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Effects of the injection timing on spray and combustion characteristics in a spray-guided DISI engine under lean-stratified operation

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HIGHLIGHTS

- ▶ We tested spray-guided direct injection single cylinder gasoline engine under lean stratified operation condition.
- ▶ We investigated flame and spray characteristics using visualization techniques.
- ▶ Over-mixing and under-mixing effects were shown at advanced and retarded injection timings respectively.
- ▶ Non-luminous flame was dominant for advanced injection timing while luminous flame increased as injection timing retarded.
- ▶ IMEP and NOx emission was verified that significantly affected by combustion phasing corresponding injection timing.

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ABSTRACT

An experimental study was carried out to investigate the effects of injection timing on spray and combustion characteristics in a spray guided direct injection spark ignition (DISI) engine under lean stratified operation. In-cylinder pressure analysis, exhaust emissions measurement, and visualization of combustion and spray were applied. Combustion in a stratified DISI engine was found to have both lean premixed and mixing controlled flame characteristics. The stratified mixture characteristic for the injection timing was verified as a dominant factor of the flame characteristics. For the early injection timing, non-luminous flame and low combustion efficiency were observed due to the over-mixed mixture formation. On the contrary, luminous sooting flame was shown at the late injection timing because of under-mixed mixture formation. In addition, smoke emission and incomplete combustion products were increased at the late injection timing due to increased locally rich area of the mixture. On the other hand, nitrogen oxides (NOx) emissions were decreased while indicated mean effective pressure (IMEP) was increased as the injection timing was retarded. The retarded combustion phasing was verified as the reason in this observation.

1. Introduction

In order to reduce hazardous emissions and the fuel consumption, direct-injection spark-ignition (DISI) concept was introduced in the gasoline engine technology [1]. Wall-guided concept, which uses the internal flow (e.g. tumble and reverse tumble) for the stratified mixture preparation, was introduced as the first type of a stratified DISI engine [2]. However, the internal flow is significantly influenced by operation condition variation such as engine speed and valve timing. Therefore, combustion stability of stratified wall-guided DISI engines is sensitive for the given operation condition. In addition, hydrocarbon (HC) and smoke emissions were high due to the fuel impingement on the piston, which is inevitable for the stratified mixture preparation [3,4]. Therefore, spray-guided concept, which only uses the spray momentum for the stratified mixture preparation, is recognized as a more appropriate system for the stratified DISI engine due to its stable operation and less piston-spray interaction [5–7].

In spray-guided DISI engines, multihole injectors and outwardly opening injectors were mainly adopted in the system. Previous one has a number of orifices and produces spray plumes in the similar manner with current diesel injectors. The latter one has a pintle type nozzle and provides hollow cone shape of spray consisting of fuel strings [8,9]. In the early studies, outwardly opening injector is known to have more benefit in terms of turbulence and mixture preparation [9,10]. In addition, outwardly opening injectors widely adopt piezo electric driven system, which enables fast response and precise injection control [11]. Therefore, they were adopted widely in today's commercialized spray guided DISI engine

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Nomenclature

I_t	intensity of overall flame
I_l	intensity of luminous flame
N	number of pixel
θ	crank angle
Q_{inj}	injection quantity (mg/stroke)
P_{inj}	injection pressure (MPa)
P_{amb}	ambient pressure (MPa)
ρ	smoke density (mg/m^3)
x_i	mass fraction of species i
$Q_{i,\mathrm{HV}}$	heating value (MJ/kg)
$\dot{m}$	mass flow rate (kg/s)

Abbreviations

BTDC	before top dead center
CAD	crank angle degree
DISI	direct injection spark ignition
EOI	end of injection
EGR	exhaust gas recirculation
FSN	filtered smoke number
HC	hydrocarbon
IMEP	indicated mean effective pressure
LIR	luminous intensity ratio
NOx	nitrogen oxide
PLIF	planar laser induced fluorescence

systems. On the other hand, multihole injectors are known that it is more advantageous in terms of cost and production. In that respect, multihole injectors are also being adopted in the newest spray guided DISI engines currently [12].

Spray guided system adopts narrow spacing concept of which injector is located near the spark plug with moderate eccentricity. Stratification of the mixture is promoted simply by the juxtaposition of the fuel injector and spark gap. Therefore, the stratification capability of the narrow spacing concept is significantly higher than wall guided type [1]. However, unfavorable mixture preparation such as inhomogenous air/fuel ratio distribution could take place which results in unstable and incomplete combustion because of its shorter mixing length and mixing time. On that account, injection strategy is known as one of the most important technical issues for the engine performance and emission improvement in spray guided DISI engines. Especially, injection timing was reported as the most essential operating parameter for emissions and combustion characteristics. In earlier studies, it was found that spray guided DISI engine has narrow range of injection timing for the stable stratified combustion limited by misfire. The optimized injection timing for the fuel consumption and cyclic variation was found to be at the middle of flammable injection timing window [8,13,14]. Furthermore, NOx emissions and smoke emission were also found to be affected by injection timing significantly. NOx emissions were reported to be decreased as injection timing was retarded while the smoke emission was increased with the retarded injection timing [14,15]. However, despite early studies reporting the effect of injection timing, further researches concentrated on injection timing as a main parameter are required to provide the physical explanation.

Visualization techniques have been actively applied in engine researches to understand physical phenomena of the in-cylinder combustion and spray. There are pioneering studies using combustion and mixture visualization in spray guided DISI engine research. Visualization of in-cylinder combustion have been carried out with the combustion diagnostics such as chemiluminescence visualization of intermediate combustion species [15–18], in-cylinder soot imaging/pyrometry [15,18,19] and flame natural luminosity imaging including endoscopic visualization [19–21]. In addition, in-cylinder mixture characteristics were investigated by various techniques such as planar laser induced fluorescence (PLIF) [22,23]. In these earlier studies, injection timing was verified to affect spray-piston and/or plug interaction and mixing characteristics.

In this study, metal engine test and visualization techniques were applied to investigate detailed effects of injection timing in a spray guided DISI engine under stratified combustion condition. In-cylinder pressure analysis and emissions measurement were conducted to investigate combustion and emission behaviors for various injection timings. PLIF technique was applied in a constant volume chamber to verify the effects of the injection timing on the stratified mixture. In-cylinder spray and combustion were visualized to provide a comprehensive understanding of the combustion and mixture formation.

2. Experimental setup and conditions

2.1. Spray visualization in a constant volume chamber

A schematic diagram of the spray visualization in a constant volume chamber is shown in Fig. 1. The spray images were taken by planar laser induced fluorescence method. The optical access to the chamber was realized through quartz windows. The chamber was pressurized with nitrogen at room temperature. The 4th harmonic wavelength (266 nm) laser beam was provided by Nd-YAG laser (Spectra Physics, Powerlites). The laser beam was formed into a collimated laser sheet with a cylindrical lens. An intensifying charged coupled device (ICCD) camera (Princeton Instruments, PI Max 2) captured the fluorescence signal with a 512 × 512 pixels spatial resolution and 10 μs of exposure time through the perpendicular window of the chamber. A 280 nm long pass optical filter was used to remove the elastically scattered laser light.

The averaged image of 10 raw ones was used to analyze spray and mixture formation. For the PLIF visualization, iso-octane was selected as a surrogate fuel of gasoline. 20 vol.% of 3-pentanone was mixed as a fuel tracer to produce a fluorescence signal, as suggested in earlier studies [24]. These species and their concentration were suggested as the solution for tracking the fuel distribution, showing non-varying fluorescence during the evaporation process as well as similarity to the physical properties of real fuels.

2.2. Research engine

A single-cylinder spray guided DISI engine with a centrally installed piezo-actuated outwardly-opening injector (Continental VDO) was tested. The schematic diagram of the experimental engine setup is shown in Fig. 2. The engine specifications are listed in Table 1. The engine speed was controlled by a DC dynamometer. A programmable injector driver controlled the injection parameters (Zenobalti Co., IDU 5000B). The in-cylinder pressure was recorded with a piezoelectric pressure transducer (KISTLER, 6052). Recording was done with a step of 0.1 crank angle degree (CAD). After measurement of 100 engine cycles, the pressure data was averaged to calculate the heat release rate and indicated mean effected pressure (IMEP). No external EGR (exhaust gas recirculation) was applied in the test.

The engine has optical access for visualization of the in-cylinder combustion and spray. An elongated piston was applied to enable the mounting of a 45° mirror beneath the piston quartz window.