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# The Effects of Injection Strategy on a Gasoline Compression Ignition (GCI) Engine

Sakda Thongchai[1] and Ocktaeck Lim[2,*]

[1] Graduate School of Mechanical Engineering, University of Ulsan, Ulsan, 680-749, South Korea
[2] School of Mechanical Engineering, University of Ulsan, Ulsan, 680-749, South Korea
[*] Corresponding Author: otlim@ulsan.ac.kr

***Abstract***

In the current study, combustion characteristics and also engine out exhaust emissions of a compression ignition engine fueled with gasoline, named as Gasoline Compression Ignition (GCI) engine has been investigated when injection pressure and duration were altered. Based on the commercial engine, Hyundai brand, the single-cylinder diesel engine was applied in the experiment. Pure gasoline added with 5 percent of biodiesel as lubricity improver was injected into the cylinder by the common rail injection system which independently varied injection pressure and duration. The injection pressures were set at 600 and 1,000 bar. The engine speed was fixed at 1,200 rpm whereas the specific range of engine oil, coolant water and intake air temperature were controlled. Analyzed by one-zone thermodynamic model, combustion features were characterized in terms of heat release rate (HRR) and burning duration. The exhaust emissions including NOx, THC, and CO were also measured. The results show that injection pressure has the significant effect on the combustion of GCI engine. The complete combustion occurred when injecting biodiesel at high injection pressure.

***Keywords:*** Gasoline Compression Ignition (GCI), Injection pressure, Injection timing.

## 1. Introduction

The larger proportion of fossil fuel consumption all around the world is used in the transportation sector which consumed fossil oils around 63.8% [1]. Using more middle distillate petroleum like diesel oils is caused the energy unbalanced problem between diesel and gasoline especially in European country [2]. Moreover, the regulations of exhaust gas emission have tended to be stricter in the future such as Euro standards and the world is looking for new energy sources.

Many researchers have endeavored to develop new technologies for the compression ignition (CI) engine as well as use the renewable alternative fuel. To increase the engine performance and reduce the exhaust gas emissions, it is very interesting to apply biodiesel in new engine concept for examples, homogeneous charge compression ignition (HCCI) and gasoline compression ignition (GCI) engines [3]. Particularly, GCI engine with a diesel common rail injection system has been developed in recent times [4]. However, there are few researches in the GCI engine with gasoline-biodiesel blended on diesel common rail injection system. Therefore, this work studied the GCI engine at low engine speed of 1,200 rpm to investigate engine behaver and used gasoline-biodiesel blend with 5% biodiesel concentration as an additive to increase the engine performance and to reduce exhaust gas emission. Meanwhile, the combustion characteristics were analyzed and discussed corresponding to cylinder pressure, mass fraction burned, and exhaust gas emission.

## 2. Materials and Method

### 2.1 Test engine

Based on the commercial Hyundai engine, a single cylinder four stroke engine with single overhead cam (SOHC) 4 valves system was used in the current study. Engine bore and stroke is 83 x 92 mm, respectively. The engine specifications are detailed in Table 1. In the common rail system, the fuel was sent from the high-pressure fuel pump to the common rail. The role of the common rail is to supply constant pressure 600 and 1,000 bar to the injector with the help of pressure control valve (PCV). In addition, to inject at desired amount of pressure, remained fuel returns back to vent line. A solenoid injector, Bosch model, was driven to introduce the fuel through 7 holes directly into the combustion chamber by peak and hold driver, ZB-5100. The injection timing and duration were controlled by multistage injection controller, Zenobalti ZB-8035 which trigger through encoder interfacing box, ZB-100. The engine was mounted on an Elin AVL Puma dynamometer comprising of a 57 kW DC motor with water and oil conditioning systems. The DC dynamometer was used to drive the engine during motoring conditions and absorb load during fired operations. Fig. 1 presents a schematic diagram of the test system. An exhaust gas analyzer, Horiba model MEXA 7100 DEGR, was used to analyze the components of the exhaust gas emissions including HC, CO and $NO_X$.

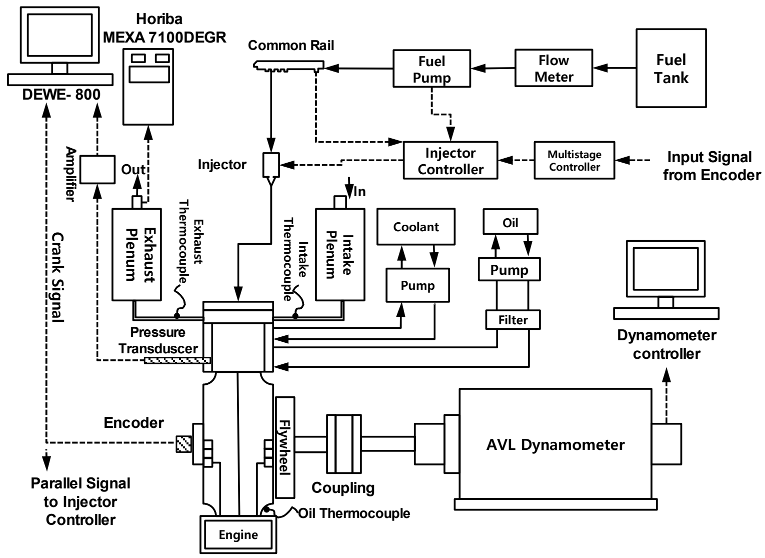


Fig. 1 Schematic diagram of experimental setup

**Table. 1 Engine specifications**

| Engine Parameters | Value |
|---|---|
| Displacement (cm$^3$) | 498 |
| Bore (mm) | 83 |
| Stroke (mm) | 92 |
| Compression Ratio | 19.5 |
| Con. Rod Length (mm) | 145.8 |
| Crank Radius (mm) | 43.74 |
| Valve System | SOHC 4 valve |
| Fuel System | Electronic Common Rail |

**2.2 Test fuels**

Commercial gasoline and diesel were purchased from the retail station in Korea while JC Chemical Co., Ltd. provided neat biodiesel. The properties of all test fuels are shown in Table 2. The lubricity of gasoline which indicated as wear scar in mm is higher than diesel fuel standard of 400 mm [5] and may result to pump and injector failure. Therefore, 5 % of biodiesel by volume was blended with gasoline as the lubricity enhancer due to its superior lubricity [6,7] and named as GB05 which used as the representative of gasoline in the current study.

Table. 2 Fuel properties

| Test Item | Unit | Test method | Gasoline | GB05 | B100 | Diesel |
|---|---|---|---|---|---|---|
| Heating value | MJ/kg | ASTM D240:2009 | 45.86 | 45.32 | 39.79 | 45.93 |
| Kinematic Viscosity @40°C | mm$^2$/s | ISO 3104:2008 | 0.735[9] | - | 4.229 | 2.798 |
| Lubricity | mm | ISO 12156-1:2012 | 548 | 290 | 189 | 238 |
| Cloud Point | °C | ISO 3015:2008 | -57 | -37 | 3 | -5 |
| Pour Point | °C | ASTM D6749:2002 | -57 | -57 | 1 | -9 |
| Density @15°C | kg/m$^3$ | ISO 12185:2003 | 712.7 | 722.3 | 882.3 | 826.3 |

**2.3 Combustion characteristic test**

In cylinder pressure was measured by a pressure transducer, Kistler type 6056. The charge signals triggered at every 0.2 crank angle were amplified by an amplifier, Kistler 5018, recorded and analyzed by a combustion analyzer, Dewetron DEWE-800-CA. An averaged in-cylinder pressure calculated from 100 cycles was used to determine the heat release rate which following one zone of thermodynamic model.

An engine speed was controlled at 1200 rpm. Intake air was naturally aspirated through the wide open throttle. Injection pressures were set at 600 and 1,000 bar. The start of injection (SOI) was fixed at 40 degree bTDC while injection duration was altered to keep stoichiometric equivalent ratio ($\lambda$=1). The injection durations of each test fuel at each injection pressure are shown in Table 3.

Table. 3 Injection duration of each test fuel.

| Injection pressure (bar) | Injection duration (μs) | |
|---|---|---|
| | GB05 | D100 |
| 600 | 1,020 | 1,775 |
| 1,000 | 750 | 775 |

## 3. Results and discussion

### 3.1 Combustion characteristics

Fig. 2 presents in-cylinder pressure of GB05 and neat biodiesel (D100) when injected into the cylinder with 600 and 1,000 bar of injection pressure. The results show the different trend between biodiesel and gasoline when injection pressure increased. When injection pressure increased from 600 to 1,000 bar the in-cylinder pressure of D100 increased but decreased for gasoline injection. Neat biodiesel yielded the higher in-cylinder pressure than those of GB05 for all test condition. Hence, in-cylinder pressure of biodiesel injected at 600 bar of injection pressure was higher than gasoline injection of 600 and 1,000 bar. Pure biodiesel yield in-cylinder pressure of 100.82 bar at 363.0 CA and 96.86 bar at 363.9 CA while gasoline produced pressure of 76.07 bar at 366.4 CA and 82.18 bar at 632.2 CA for injection pressure of 1,000 and 600 bar respectively.

Due to oxygen content in its molecule, more amount of biodiesel could be injected to keep the same stoichiometric equivalent ratio when compared with gasoline. Therefore, energy input may be possibly higher for biodiesel injection. In addition, more complete combustion occurred with more available oxygen in biodiesel for oxidation. Also, biodiesel has the higher cetane number which can decrease the ignition delay and promote the higher cylinder pressure. As the results, in-cylinder pressures of biodiesel are significantly higher than GB05.

In-cylinder pressure of biodiesel increased when increasing injection pressure because the spray could be atomized with the smaller droplet and then easily evaporate and mixed with the air. Consequently, ignition delay was advanced. Contradictorily, with the increased injection pressure, in-cylinder pressure of gasoline decreased. Due to relatively low viscosity and low bulk modulus, gasoline could not resist the high compression at high injection pressure. GB05 may leak as ligament into the combustion chamber and spray velocity is low. Therefore, fuel-air mixing process hardly occurred thus delaying the ignition timing.

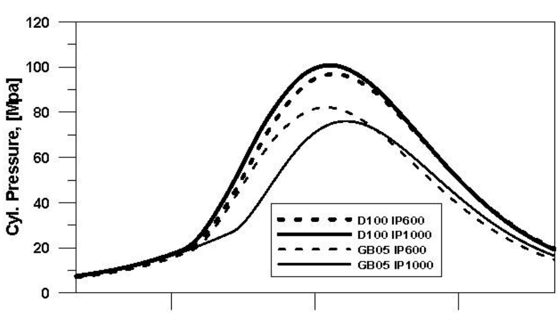


Fig. 2 In-cylinder pressure of GB05 and D100 injected into the cylinder with 600 and 1,000 bar of injection pressure.

Fig.3 shows the heat release rate and the crank angle and duration at 5 %, 10%, 50% and 90 % mass fraction burned of GB05 and neat biodiesel (D100) when injected into the cylinder with 600 and 1,000 bar of injection pressure. Due to evaporation process, the injected fuels required the heat for vaporization. As the results, the negative value of heat release rate was presented. The heat release rates of biodiesel for both injection timings and GB05 at low injection pressure of 600 bar are similar while GB05 at high injection pressure of 1,000 bar showed the obviously different. For biodiesel, premixed and diffusion combustion showed the similar maximum heat release rate while GB05 at injection pressure of 1,000 bar indicated the maximum heat release rate during the diffusion phase. When injection pressure increased, ignition delay of biodiesel was advanced while GB05 delayed. As discussed above, the small droplet and easier air-fuel mixing process the combustion of biodiesel at high injection pressure could readily commence and resulted in higher rate of heat release than low injection pressure. However, the less fuels were left for diffusion combustion. Therefore, the heat release rate are slightly lower than the low injection pressure.

For gasoline combustion, the fuel injected at the low pressure can evaporate and mix with air and then combust early. Consequently, the premixed combustion showed higher heat release rate. However, after injection pressure increased, the gasoline ligament hardly evaporated with the high latent heat of vaporization [8,9] indicated by the much more negative value. The less mature mixture can be oxidized during premixed combustion phase. As the results, more fuels are left to combust at diffusion phase.

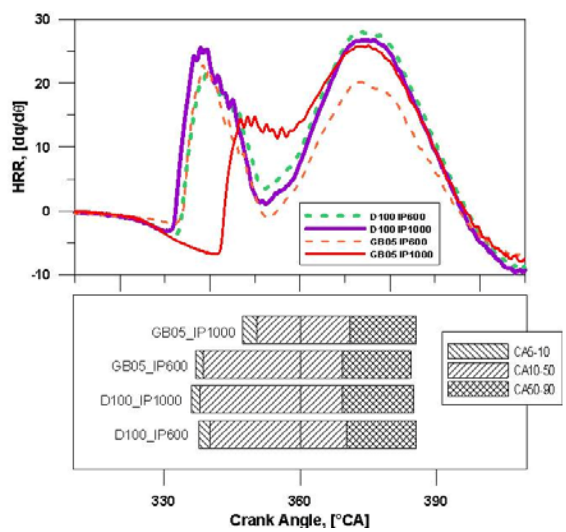


Fig. 3 Heat release rate (top) and crank angle of mass fraction burned (bottom) of GB05 and D100 injected into the cylinder with 600 and 1,000 bar of injection.

Biodiesel at high injection pressure yielded slightly longer combustion duration than those of low injection pressure and GB05 as seen in Fig.3 (bottom).

# AEC0024

At high injection pressure, GB05 had the lowest combustion duration. The combustion started later but terminated as the same time with other conditions. Most of the injected gasoline fuel was combusted after top dead center. This resulted in lower in-cylinder pressure in Fig.2. Fifty percent of mass for all test conditions was burned nearly the same crack angle after top dead center.

### 3.2 Exhaust gas emissions

Exhaust gas emissions including carbon monoxide (CO), total hydrocarbon (THC) and oxide of nitrogen ($NO_X$) are presented in Fig. 4. The levels of CO emission decreased for biodiesel combustion but increased for GB05 when injection pressure increased. As discussed previously, more complete combustion occurred when injection pressure increased for biodiesel and poor oxidation happened in case of gasoline. Gasoline combustion at low injection pressure showed the advantage to decrease CO emissions over biodiesel at the same injection pressure.

THC concentrations decreased with the increase injection pressure for both of biodiesel and GB05. More complete combustion is the cause of THC reduction of biodiesel at high injection pressure. For gasoline at lower injection pressure, the higher in-cylinder pressure during the compression and combustion stroke forced more gases which will escapes from the primary combustion into the crevices or narrow volumes. Those gases will leave the crevices in the expansion stroke and be measured as unburned hydrocarbon. In addition, with low spray velocity of gasoline at high injection pressure, the spray penetration tip did not attach the piston and the wall. Therefore, hydrocarbon could be oxidized in the combustion process. At lower injection pressure, biodiesel produced THC lower than GB0 due to the better fuel-air mixing process and more complete combustion of biodiesel. At higher injection pressure, more unburned fuel escaping into the crevices from higher in-cylinder pressure of biodiesel combustion played the major role to increase THC higher than gasoline combustion.

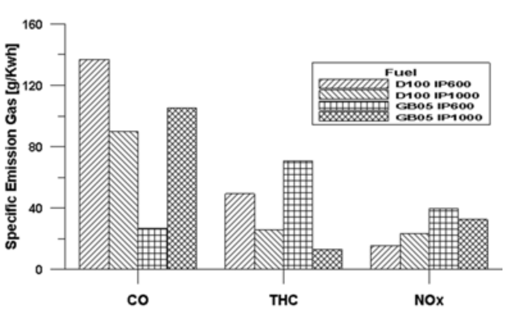


Fig. 4 Exhaust emissions of GB05 and D100 combustion at 600 bar and 1,000 bar of injection pressure.

It is surprising that $NO_X$ emissions of biodiesel were lower than that of gasoline for all conditions. Although the combustion temperature of biodiesel were higher than gasoline combustion, much more time after the combustion allowed more heat transferring to the chamber walls. Therefore, the temperature at the end of combustion and expansion stroke decreased as shown in Fig. 5. $NO_X$ formation was frozen and lower than the late combustion of gasoline.

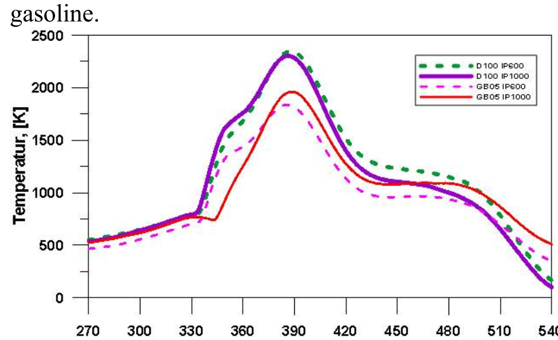


Fig. 5 In-cylinder temperature of GB05 and D100 combustion at 600 bar and 1,000 bar of injection pressure.

## 4. Conclusions

1. At the same injection pressure, ignition delay was lengthened when using gasoline relative to biodiesel.
2. At high injection pressure, the diffusion phase of gasoline combustion was dominated than premixed combustion.
3. Increasing injection pressure could increase in cylinder pressure and heat release rate of biodiesel while gasoline showed the different trend
4. The combustion duration of gasoline at low injection pressure was similar to biodiesel but significant shorten at high injection pressure
5. GB05 can reduce CO but increase NOx while THC is depended on injection pressure.
6. Further investigation is required to find the optimum injection pressure for GB05.

## 5. Acknowledgement

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**AEC0024**

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