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Full Length Article

Application of double-injection strategy on gasoline compression ignition engine under low load condition

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HIGHLIGHTS

- Double-injection strategy was applied to GCI engine under low load condition.
- MPRR was greatly reduced with double-injection strategy at the expense of fuel economy, IMEP and emissions.
- Double-injection GCI operated with limited operating ranges due to combustion instability.
- Strong natural luminosity by soot incandescence is attributed to diesel-like diffusion flame with double-injection strategy.

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ABSTRACT

Gasoline compression ignition (GCI), or gasoline direct-injection compression ignition (GDCI), is a concept that utilizing gasoline instead of conventional diesel fuel in a compression ignition (CI) engine for higher efficiency and lower emissions. Even though the single-injection GCI engine works well under the low load condition of 0.45 MPa indicated mean effective pressure (IMEP). In this study, the double-injection strategies including pilot- and main-injections were applied on a GCI engine under the low load condition to reduce the combustion noise. The effects of the pilot-injection timing and the pilot-injection quantity on a double-injection GCI engine with a fixed main-injection timing were investigated and compared with the single-injection GCI in a single-cylinder heavy-duty CI engine under the low load condition. In addition, the direct imaging of the flame propagation of gasoline double-injection was conducted in an optically accessible engine that was modified from the same engine to infer the emission trends. First of all, the double-injection GCI showed a reduction of the maximum pressure rise rate from 1.3 MPa/degree to $0.2 \sim 0.3$ MPa/degrees. In addition, the reduction of nitrogen-oxide (NOx) levels in half was measured compared with the single-injection GCI due to the lower combustion temperature. However, the double-injection GCI operated with nearly 5% coefficient of variation (COV) in IMEP under the most experimental conditions. IMEP and fuel economy were slightly decreased. A significant increase of the carbon monoxide (CO) and soot emissions were also shown, although the emission levels were much less than that from the conventional diesel CI engine. The flame images demonstrated that the gasoline main-injection showed a diesel-like luminous diffusion flame, which would be a main source of the soot formation, because the pilot-injection give rises to a high temperature and high pressure conditions in which gasoline from the main-injection can be ignited with shorter ignition delays.

1. Introduction

The compression ignition (CI) engine is a more attractive type of internal combustion engine for a higher thermal efficiency due to its high compression ratio and a lack of pumping losses, and its lower hydrocarbon (HC) and carbon-monoxide (CO) emissions than the spark ignition (SI) engine [1–3]. CI engines have been utilized not only in heavy-duty applications such as trucks, construc-

Abbreviations: CI, compression ignition; GCI, gasoline compression ignition; HCCI, homogeneous charge compression ignition; PCCI, premixed charge compression ignition; TDC, top dead center; HC, hydrocarbon; SINL, spatially integrated natural luminosity; Fps, frame per second; Isfc, indicated specific fuel consumption; SI, spark ignition; GDCI, gasoline direct-injection compression ignition; LTC, low temperature combustion; CAD, crank angle degree; IMEP, indicated mean effective pressure; CO, carbon monoxide; NO_x, nitrogen oxides; COV, coefficient of variation; MPRR, maximum pressure rise rate.

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Nomenclature

SOI	start timing of injection
SOIm	start timing of main injection
SOIp	start timing of pilot combustion
aTDC	after top dead center
SOIp	start timing of pilot injection
SOC	start timing of combustion
SOCm	start timing of main combustion

tion machines and ships, but also in light-duty passenger cars for these reasons. The strict emission regulations for nitro-oxides (NOx) and soot, however, annually forced manufacturers and researchers to improve CI engine related technologies to meet the regulations. The simultaneous reduction of NOx and soot emissions is difficult due to their trade-off characteristic [1–4]. Many of the advanced combustion technologies, including homogeneous charge compression ignition (HCCI), premixed charge compression ignition (PCCI) and low temperature combustion (LTC), have been applied to reduce the NOx and soot emissions simultaneously. For HCCI and PCCI, homogenous or premixed mixtures are applied before the compression ignition to reduce the fuel-rich regions that are the main source of the NOx and soot emissions [2,5–8]. The PCCI combustion adopts a moderately early injection timing to improve the combustion phase controllability and to reduce HC and CO emissions which are the most challenging problems in HCCI combustion [8]. Conventional diesel fuels have high cetane number of greater than 40. In the HCCI or PCCI combustion, the diesel fuel shows a short ignition delay before a sufficient mixing time for the fuel and air inside cylinder is reached [9]. In addition to the high cetane number, its low volatility gives rise to unfavorable mixing characteristics during the compression stroke so that locally fuel-rich mixtures can be created [10]. The soot is generated during the oxidation process in the fuel-rich mixtures through the reaction of the fuel and air. Then, this fuel-rich mixture burns out in a high-temperature diffusion flame at the jet periphery, leading to the NOx formation [11].

Since Kalghatgi et al. [9–11] initially suggested the possibility of using gasoline-like fuel in a HCCI engine, studies on the application of gasoline-like fuels for CI engines have demonstrated that the superior resistance to auto-ignition. The higher volatility of those fuels are suitable for well-premixed or properly stratified mixture prior to the ignition to reduce both the NOx and soot emissions while maintaining high efficiency that is comparable to those of conventional diesel CI engines [12–17]. For these studies, conventional CI engines fueled with gasoline or gasoline-like fuels, which are termed the gasoline compression ignition (GCI) engine or the gasoline direct injection compression ignition (GDCI) engine, were used. Due to the differences in the fuel properties between gasoline and diesel, fundamental studies about the spray characteristics and chemical kinetics have been conducted over the last 10 years. Payri et al. [18] and López et al. [19] compared the injection rate and macroscopic spray characteristics including the liquid length and the spray angle of gasoline and diesel in a constant volume vessel under non-evaporative and evaporative conditions using the common-rail injection system. They demonstrated that both fuels showed similar spray characteristics under the non-evaporative condition; however, the gasoline spray exhibited a shorter liquid length than that of the diesel spray under the evaporative condition due to the difference of the vaporized fuel mass fraction.

The multiple-injection strategy has been known as a useful tool for the mitigation of the NOx/soot trade-off and for the decrease of the combustion noise with maintaining a low fuel consumption. The great flexibility and repeatability are now available thanks to the development of the injection system including common-rails, injectors and control logics for the injection timing, the injection quantity and the number of injections [20]. Pilot injections are usually used to reduce both the ignition delay and air-fuel mixing of the main injection, which could reduce NOx, CO and HC emissions [21,22] as well as to reduce combustion noise [23–25]. The reduced air-fuel mixing means the increase of diffusion combustion which leads to soot formation [22]. To overcome this soot formation, the post-injection can be used [26].

Under the high load condition of the GCI engine, the multiple-injection strategy is applied obligatorily for the reduction of the combustion noise [10,14]. However, there is a lack of research regarding multiple-injection under the low load condition because the combustion instability becomes a more important problem under the low load condition. Based on the authors' previous research [27], the stable combustion of the GCI engine showed the high maximum pressure rise rates under the low load condition, at which the maximum pressure rise rate is near 1.3 MPa/degree. This is a serious problem for the maintenance of the GCI engine, even under the low load condition.

Therefore, in this research, the double-injection strategy including a pilot injection and a main injection was applied in a GCI engine to reduce the combustion noise, while the engine performance and emissions were kept within reasonable levels, even under low load condition of 0.45 MPa IMEP. From the authors' previous research [27], the reference condition for the single-injection GCI case is the maximum IMEP condition. The effects of the pilot-injection timing and the pilot-injection quantity were investigated and compared with the single injection in a conventional heavy-duty CI engine, as well as in an optically accessible engine modified from the identical engine. The trend of engine performance and emission results were inferred by the captured flame images.

2. Experimental apparatus and conditions

2.1. Experimental apparatus

A four-stroke heavy-duty CI engine was modified into a single-cylinder engine, which is the same engine used in the authors' previous research [27], for this research. The details of the engine specifications are listed in Table 1. The engine has a bore of 100 mm and a stroke of 125 mm with a compression ratio of 17.4:1. The displacement volume is 981 cc. An experimental schematic diagram is shown in Fig. 1. The conventional common-rail

Table 1
Engine specification.

Single-cylinder, four-stroke, direct-injection, four-valves, compression ignition engine	
Bore (mm) × stroke (mm)	100 × 125
Displacement (cc)	981
Compression ratio	17.4:1
Fuel injection type	Common-rail injection system
Injector	8 holes, Hydraulic Flow Rate (HFR) 460 cc/30 s, injection angle 146°, nozzle diameter 0.146 mm