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Optimization of the injection parameters and combustion chamber geometries of a diesel/natural gas RCCI engine

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ABSTRACT

This study aims at finding the favorable combinations of the diesel injection parameters and combustion chamber shape of a diesel/natural gas dual fuel engine to achieve lower fuel consumption and pollution emissions. The genetic algorithm NSGA-II coupled with the KIVA-3V code was employed for the multi-objective optimizations. The results show that the straight combustion chamber is effective to reduce the CH_4 emission and improve the fuel economy, and the indicated thermal efficiency reaches 50.2% with an injection timing of −16.45 °CA ATDC. The NO emissions are the lowest when the reentrant-type combustion chamber is used, while CH_4 emissions and ISFC are higher than the other two types of the combustion chamber. When the injection timing is far away from the top dead center, the NO emissions, CH_4 emissions and ISFC are very close to each other for the three types of the combustion chamber. Slightly narrow spray angle is favorable to improve the performance of the dual fuel engine.

1. Introduction

The diesel engine has the highest thermal efficiency due to its very high compression ratio, which makes the operating cost lower than any other practical internal combustion engine. This important feature makes it the most preferred engine especially for the heavy-duty vehicles. However, the NO*x* and Soot emissions from diesel engines are very high due to its combustion characteristics. Many researches have been done to investigate the method of reducing the NO*x* and soot simultaneously in diesel engines. New combustion concepts have been proposed for diesel engine to meet the increasingly stringent emission regulations, such as Homogeneous Charge Compression Ignition (HCCI), Low Temperature Combustion (LTC) and Premixed Charge Compression Ignition (PCCI) [1–3]. Among them, the Reactivity Controlled Compression Ignition (RCCI) concept is the most promising method to be applied for diesel engine [4].

For the RCCI combustion strategy, the low reactivity fuel was introduced from port injection to form a homogeneous mixture in the cylinder, and the high cetane number (CN) fuel was injected directly into the cylinder to control the combustion phasing and duration. High octane number (ON) fuel is favorable for the premixed fuel, because it has higher resistance to the spontaneous ignition, which is benefit to extend the upper load limit of the dual fuel engine. Therefore, natural gas with high ON is the best choice for dual fuel combustion application.

Yousefi et al. studied the effect of diesel injection timings on the combustion performance and emissions of a heavy duty natural gas/diesel dual-fuel engine at 25% engine load. Both experimental and numerical results revealed that advancing the injection timing up to 30 °CA BTDC increases the maximum in-cylinder pressure [5]. Rahnama et al. investigated the effect of reformer gas (syngas) composition on the performance and exhaust emissions properties of a natural gas/diesel RCCI engine at low loads numerically. The results indicated that reformer gas addition could enhance the combustion efficiency and decrease CO emission [6,7]. Wang et al. investigated the diesel injection timing on diesel/natural gas dual fuel ignition mode. With advancing diesel injection timing, engine combustion and emissions characteristics, including cylinder pressure, cylinder temperature, heat release rate, start of combustion (SOC), ignition delay, combustion duration, crank angle of 50% heat release (CA50), nitrogen oxides (NO*x*) and total hydrocarbon (THC), show completely different variation trends in different ignition modes [8]. Papagiannakis et al. revealed that for the examined test engine operating under constant natural gas/diesel mass ratio, a restricted increase in the diesel fuel injection timing

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could be a promising solution for engine efficiency improvement and CO emission mitigation [9]. Poorghasemi et al. investigated the effects of several parameters, including the premixed ratio of NG, diesel fuel fraction in first and second injection pulses, first and second start of injection timing, injection pressure and the spray angle on the engine performance and emission characteristics. The results indicated that these parameters have significant effects on the light duty RCCI engine performance and engine out emissions [10]. Li et al. showed that the increase of time-sequenced coefficient and heat release rate-balanced coefficient can decrease HC (hydrocarbon) emissions and improve the BTE (brake thermal efficiency) significantly [11]. Song et al. showed that using low-pressure direct injection (LPDI) systems could be an alternative for current high-pressure common rail injection systems, which would significantly reduce the system cost. And larger advanced injection timing was used to realize low temperature combustion and achieve long ignition delay in order to counteract the negative impact of relatively poor atomization quality caused by the low injection pressure [12]. The study of Yang et al. indicated that the particle number concentration (in particular to the ultrafine particle) could be reduced dramatically with increased pilot injection pressure and the percentage energy substitution as well as engine loads [13].

The combustion chamber geometry plays a critical role in the combustion process of the diesel engines. The combustion of a heavy-duty diesel engine was optimized by coupling a multi-dimensional computational fluid dynamics (CFD) code with genetic algorithm (GA). At each load, a comprehensive optimization of the operating parameters was conducted in order to simultaneously minimize ISFC (indicated specific fuel consumption), NO_x (nitrogen oxides) and soot emissions [14]. Jung et al. investigated the fundamentals of dual-fuel combustion and the effects of intake valve closure (IVC) changes in dual-fuel mode using a 1D engine simulation. It is shown that IVC could increase combustion efficiency and affect NO_x emissions by controlling the Air/Fuel ratio [15]. The optimization processes of a diesel engine fueled with DME were performed by Park et al. [16], which is based on a micro-genetic algorithm with a population number of five for each generation. In addition, the computational mesh was generated by an auto-mesh generator, which was able to produce a computational mesh based on the given parameters, such as cup depth and Beizer curve definitions. The optimization of the combustion chamber geometry for natural gas engines was carried out by Wang et al. using the multi-objective non-dominated sorting genetic algorithm II (NSGA-II) coupled with Kriging-based meta-model [17]. To generate the various combustion chamber geometries, the bowl outline is parameterized by the two cubic Bezier curves while keeping the compression ratio constant. With the optimization, the HC and CO emissions are reduced by 56.47% and 33.55%, respectively. The piston bowl geometry and the operating conditions of a dual-fuel engine were optimized by Lee et al. [18]. As a result of optimization, a 9% improvement in the gross indicated specific fuel consumption and a simultaneous decrease of the overall NO_x and soot emissions was achieved. The baseline case has a re-entrant shape, while the optimized case has a shallow shape and a narrower spray angle. The orthogonal design method and multi-objective NLPQL algorithm were employed by Chen et al. to optimize the combustion chamber of DI diesel engine [19]. The combination of the Computational Fluid Dynamics (CFD) modeling and the statistical Design of Experiments (DOE) technique, known as Response Surface Method (RSM) was utilized by Benajes et al. for optimizing the combustion system of Compression Ignition (CI) engines [20]. The genetic algorithm (GA) method was used by Kim et al. to optimize the operating conditions of diesel and dimethyl-ether (DME) fuel in a diesel engine [21]. And different variables of the operating conditions were determined for the analysis of the optimization conditions. The optimization study of Kavuri et al. showed that an optimum CR of 13.1 with a bowl geometry that has two distinctive regions benefit the low load and high load operating conditions, respectively [22]. Results also showed that a narrow spray angle for diesel fuel and a wide spray angle for gasoline would be necessary to target the two different regions in the bowl.

So far, few researches focus on the effect of combinations of the diesel injection parameters and combustion chamber shape on the performance and exhaust gas emissions of the duel fuel natural gas engine. The objectives of the present study are to optimize the combination of injection parameters and the combustion chamber geometries of a diesel/natural gas dual fuel engine to achieve low fuel consumption and low pollution emissions. The genetic algorithm coupled with the KIVA-3V code was employed for the multi-objective optimizations. Two pilot injection parameters (pilot diesel spray angle and start of injection) and three combustion chamber parameters (central pip height, throat radius and maximum bottom radius of the combustion chamber) were optimized simultaneously. In addition, an in-house developed auto mesh generator was used to generate the combustion chamber mesh automatically in order to meet the requirements of the genetic algorithm.

2. Experimental apparatus and setup

In this study, a modified WEICHAI WP10 heavy-duty diesel engine was used for the experiments. The exhaust emissions were analyzed by the Horiba MEXA7100DEGR analyzer. The diesel and natural gas fuels were obtained from the local distribution network in Beijing City.

2.1. Test engine

The experiments were carried out on a WEICHAI WP10 heavy-duty diesel engine, which is a six-cylinder turbo charged engine with common rail system. The summary of the engine's specification can be found in Table 1. The injection timing and quantity of the diesel and the natural gas were controlled by an in-house developed dual-fuel control unit.

2.2. Instrumentation

The Dynamometer used in this study is the Horiba-Schenck HT350 AC Transient Dynamometer with relevant signal acquisition and data logging module. Cylinder pressure signal was acquired by a mass-produced piezoresistive cylinder pressure sensor in conjunction with a charge amplifier (Kistler 5018).

The Horiba MEXA7100DEGR analyzer was used for the measurement of the engine out emissions. Nitrogen oxides (NO_x)

Table 1
Summary of engine specification.

Bore × Stroke	126 × 130 mm
Number of cylinders	6
Displacement	9.726 L
Maximum torque/speed	1250 N·m/1200 ~ 1600 rpm
Rated power/speed	247kW/2200 rpm
Compression ratio	17.0
Number of Injector nozzle holes	7
Injector nozzle spray angle	146
Exhaust valve closing timing	21°CA ATDC
Exhaust valve opening timing	131°CA ATDC
Inlet valve closing timing	146°CA BTDC
Inlet valve opening timing	20°CA BTDC