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Combustion performance, flame, and soot characteristics of gasoline–diesel pre-blended fuel in an optical compression-ignition engine

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ABSTRACT

Among the new combustion technologies available for internal combustion engines to enhance performance and reduce exhausted emissions, the homogeneous charge compression ignition method is one of the most effective strategies for the compression-ignition engine. There are some challenges to realize the homogeneous charge compression ignition method in the compression-ignition engine. The use of gasoline–diesel blended fuel has been suggested as an alternative strategy to take advantages of homogeneous charge compression ignition while overcoming its challenges. Gasoline and diesel fuels are reference fuels for the spark-ignition and compression-ignition engines, respectively, both of which are widely used. The application of both these fuels together in the compression-ignition engine has been investigated using a hybrid injection system combining port fuel injection (gasoline) and direct injection (diesel); this strategy is termed reactivity controlled compression ignition. However, the pre-blending of gasoline and diesel fuels for direct injection systems has been rarely studied. For the case of direct injection of pre-blended fuel into the cylinder, various aspects of blended fuels should be investigated, including their spray breakup, fuel/air mixing, combustion development, and emissions.

In the present study, the use of gasoline–diesel pre-blended fuel in an optical single-cylinder compression-ignition engine was investigated under various conditions of injection timing and pressure. Furthermore, KIVA-3V release 2 code was employed to model the formation of fuel/air mixtures in the cylinder. Neat diesel fuel was tested, as well as gasoline–diesel blends of 20% and 40% gasoline mass fraction. Experiments on the mixed fuels showed that the inclusion of gasoline fuel improved fuel/air mixing, yielding more homogeneous mixtures over wider cylinder areas. The low cetane index of gasoline fuel induced long ignition delays in the mixed fuels. Compared with neat diesel combustion flame, blended fuel did not produce the soot flame, white-yellow flame. Soot intensity was calculated based on captured flame images, and its variations were investigated as a function of fuel type and injection conditions.

1. Introduction

The desire to enhance fuel economy and thermal efficiency in the internal combustion engine is driving high technology and various investigations of combustion. Also, the environmental protection movement has led to regulations in many countries requiring low exhausted emissions from transportations. To meet these demands, new combustion or engine concepts have been developed, such as modulated kinetics combustion, lean-burn, and fuel direct-injection. Among these new ideas, the homogeneous charge compression-ignition (HCCI) concept has emerged as a means to achieve high engine performance and considerable reduction of emissions simultaneously in the compression-ignition (CI) engine. Although the CI engine has high power and low fuel consumption, it tends to produce high noxious emissions, making it difficult to design for meeting strict emission regulations.

HCCI increases the fuel/air mixture homogeneity, leading to high thermal efficiency and low levels of nitrogen oxides (NO_x) and particulate matter (PM) [1]. Yao et al. [2] reported the advantage of the HCCI regime on NO_x and PM emissions, summarizing various literatures. Imtenan et al. [3] accounted for low emission

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Nomenclature

ALE	arbitrary Eulerian–Lagrangian	NO_x	nitrogen oxides
ATDC	after top dead center	$P_{inj.}$	injection pressure
BMEP	brake mean effective pressure	PM	particulate matter
BTDC	before top dead center	PRFs	primary reference fuels
CA	crank angle	RCCI	reactivity controlled compression ignition
CI	compression ignition	RNG	renormalized group
DICI	direct injection compression-ignition	ROI	radius-of-influence
DMC	discrete multi-component	RT	Rayleigh–Taylor
HCCI	homogeneous charge compression ignition	SCRE	single-cylinder research engine
KH	Kelvin–Helmholtz	SOI	start of injection
LHV	lower heating value	SOC	start of combustion
LTC	low temperature combustion	TDC	top dead center
m/m	mass by mass	$\tau_{inj.}$	injection timing

concentration from a HCCI engine as one of low temperature combustion strategies. However, there are many challenges to overcome to be able to realize this idea in the CI engine. It is difficult to control the ignition timing and combustion phasing in the HCCI engine. In addition, diesel-like fuels with high cetane number advance the ignition timing, leading to insufficient mixing time. Therefore, new methodologies have been introduced to overcome the drawbacks of HCCI. Recently, gasoline-like fuels have been employed in the CI engine as a fuel, although they have poor auto-ignition and high octane numbers. Their poor self-ignition can extend the fuel/air mixing time between the start of injection (SOI) and the start of combustion (SOC), similar conditions as those brought about by using HCCI. Because applying pure gasoline-like fuels in the CI engine is challenging, many research groups have investigated dual-fuel, gasoline–diesel blended fuels.

The physical properties of gasoline fuel affect fuel injection, atomization, mixture formation and ignition timing. Kim et al. [4] conducted spray and combustion experiments to compare gasoline and diesel fuels in the CI engine; they found that the distillation temperature of gasoline is around 50% lower than that of diesel, which accelerates fuel evaporation and fuel/air mixing processes. Since gasoline fuel is lower density and viscosity properties than those of diesel, injection rate could be lower than diesel and it affects the injector's needle dynamic [5]. Kook and Pickett showed that low density and viscosity properties induced the increase in the air entrainment and shorter spray penetration length compared to that of diesel spray [6]. When gasoline and diesel are mixed, the mixed fuel thus has considerably different spray behaviors. Park et al. [7] investigated the effects of gasoline fuel on gasoline–diesel blended fuel in terms of spray and combustion characteristics. As the portion of gasoline is increased within the blend, the blended fuel decreases in density and viscosity. In addition, they reported that increasing the gasoline content and thereby decreasing the surface tension of the blended fuel makes fuel droplets break up more easily, consequently speeding up the fuel/air mixture process. An experimental study by Han et al. [8] showed that increasing the gasoline content of blended fuel increases the injection rate due to the lower density and viscosity of gasoline fuel. They observed by means of a visualization system that mixed fuel with higher gasoline content breaks up more and then spreads out toward the ambient gas. In spray pictures, the fuel droplets decreased in size with increased gasoline ratio. However, the difference in penetration length between diesel and gasoline–diesel blended fuels decreased as the development of both sprays progressed.

The extended ignition delay caused by the poor auto-ignition of gasoline leads to the formation of homogeneous fuel/air mixtures and to premixed low temperature combustion (LTC) [9]. The effects of gasoline fuel on the ignition delay was studied by Thoo et al. [10]. This is effective in reducing emissions from the CI engine. Benajes et al. [11] reported that the controlling auto-ignition by gasoline achieved the reduction of NO_x and soot emissions simultaneously, meeting EURO VI emission limits. In general, soot emission is generated in fuel-rich conditions, which is highly related to the fuel/air homogeneity. High combustion temperature is proportionally correlated with the formation of NO_x. Thus, the benefits of good fuel/air homogeneity and LTC have encouraged researchers to investigate the use of gasoline–diesel blended fuel combustion in the CI engine. To further extend the ignition delay period, a method called the reactivity controlled compression ignition (RCCI) method has been developed whereby the gasoline fuel is injected into the intake port to allow gasoline and air to mix, followed by direct injection of the diesel fuel into the combustion chamber [12]. Kokjohn et al. [13] demonstrated the RCCI concept as a new clean combustion method experimentally, comparing the conventional diesel engine. The verity of investigation of RCCI has been performed in terms of injection timing, fuel types and blending ratio. Benajes et al. [14] conducted the combustion and emission experiments of the RCCI engine under various direct injection timing with four different gasoline fuels. They used different reactivity gasoline fuels which contains different ratio of ethanol. Lee's research group introduced propane fuel as a low reactivity fuel [15]. Li et al. [16] used two different high reactivity fuels; diesel and biodiesel with gasoline fuel for the RCCI method. They expanded the new combustion method to the various fuel types. Lu et al. [17] varied the gasoline/diesel ratio from 30% to 50% gasoline contents by volume in the RCCI concept. They concluded that the 30% gasoline condition reduced the NO_x and soot emissions, simultaneously. Because the RCCI systems require the use of an additional injection system for gasoline fuel, a pre-mixed gasoline–diesel blend and a direct injection (DI) method were used in the present work, which also allows to use the spray characteristics for gasoline fuel in the cylinder. These two kinds of injection methodologies was compared in the Lu et al. research [18]. For the pre-blended gasoline–diesel fuel, the manufacture is simple; these fuels mix well and do not undergo phase separation [7]. Han et al. [19] produced premixed LTC conditions for gasoline–diesel blended fuel in a modified CI engine. They used a high exhaust gas recirculation rate and tested various gasoline ratios in blended fuel, thereby achieving LTC. In their results, the conventional trade-off between NO_x and soot emissions was still observed and lower soot emissions were observed with increasing gasoline content. The soot concentration was not affected by variations in the oxygen content. The combustion and emissions performance of gasoline–diesel blended fuel in a DI engine has been numerically investigated by Li et al. [20]. They used the integrated KIVA4-CHEMKIN code to study the differences in combustion