


Figure 3: Ignition timing effect.

Next, H_2 injection timing will be checked in Fig. (**4**). The horizontal axis presents the injection timing, with the left vertical axis describing power output and the right one being efficiency. The same as Fig. (**4**), λ is set at 2.2 with engine speed at 1500 rpm. In contrast to ignition timing, it is interesting to see that little effect can be seen from H_2 injection timing, that only a slight increase is observed from -300 to 0 in both power output and efficiency. Therefore, MBT is marked at 0 deg TDC. Furthermore, 0 deg TDC will be used for all the experiments in the following test. Generally, injection timing would change the mixture stratification in the cylinder. However, owing to the limited volume in the cylinder (0.21 L) and the fast flame speed of H_2, the stratification effect is not apparent, leading to less variation in power output and brake thermal efficiency, which may be one possible reason for this phenomenon. Besides, the heat loss of this small engine should also be responsible for this phenomenon.

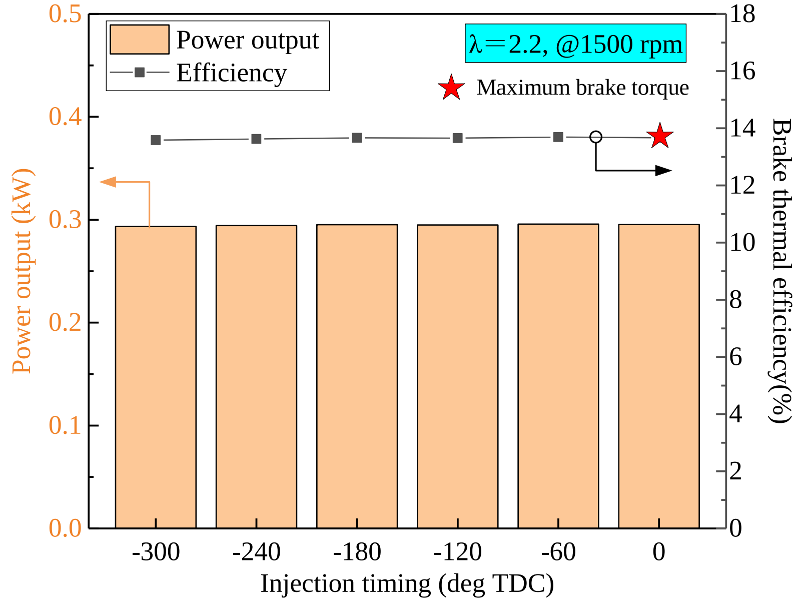


Figure 4: Injection timing effect.

In Fig. (**5**), the injection pressure effect is studied. The horizontal axis presents the injection pressure, with the left vertical axis describing power output and the right describing efficiency. For this case, λ is set at 2.8 with engine speed at 1500 rpm. It should be noted that although power output decreases slightly with higher injection pressure, efficiency increases correspondingly. This is because with higher injections, to ensure λ is the same value, injection duration should be shortened, thus decreasing the power output. However, efficiency is the most important parameter for consideration. Low H_2 volumetric energy density requires elevated injection pressures to deliver a sufficient fuel mass. Consequently, a high-pressure under-expanded jet is produced with a complex turbulent flow involving expansion fans and shock waves with subsequent nonlinear fluid properties. Therefore, 10 MPa should be adopted in the current case, which will be used in the following section.

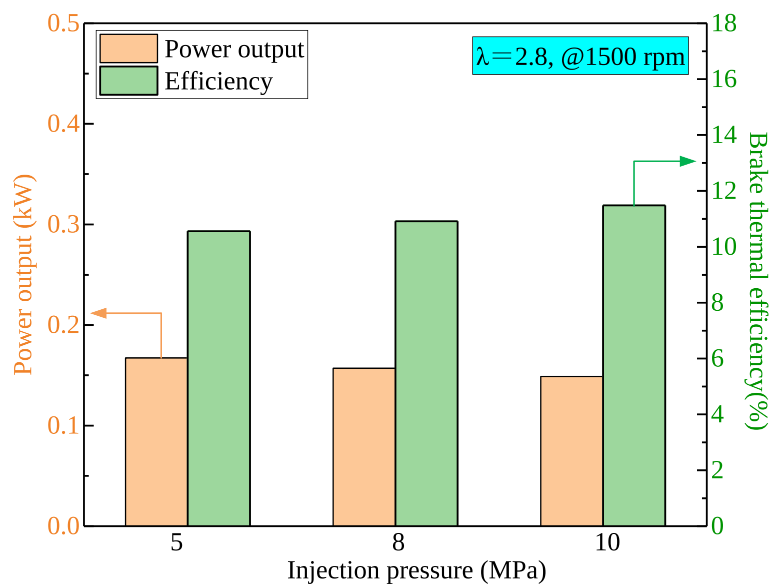


Figure 5: Injection pressure effect.

Next, owing to the high laminar flame speed and low minimum ignition energy, H_2 could facilitate lean-burn combustion. In other words, H_2 could improve the efficiency at lean-burn conditions. Furthermore, this is the main reason for our previous study of H_2 addition in CH_4 for power generation. However, when transferred to H_2 DI, the lean limitation should be clarified here. Therefore, larger λ at 3, 3.5, and 4 are selected. As shown in Fig. (**6**), the horizontal axis presents λ, with the left vertical axis describing power output and the right one describing efficiency. Results show that power output and efficiency decrease sharply when λ is larger than 3. Furthermore, in this case, efficiency is lower than 10% compared with Figs. (**4** and **5**), suggesting that even for H_2 DI combustion, high efficiency should be adjusted with λ smaller than 3.

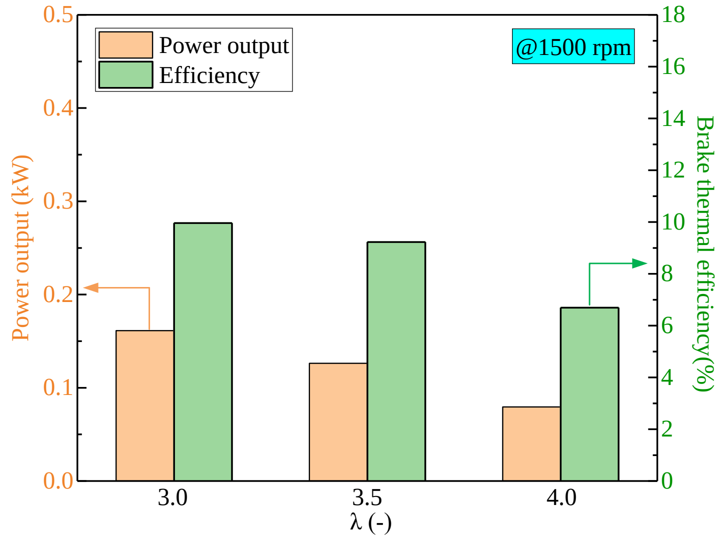


Figure 6: λ effect.

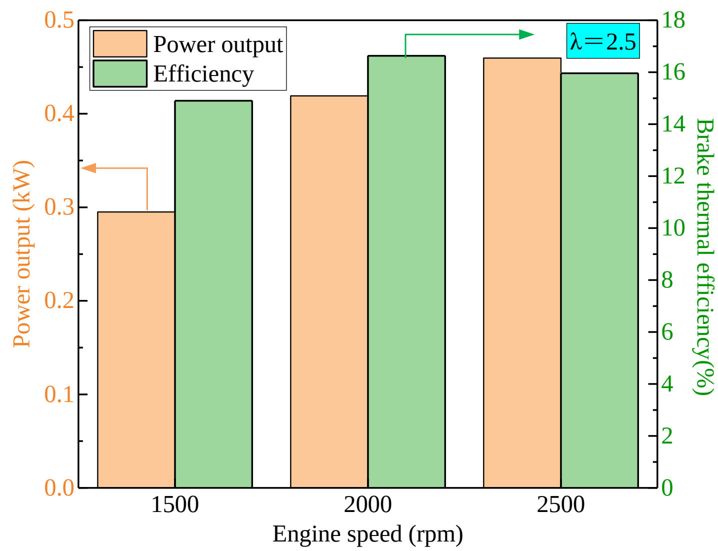


Figure 7: Engine speed effect.

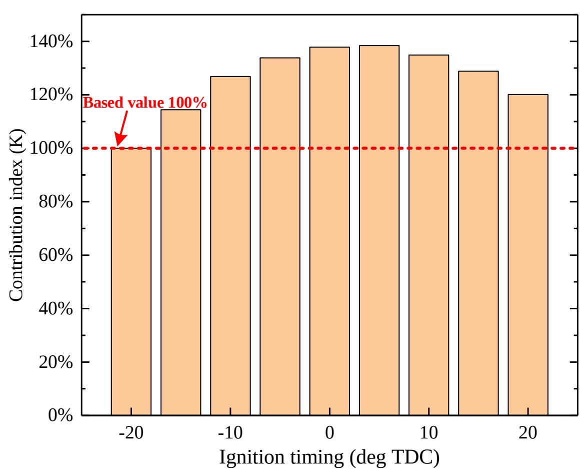
Finally, the engine speed effect is compared. As shown in Fig. (**7**), the horizontal axis presents engine speed, with the left vertical axis describing power output and the right one describing efficiency. It is interesting to see that different with injection pressure or λ, both power output and efficiency increase then decrease with an increase in engine speed, leading to the highest efficiency at 2000 rpm. The efficiency could reach almost 17%. Because in this research, the tested engine is modified from a small gasoline engine with a larger engine speed, the mechanical friction and heat loss would increase correspondingly, which may be the possible reason for this behavior. As a result, in future study, 2000 rpm should be applied for the investigation. Besides, CH_4 and CO_2 should also be used as the primary fuels to simulate the biogas fuel in our subsequent study.

Generally, efficiency is the most important target in engine performance. Therefore, the contribution indices are used to quantitatively analyze the boundary conditions, indicating the influence of Ignition timing, Injection timing, Injection pressure, λ, and Engine speed on BTE. The contribution index was calculated as Equation (1), and the results are illustrated in Fig. (**8**).

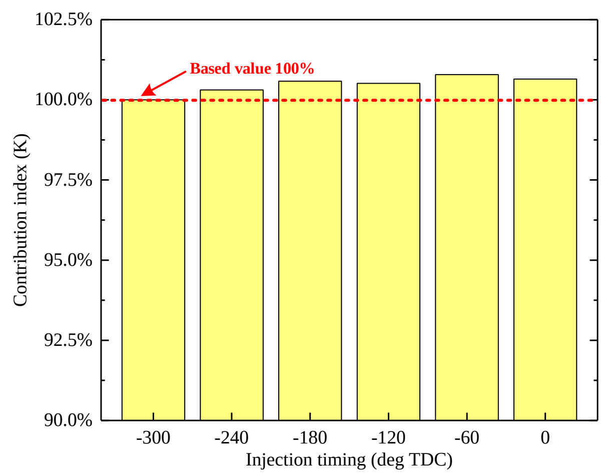
$$K=\eta_i/\eta_0\times 100\% \tag{1}$$

where K is the contribution index in different parameters under boundary conditions; η_i and η_0 are each efficiency and the based one. Thus, this parameter can increase efficiency by changing boundary conditions if K is greater than 100%.

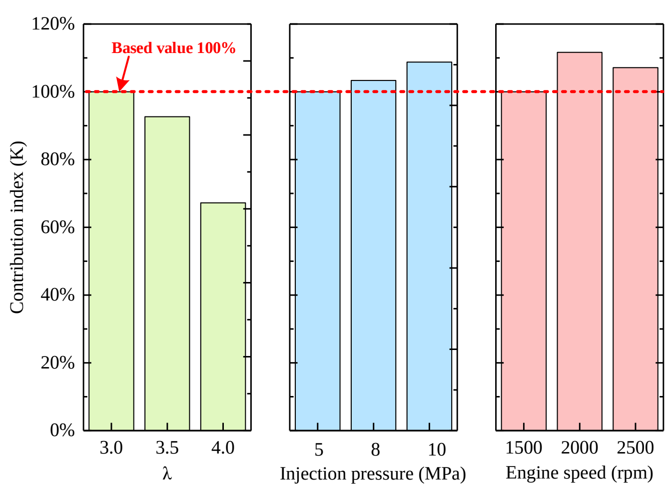
As depicted in Fig. (**8**), it is interesting that injection timing shows less contribution index on efficiency. However, in contrast to injection timing, ignition timing and λ show larger contribution index efficiency. Furthermore, delaying the ignition timing could increase efficiency, but a larger λ decreases efficiency. Moreover, injection pressure and engine speed show a medium contribution index on efficiency. Moreover, higher injection pressure could increase it from 5 to 10 MPa. However, higher engine speed firstly increases then decreases thermal efficiency. Among them, 40% increase from ignition timing and 10% increase from engine speed should be the most noteworthy indicating that when enlarging the efficiency, these two parameters should be prioritized to be optimized.



(a) Ignition timing



(b) Injection timing



(c) λ, injection pressure, and engine speed

Figure 8: Contribution index analysis.

5. Conclusion

Combustion experiments were conducted for H_2 direct injection in this modified engine. Different injection timings and ignition timings were checked first to achieve higher efficiency. Then, injection pressure, λ, and engine speed were compared by evaluating power output and efficiency. Moreover, the main conclusions were summarized as follows:

1. By delaying the ignition timing from -20 to 20 deg TDC, power output and efficiency firstly increase then decrease. Moreover, the highest ones can be seen at the ignition timing of 5 deg TDC. However, only a slight increase can be obtained when the injection timing is changed to 0 deg TDC.
2. Larger λ decreases efficiency and power output significantly, indicating that the lean-burn limitation also exists even for H_2 DI combustion, which should be controlled smaller than 3. Furthermore, higher injection pressure could increase efficiency but decrease power output. However, engine speed increases power out from 1500 to 2500 rpm, and efficiency increases and decreases correspondingly.
3. The contribution index for power generation with high efficiency evaluates different parameters. Finally, the ignition and injection timing was decided at 5 deg and 0 deg TDC separately. Moreover, λ should be controlled lower than 3 with 10 MPa of injection pressure. Additionally, the engine speed should be set at 2000 rpm.
4. Through analyzing all these parameters, ignition timing and engine speed should be considered and optimized to achieve higher efficiency owing to the higher contribution index.

Furthermore, the limitation in this study should be noted that until now, BTE has been quite low. Two possible reasons are involved. The original engine is only a one-cylinder engine used in a motorcycle with low efficiency. After retrofitting for gas fuel, BTE would decrease much more. Another reason is that these experiments were conducted in lean-burn combustion ($\lambda > 2$). Without turbulent assistance (normally aspirated engine), BTE decreases sharply here. Therefore, next, we will analyze the H_2 DI combustion when $\lambda < 2$. Moreover, cylinder pressure and NOx emission will be measured as well.

List of Abbreviations

BTE	=	Brake thermal efficiency
CH_4	=	Methane
CO	=	Carbon monoxide
CO_2	=	Carbon dioxide
COV	=	Coefficient of variation
CR	=	Compression ratio
DI	=	Direct injection
HC	=	Hydrocarbon
H_2	=	Hydrogen
ICEs	=	Internal combustion engines
MBT	=	Maximum brake torque
NH_3	=	Ammonia

NO_x	=	Nitrogen oxide
PFI	=	Port fuel injection
rpm	=	Revolution per minute
SI	=	Spark ignition
TDC	=	Top dead center
λ	=	Excess air ratio

Acknowledgements

The authors would like to acknowledge the Foundation of State Key Laboratory of Engines [No. K2022-12] and the Environment Research and Technology Development Fund (JPMEERF20203001) of the Environmental Restoration and Conservation Agency of Japan.

Conflict of Interest

The authors declare no conflict of interest.

References

[1] Handayani K, Filatova T, Krozer Y, Anugrah P. Seeking for a climate change mitigation and adaptation nexus: Analysis of a long-term power system expansion. Appl Energy. 2020; 262: 114485. https://doi.org/10.1016/j.apenergy.2019.114485

[2] Mallapaty S. How China could be carbon neutral by mid-century. Nature. 2020; 586: 482-3. https://doi.org/10.1038/d41586-020-02927-9

[3] Rosa L, Sanchez DL, Mazzotti M. Assessment of carbon dioxide removal potential via BECCS in a carbon-neutral Europe. Energy Environ Sci. 2021; 14: 3086-97. https://doi.org/10.1039/D1EE00642H

[4] Muradov NZ, Veziroğlu TN. "Green" path from fossil-based to hydrogen economy: An overview of carbon-neutral technologies. Int J Hydrogen Energy. 2008; 33: 6804-39. https://doi.org/10.1016/j.ijhydene.2008.08.054

[5] Huovila A, Siikavirta H, Antuña Rozado C, Rökman J, Tuominen P, Paiho S, *et al*. Carbon-neutral cities: Critical review of theory and practice. J Clean Prod. 2022; 341: 130912. https://doi.org/10.1016/j.jclepro.2022.130912

[6] Luo H, Chang F, Jin Y, Ogata Y, Matsumura Y, Ichikawa T, *et al*. Experimental investigation on performance of hydrogen additions in natural gas combustion combined with CO2. Int J Hydrogen Energy. 2021; 46: 34958-69. https://doi.org/10.1016/j.ijhydene.2021.08.037

[7] Jin Y, Luo H, Zhang G, Zhai C, Ogata Y, Matsumura Y, *et al*. Ignition timing effect on the combustion performance of hydrogen addition in methane fermentation gas in a local energy system. Fuel. 2022; 324(ptB): 124714. https://doi.org/10.1016/j.fuel.2022.124714

[8] Luo H, Jin Y, An Y, Matsumura Y, Ichikawa T, Kim W, *et al*. Combustion performance of methane fermentation gas with hydrogen Addition under various ignition timings. No. 2022-32-0043. SAE Technical Paper, Oct 2022.

[9] Oikawa M, Kojiya Y, Sato R, Goma K, Takagi Y, Mihara Y. Effect of supercharging on improving thermal efficiency and modifying combustion characteristics in lean-burn direct-injection near-zero-emission hydrogen engines. Int J Hydrogen Energy. 2022; 47: 1319-27. https://doi.org/10.1016/j.ijhydene.2021.10.061

[10] Verhelst S, Wallner T. Hydrogen-fueled internal combustion engines. Prog Energy Combust Sci. 2009; 35: 490-527. https://doi.org/10.1016/j.pecs.2009.08.001

[11] Thawko A, Persy S-A, Eyal A, Tartakovsky L. Effects of fuel injection method on energy efficiency and combustion characteristics of SI engine fed with a hydrogen-rich reformate, No. 2020–01-2082, United States: SAE Technical Paper; 2020. https://doi.org/10.4271/2020-01-2082.

[12] Gürbüz H, Akçay İH. Evaluating the effects of boosting intake-air pressure on the performance and environmental-economic indicators in a hydrogen-fueled SI engine. Int J Hydrogen Energy. 2021; 46: 28801-10. https://doi.org/10.1016/j.ijhydene.2021.06.099

[13] He F, Li S, Yu X, Du Y, Zuo X, Dong W, *et al*. Comparison study and synthetic evaluation of combined injection in a spark ignition engine with hydrogen-blended at lean burn condition. Energy. 2018; 157: 1053-62. https://doi.org/10.1016/j.energy.2018.06.112

[14] Yu X, Zuo X, Wu H, Du Y, Sun Y, Wang Y. Study on combustion and emission characteristics of a combined injection engine with hydrogen direct injection. Energy & Fuels. 2017; 31: 5554-60. https://doi.org/10.1021/acs.energyfuels.6b03300

[15] Shi W, Yu X, Zhang H, Li H. Effect of spark timing on combustion and emissions of a hydrogen direct injection stratified gasoline engine. Int J Hydrogen Energy. 2017; 42: 5619-26. https://doi.org/10.1016/j.ijhydene.2016.02.060

[16] Sun Y, Yu X, Dong W, Tang Y. Effects of hydrogen direct injection on engine stability and optimization of control parameters for a combined injection engine. Int J Hydrogen Energy. 2018; 43: 6723-33. https://doi.org/10.1016/j.ijhydene.2018.02.033

[17] Yu X, Wu H, Du Y, Tang Y, Niu R. Research on cycle-by-cycle variations of an SI engine with hydrogen direct injection under lean burn conditions. Appl Therm Eng. 2016; 109: 569-81. https://doi.org/10.1016/j.applthermaleng.2016.08.077

[18] Du Y, Yu X, Wang J, Wu H, Dong W, Gu J. Research on combustion and emission characteristics of a lean burn gasoline engine with hydrogen direct-injection. Int J Hydrogen Energy. 2016; 41: 3240-8. https://doi.org/10.1016/j.ijhydene.2015.12.025

[19] Niu R, Yu X, Du Y, Xie H, Wu H, Sun Y. Effect of hydrogen proportion on lean burn performance of a dual fuel SI engine using hydrogen direct-injection. Fuel. 2016; 186: 792-9. https://doi.org/10.1016/j.fuel.2016.09.021

[20] Sun Y, Yu X, Jiang L. Effects of direct hydrogen injection on particle number emissions from a lean burn gasoline engine. Int J Hydrogen Energy. 2016; 41: 18631-40. https://doi.org/10.1016/j.ijhydene.2016.07.224

[21] Fan B, Wang J, Pan J, Zeng Y, Fang J, Lu Q, *et al*. Computational study of hydrogen injection strategy on the combustion performance of a direct injection rotary engine fueled with natural gas/hydrogen blends. Fuel. 2022; 328: 125190. https://doi.org/10.1016/j.fuel.2022.125190

[22] Fischer M, Sterlepper S, Pischinger S, Seibel J, Kramer U, Lorenz T. Operation principles for hydrogen spark ignited direct injection engines for passenger car applications. Int J Hydrogen Energy. 2022; 47: 5638-49. https://doi.org/10.1016/j.ijhydene.2021.11.134

[23] Bao L, Sun B, Luo Q. Experimental investigation of the achieving methods and the working characteristics of a near-zero NOx emission turbocharged direct-injection hydrogen engine. Fuel. 2022; 319, 123746. https://doi.org/10.1016/j.fuel.2022.123746

[24] Wang J, Huang Z. Effect of partially premixed and hydrogen addition on natural gas direct-injection lean combustion. Int J Hydrogen Energy. 2009; 34: 9239-47. https://doi.org/10.1016/j.ijhydene.2009.09.018

[25] Wang J, Huang Z, Tang C, Miao H, Wang X. Numerical study of the effect of hydrogen addition on methane–air mixtures combustion. Int J Hydrogen Energy. 2009; 34: 1084-96. https://doi.org/10.1016/j.ijhydene.2008.11.010

[26] Hu E, Huang Z, Liu B, Zheng J, Gu X. Experimental study on combustion characteristics of a spark-ignition engine fueled with natural gas–hydrogen blends combining with EGR. Int J Hydrogen Energy. 2009; 34: 1035-44. https://doi.org/10.1016/j.ijhydene.2008.11.030

[27] Wang J, Huang Z. Effect of hydrogen addition on early flame growth of lean burn natural gas–air mixtures. Int J Hydrogen Energy. 2010; 35: 7246-52. https://doi.org/10.1016/j.ijhydene.2010.01.004

[28] Stępień Z. A comprehensive overview of hydrogen-fueled internal combustion engines: achievements and future challenges. Energies (Basel). 2021; 14: 6504. https://doi.org/10.3390/en14206504

[29] Onorati A, Payri R, Vaglieco B, Agarwal A, Bae C, Bruneaux G, *et al*. The role of hydrogen for future internal combustion engines. Int J Eng Res. 2022; 23: 529-40. https://doi.org/10.1177/14680874221081947