Combustion and Performance Characteristics of the Spark Discharge Energy Effect on Rapid Compression and Expansion Machine (RCEM) Working with Propane and Diesel Fuel Direct Injection as Marine Fuel

Cahyani Windarto[1] and Ocktaeck Lim[2](✉)

[1] Graduate School of Mechanical Engineering, University of Ulsan, DaeHak-ro 93, Nam-gu, Ulsan 44610, South Korea
cahyaniwindarto@kemnaker.go.id

[2] School of Mechanical Engineering, University of Ulsan, DaeHak-ro 93, Nam-gu, Ulsan 44610, South Korea
otlim@ulsan.ac.id

Abstract. Propane with lower carbon content than other fossil fuels and which is easily vaporized at ambient conditions has the advantage of lowering CO_2 emissions and optimizing the combustion process. The possible combination of using it in high-efficiency compression ignition engines makes it worth analyzing the innovative method of using liquid propane injection. Since propane has a very low cetane number, spark plug operating is provided to achieve reliable ignition. Experiments and simulations were carried out to investigate combustion and performance of spark discharge energy effect on propane direct injection. A rapid compression and expansion machine (RCEM) was used to carry out the experimental work. The results are the liquid propane injection provided reduction in emission by a modest improvement in energy efficiency. The use spark plug ignition was experienced in obtaining reliable ignition to achieving reliable ignition and reasonable ignition delays.

Keywords: propane · RCEM · spark discharge energy · combustion · performance characteristics

1 Introduction

Energy conservation, emission reduction, and ecologically friendly and sustainable energy supply are all hot topics these days. Global energy consumption estimates continue to foresee rising demand for liquid hydrocarbon fuels [1], which will be used mostly by internal combustion (IC) engines in the near future as it is abundant, cheap and convenient [2, 3]. Therefore, it is important to promote and develop a novel engine technology and combustion strategy that pursuit of high efficiency and clean internal combustion engines [4]. Faced with the challenge of lowering greenhouse gas emissions and shifting

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to a greater use of renewable energy sources, propane is becoming more widely recognized as a viable “green” transportation fuel, particularly for maritime applications [5, 6]. Propane gas is considered to be a viable alternative to liquid petroleum-based fuels and could be converted to liquefied petroleum gas (LPG) at easily the right temperature and pressure [7, 8]. As a global resource natural gas is abundant, propane is produced from liquid components recovered during natural gas processing. It is particularly well suited for advanced combustion techniques in a compression ignition (CI) engine offer the potential to increase efficiency [9] while also addressing the high NO_x-soot emission problem [10], which is one of the fundamental disadvantages of diesel engines. In particular, the propane is like diesel fuel. It can be liquefied under 760–1030 kPa pressure at ambient temperature and mixed with diesel in any proportion. Theoretically, the high-octane number (correspondent to low cetane number) makes the fuel suitable for operating in high compression ratio CI engines [11, 12]. Compression-ignition (CI) engines as a result of initiation of combustion depends on air heated by compression instead of on an electrical spark which is characterized by fuel-lean equivalence ratios [13, 14], which lead to very low THC and CO emissions [15, 16].

CI engines are much more efficient than SI engines for several reasons. Among of them are CI engines do not suffer from knocking at high loads and, hence, can have higher compression ratios compared to SI engines, CI engines can run at part load by reducing the amount of fuel injected and in a CI engine, during the compression stroke, only air is compressed, rather than a mixture of fuel and air, which brings the performance closer to the ideal cycle efficiency [17]. Propane in diesel engines produce high output torque and a better thermal efficiency due to a larger lower heating value [18]. It also helps to reduce the NO_x emissions by lowering the charge temperature, which reduces the NO_x formation [7]. Propane is also attractive in terms of its energy content but exhibits relatively weaker knock resistance. While the increased reactivity of propane results in faster burn rates and potentially higher brake thermal efficiencies, the engine operating range (viable speeds and loads) may be limited by either end-gas knock or premature propane autoignition [6]. Since propane has a very low cetane number [8], spark plug operating must be provided to achieve reliable ignition. Based on these facts, a breakthrough combustion strategy is necessary to achieve high efficiency similar to that of a diesel engine while producing reduced emissions similar to that of a gasoline engine. Both experimental and computational fluid dynamics modeling are performed concurrently to perform a comparative study of the combustion and performance of a diesel engine running with diesel fuel only, called as diesel baseline and running with propane to analyze effect of the spark discharge energy effect of CI engine fueled with propane.

2 Material and Methods

2.1 Methodology

An investigation was performed using RCEM research engine and CFD simulations using CONVERGE®. Experimental research was conducted on a rapid compression and expansion machine (RCEM) that has characteristics similar to a gasoline compression ignition (GCI) engine, using propane with fuel injection pressures varying from 200 to

500 bar. The engine compression ratio was set at 17, with 1000 μs of injection duration and 20 degrees before top dead center (BTDC).

Computational fluid dynamics (CFD) is currently a popular technique used in both industry and research to model the performance of ICEs and give data that can be utilized to enhance the design of future combustion systems. CONVERGE® will generate a completely orthogonal and organized grid at runtime depending on user-defined grid control parameters.

2.2 Fuel Preparation

The properties of diesel and propane based on an international standard are presented in Table 1. The injection flow rate was measured using a Bosch 7-holes injector for diesel fuel and Denso DENSO 33800–52800 injector which attached to an injection rate-measuring vessel. The injector was triggered internally using a Zenobalti multistage injection engine controlled ZB-8035 combined with a common rail solenoid injector peak and hold driver ZB-5100 to adjust the SOI timing. The injection pressures were 50 MPa for diesel fuel and 20 MPa for propane fuel produced from common rail and a high-pressure pump controlled by a common rail PCV driver ZB-1100 and three-phase electric motor controller, respectively. The injection quantity test was conducted 500 cycles prior to obtain same energy value for each fuel with equivalence ratio 0.5.

The stoichiometric formula for propane in air is as follows:

$$C_3H_8 + 5(O_2 + 3.76N_2) \rightarrow 3CO_2 + 4H_2O + 5 * 3.76N_2 \tag{1}$$

While the equivalence ratio, ϕ, is defined as the ratio of the actual fuel/oxidizer ratio to the fuel/oxidizer ratio in the stoichiometric formula as shown in Eq. (1).

$$\phi = \frac{(A/F)_{stoic}}{A/F} = \frac{X_{C_3H_8}/X_{O_2}}{\left(X_{C_3H_8}/X_{O_2}\right)_{stoich}} = 5\left(X_{C_3H_8}/X_{O_2}\right) \tag{2}$$

The engine operating parameters and injection strategies are presented in Table 2.

Table. 1 Properties of diesel and propane

Properties	Diesel	Propane
Chemical formula	$C_xH_{1.8x}$	C_3H_8
Molecular weight [g/mol]	190–220	44.1
Density [g/cm^3]	0.831	0.493 (at 25 °C)
Low heating value [MJ/kg]	44	46.33
Auto-ignition temperature [K]	523	763
Stoichiometric ratio of AF [wt.%]	14.6	15.6
Cetane number	45–55	5

Table. 2 Self Ignition and spark discharge operating injection strategies

Ignition strategies	Timing	Injected fuel	Driver type	Injector Type
Diesel Self Ignition	10~ 0 ^{O}CA BTDC	2900 µs (130.24 mg)	ZB-5100	Bosch 0445110 327
Propane Self Ignition	20~0^{O}CA BTDC	6250 µs (122.13 mg)	ZB-5014	Denso 33800 52800
Spark discharge operating	-Propane 20 ~0^{O}CA BTDC -Spark + 0 ~ 5 after SOI Propane	6250 µs (122.13 mg)	ZB-5014	Denso 33800 52800

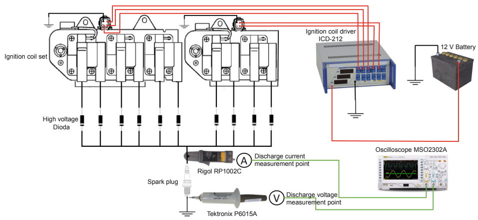


Fig. 1. Schematic of enhanced ignition system

2.3 Spark Discharge Energy

For this investigation, a high-energy inductive ignition system with a single spark plug, 10 spark coils, and an ignition driver controller was built. As shown in Fig. 1, two sets of ignition coils were connected and paralleled with one spark plug. Each of discharge coils was connected to the ignition driver ICD-212. Ignition driver ICD-212 has 3 mode of ignition control, i.e. Pair mode (series of pairing two coil channels); individual mode (series of individual output for each coil channel); simultaneous mode (parallel simultaneous output for all coil channels). The timing for the ignition signals cam be varied from 1.0 until 65.4 ms ignition interval between channels. Following the transmission of the initial ignition signal, the following ignition signals were communicated in the time domain, in line with the timing for the ignition signals.

2.4 Experimental Setup

The experiment was conducted out using an RCEM that was meant to imitate the phenomena of a CI system in a single cycle. Without the complicated fluid dynamics features of a conventional internal combustion engine, the single-shot, quick compression of a test fuel may be explored in RCEM in a well-defined and controlled environment. The schematic diagram of RCEM is shown in Fig. 2. It has a 100-mm bore and a 420-mm stroke and is powered by a 22-kW electric motor. The compression ratio, which can vary from 10 to 23, can be changed by adjusting the screw in the base of the

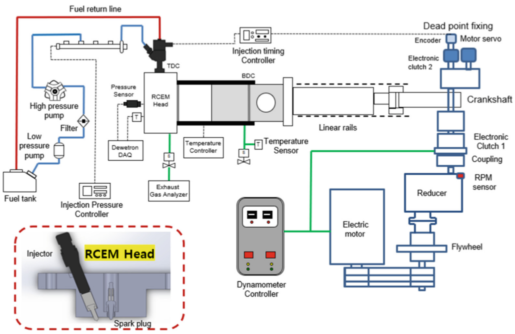


Fig. 2. RCEM with spark plug schematic diagram

crankshaft. To assure the consistency of the starting temperature, which might reach a maximum of 393 K, temperature sensors were fitted in the TDC, body, and BTDC. The engine's in-cylinder pressure was measured using a Kistler 6052CU20 pressure transducer and a Kistler 5018 amplifier. The crank angle position was measured using an Autonics E40S8–1800-3-T-24 rotary encoder. To log the data, the sensors were linked to a Dewetron DEWE-800-CA. An injector controller (a Zenobalti ZB-8035 multi-stage injection device) and a common rail solenoid injector peak were used with the fuel injector. An encoder interface ZB-100 and a ZB-5100 hold driver were utilized to manage the injection duration and timing.

2.5 CFD Simulation

CONVERGE® was performed on a Windows PC with an Intel (R) Core (TM) i7 77003.60 GHz processor and 32 GB RAM. This simulation includes the calculation method used, the surface treatment of the graphics preprocessor, computer network calculations, initial and boundary conditions, and the post-treatment. It also displays the results in a Tecplot. Except for the piston, which were considered movable boundaries, all limitations were considered permanent. The temperatures and pressures at the input were set to 383 K and 1 bar, respectively. The grid size was adjusted to 4 mm to assure simulation fidelity, and the main area valves were revised using the automatic mesh refinement (AMR) tool.

3 Results and Discussion

3.1 Combustion Analysis

Figure 3 shows the in-cylinder pressure and heat release rate when the engine is operated with different ignition strategies. The SOI of diesel was 10 ^{o}CA BTDC while the SOI of propane was 20 ^{o}CA BTDC. The highest maximum in-cylinder pressure occurred when ignition strategies operated with spark operating at propane 20 ^{o}CA BTDC at about 5.6 MPa. Meanwhile, the lowest maximum in-cylinder pressure occurred when ignition strategies operated with diesel self-ignition, with the from 20 to 0 ^{o}CA BTDC.

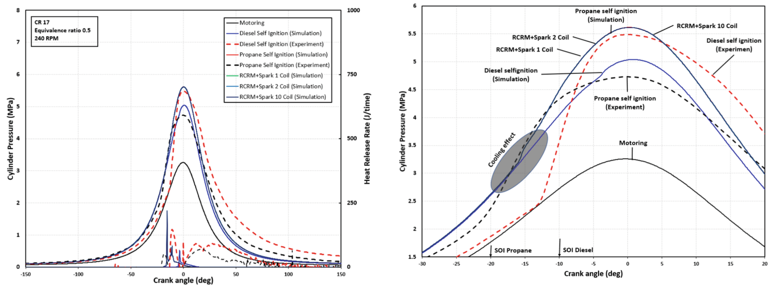


Fig. 3. Pressure and integrated heat release inside the RCEM cylinder

The propane cooling effect is detectable in the interval −15 to −5 CA BTDC. The increase of in cylinder pressure of propane relates to the blends cooling effect on the in-cylinder charge temperature before the combustion. In this experiment, it was proved that propane self-ignition happened in a compression ratio of 17 was associated with an SOI range 20 to 0 °CA BTDC of in cylinder value of approximately 4.8 MPa.

Simulation results have been spatially averaged flow velocity pattern of spark discharge duration, as illustrated in Fig. 4. As a result, these readings show low-pass spatially filtered values around the spark plug with increasing spark discharge energy. The measuring plane does not cross directly around the spark plug, as previously stated. The establishment of a propane self-ignition combined with spark energy discharge around the spark plug might contribute to faster flame formation, as well as exposing the kernel development to a wider range of variable velocities. Hence, flow conditions surrounding the spark plug gap during ignition impact the growth of the flame kernel and the subsequent combustion process plug by increasing the spark discharge energy.

Figure 5 shows the combustion duration from 10% CA to 90% CA. The combustion duration for every ignition strategy is almost the same except for the experiment of propane self-ignition strategy. In this range, the combustion duration of propane self-ignition strategy is longer than for propane spark operating strategy. The lower cetane of propane influences the chemical reaction of the combustion process, hence the advanced combustion phasing result in shorter ignition delay.

3.2 Performance Analysis

The performance effect of various spark discharge energy on RCEM fueled with propane is shown in Fig. 6. Propane strategy performed higher torque, indicated power and power than diesel strategy. The lower heating value of propane direct injection lead to higher flame temperature and effective combustion. Figure 7 shows the combustion efficiency of ignition strategy with various spark discharge energy. The indicated thermal efficiency for ignition strategy was found to be almost equivalent for diesel and propane fuel. The significance gap occurred between diesel self-ignition experiment and simulation. This condition can explain the sensitivity of the RCEM to volatile fuel, which in this case, is the high auto ignition temperature of propane that caused cooling effect on the combustion process. In the propane self-ignition and spark operating strategy performed

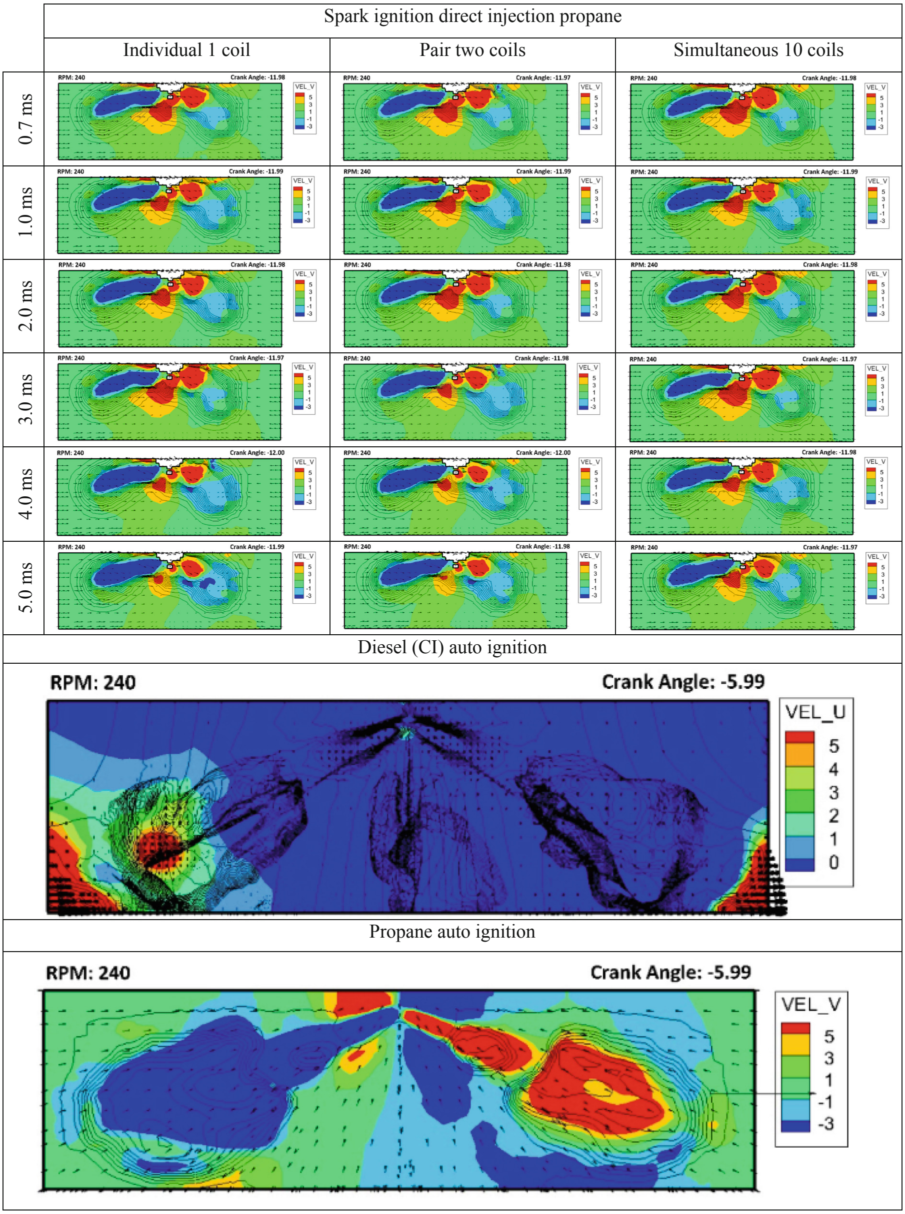


Fig. 4. Flow velocity pattern of spark discharge duration study on RCEM fueled with diesel and propane direct injection with ignition modes (individual, pair and simultaneously) and spark duration captured at crank angle ~ 11 ^{O}CA BTDC with SOI 20 ^{O}CA BTDC, Spark 5 ^{O}CA BTDC, speed 240 RPM, slice z position -0.004, slice y position 0.01, compared with diesel RCEM auto ignition

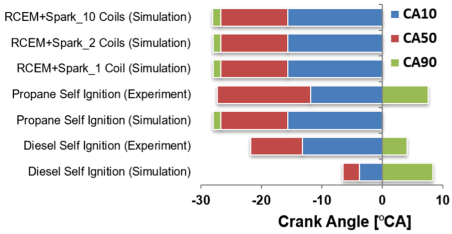
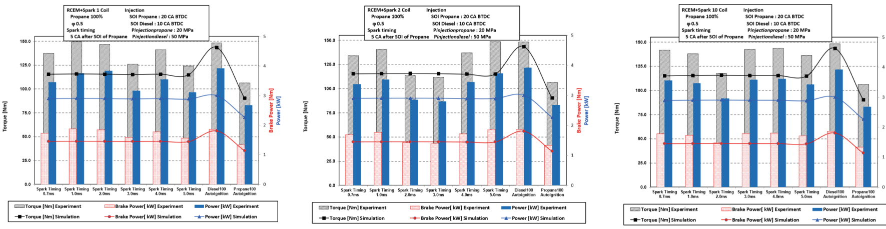
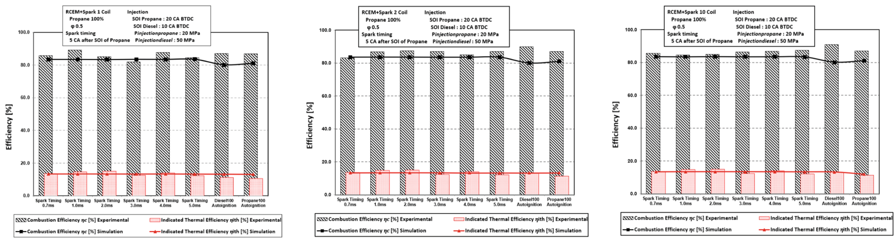


Fig. 5. Combustion duration at various ignition strategy



(a) Individual mode (b) Pair mode (c) Simultaneous mode

Fig. 6. Torque, indicated power and power with ignition strategy with various spark discharge energy



(a) Individual mode (b) Pair mode (c) Simultaneous mode

Fig. 7. Combustion efficiency of ignition strategy with various spark discharge energy

higher torque and power than diesel strategy. The higher thermal efficiency of propane is due to the higher LHV of the propane fuel compared to diesel.

4 Conclusions

In this study, the spark discharge effect of direct injection of propane into RCEM on combustion and performance has been investigated. The approach experimental dan simulation were designed at the feasibility using different ignition strategy on diesel and propane direct injection.

The combustion of 100% propane direct injection in RCEM produces lower in-cylinder pressure (approximately 5.6 MPa) than 100% diesel (4.8 MPa). The injection of liquid propane causes a cooling effect into the chamber due to the low temperature of liquid propane (below −42 °C).

The establishment of a propane self-ignition combined with spark energy discharge around the spark plug might contribute to faster flame formation, as well as exposing the kernel development to a wider range of variable velocities.

Future activities will be addressed to investigate the injection position of propane to produce the maximum combustion efficiency and expand combustion parameters of a proper propane ignition strategy to improves fuel economy and exhaust emissions.

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