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Influences of fuel injection strategies on combustion performance and regular/irregular emissions in a turbocharged gasoline direct injection engine: Commercial gasoline versus multi-components gasoline surrogates

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ABSTRACT

Injection strategies and fuel properties have significant effect on the mixing process of fuel and air in the cylinder, which further affects the combustion and emissions. Three types of gasoline surrogate fuels were tested on a gasoline direct injection (GDI) engine in this paper. The effects of different injection pressures and injection timings on the combustion and emissions of the surrogate fuels were investigated, and the results were compared with those of a commercial gasoline with an octane number of 95. Also, the experiments were conducted at a stoichiometric air-fuel ratio with the engine speed of 2000 rpm and a load of 6 bar. The results show that injection pressure and injection timing have certain effects on the combustion and emissions of the surrogate fuels, which indicates clear differences with the commercial gasoline. In addition, the combustion and emissions of the surrogates are also different due to different compositions. The surrogates have higher in-cylinder pressure and temperature and more advanced combustion phase than commercial gasoline. The surrogates have advantages in NOx emissions and PM emissions under all the testing conditions. Nevertheless, gasoline has much lower CO emissions, THC emissions and most irregular emissions. Generally, low injection pressure and retarded injection timing can be applied to obtain higher thermal efficiency of the surrogate fuels, whereas for gasoline, the injection timing need to be kept at around 300 ^{o}CA BTDC. To obtain low CO and THC emissions, gasoline should be applied with low injection pressure and the injection timing should be postponed. On the other hand, for low PM and NOx emissions, the surrogate fuels should be utilized with high injection pressure and the injection timing should be around 300 ^{o}CA BTDC.

1. Introduction

To achieve higher efficiency and lower emissions, conventional gasoline engines usually require significant development of highly efficient and clean combustion. A way to improve fuel efficiency without making a major shift away from the conventional internal combustion technologies has been well recognized in the usage of changing the injection strategies, while direct injection has been found to form a better mixture in comparison with the port fuel injection (PFI) engines due to the more precise control of fuel injection [1–3]. In particular, gasoline direct injection (GDI) engines have been widely studied due to the high compression ratio and low pump loss which lead to excellent fuel economy and high output power [4,5]. Wang et al. [6] applied a two-stage GDI system to investigate the effects of injection strategies on the mixing process and engine performance. The results showed that the spray penetration increased with the increase of injection pressure, and there was an optimal injection timing to obtain a good engine performance. In addition, the fuel consumption of the GDI engine was 15%–24% lower than that of the PFI engines. Jang et al. [7] conducted an investigation utilizing gasoline and liquefied petroleum gas on a 1.6-L GDI engine. The results indicated that the fuel economy of gasoline used in direct injection engine was 15–18% higher than that of the liquefied petroleum gas. Park et al. [8] analyzed the effects of a GDI combustion system on the stratified lean combustion in a single-cylinder engine. According to the results, the injection timing was closely related and sensitive to the

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Nomenclature

ATDC	after top dead center
BMEP	brake mean effective pressure
BTDC	before top dead center
CA	crank angle
CA10	crank angle for 10% of the heat release
CA50	crank angle for 50% of the heat release
CO	carbon monoxide
CTRF	cyclohexane-toluene reference fuel
CDTRF	cyclohexane-diisobutylene-toluene reference fuel
GDI	gasoline direct injection
GMD	geometric mean diameter
IMEP	indicated mean effective pressure
LHV	low heating value
NOx	nitrogen oxide
PFI	port fuel injection
PM	particulate matter
Pmax	the maximum in-cylinder pressure
PRRmax	the maximum in-cylinder pressure increase rate
PRF	primary reference fuel
RON	research octane number
TRF	toluene reference fuel
THC	total hydrocarbon
Tem	exhaust manifold temperature
Tmax	the maximum in-cylinder temperature
λ	equivalence ratio
η	indicated thermal efficiency

combustion efficiency, and the smoke emissions were not reduced when the injection pressure increased to 20 MPa. Researches carried out by Li et al. [9] illustrated that injection timing had a significant effect on the controlled auto-ignition.

However, GDI engines are still facing the challenge of high particulate matter (PM) emissions, which have attracted the attention of many researchers [10–15]. PM emissions from GDI engines are mainly derived from two types of rich burn, including the local fuel-rich region and the diffusion combustion of the oil film on the piston and cylinder wall, which is called “pool” [16–18]. Even though GDI engines facilitate full mixing in the cylinder, inhomogeneous premixed combustion still exist due to the insufficient evaporation and mixing, especially for those small supercharged engines under high load conditions where a large amount of fuel is injected into the cylinder [12,17]. As suggested by Maricq et al. [19], another source of PM formation, especially while GDI engines are operating in the stratified mode, is attributable to the incompletely volatilized fuel droplets, as the unburned gas is swept across by the incoming flame front. Meanwhile, injection strategies have significant effect on the air-fuel mixture in the cylinder, which has close relation to engine efficiency and emissions [20,21]. Wang et al. [22] investigated the effect of injection pressure on particle emissions in a spray-guided GDI engine. The results indicated that with the increase in the injection pressure, the particle mass and particle number emissions reduced by up to 22% and 78%, respectively. Huang et al. [23] studied the effect of direct injection timing on the fuel evaporation, mixing, combustion and emission processes. According to the results, the retarded injection timing resulted in severe fuel impingement, local over-cooling effect and over-rich mixture. As a result, the combustion speed and temperature decreased, leading to the reduction of NO emission as well as the increase of HC and CO emissions. Therefore, adjusting different injection strategies is of great importance to enhancing the efficiency and emissions of GDI engines.

Another factor affecting air-fuel mixture in the cylinder is the properties of the fuel [24]. Building reliable and efficient chemical reaction kinetics of gasoline play a significant role in understanding the process of generating combustion and emissions. Commercial gasoline contains hundreds of hydrocarbons compounds [25–28], and the content of each compound varies significantly due to the source of crude oil, refinery process and product specifications. Different types of gasolines with the same octane number may be vastly different in composition, properties and molecular structure [29]. Hence, it is unrealistic to build chemical kinetic models of each gasoline component. In this case, a surrogate fuel is generally applied to describe the behavior of the combustion of real fuel with several representative components of each type of hydrocarbon.

Matching the physical and chemical properties of real fuels accurately is of great importance yet is still facing challenges due to the complicated compositions and reaction mechanisms. The vital goals of surrogate fuels relate to the physical properties, including viscosity, density, volatilization characteristics and so forth. In terms of chemical properties, molecular structures, H/C ratio and combustion behavior may be essential. Isooctane is considered as the simplest surrogate fuel due to its high-octane number, and is utilized in computational fluid dynamics and chemical kinetic simulations [30]. In addition, *n*-heptane is often applied to represent diesel fuel due to its low octane number. Generally, the blends of *n*-heptane and isooctane can be defined as the primary reference fuels (PRF) which are considered to be practical gasoline surrogate fuels and have been widely utilized due to the variable octane numbers [31–33]. With the extensive researches of surrogate fuels, aromatics are widely added as surrogate fuel components [27,34,35], since PRF cannot provide a full picture of fuel combustion properties [27,35–38].

Pera et al. [39] conducted an experiment utilizing the toluene reference fuel that contained 13.7% *n*-heptane, 42.8% iso-octane and 43.5% toluene in the controlled auto-ignition combustion mode, as well as compared the results with those of gasoline. The results indicated that the surrogate fuel had similar auto-ignition, efficiency and emissions to gasoline. In addition, Chung et al. [40] carried out an experiment to find a better explanation for the two-stage ignition characteristics of gasoline and its surrogates. According to the findings, the surrogates containing a high portion of cyclic alkenes (approximately 20%) could better simulate gasoline autoignition, including the two-stage ignition characteristics. Andrae et al. [41] applied the detailed chemical dynamics models, demonstrating that each component of the surrogate fuel, consisting of *n*-heptane, iso-octane, toluene, diisobutylene and ethanol, had an essential effect on auto-ignition. A large number of surrogate fuels have been proposed so far, and then evaluated on the basis of internal combustion engine experiments [25,42–45] and numerical studies [46–50].

In fact, many researches have been conducted on GDI engines whereas few studies have been done on the combustion and emissions of surrogate fuel on GDI engines. Five neat fuels, including *n*-heptane, iso-octane, toluene, cyclohexane and diisobutylene were selected to build toluene reference fuel (TRF), cyclohexane-toluene reference fuel (CTRF) and cyclohexane-diisobutylene-toluene reference fuel (CDTRF), which all had the same research octane number of 95. The investigations into the combustion and emissions effects of injection pressure and injection timing utilizing the three surrogate fuels were reported, and the results were compare with those of the commercial gasoline.