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Extension of PREMIER combustion operation range using split micro pilot fuel injection in a dual fuel natural gas compression ignition engine: A performance-based and visual investigation

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HIGHLIGHTS

- Split injection can suppress knocking to PREMIER combustion.
- Split injection can promote normal combustion to PREMIER combustion.
- Maximum of usable thermal efficiency is extended by suppressing knocking.
- Flame kernel size and rate of growth changes the combustion mode.
- Flame kernel properties are affected by timing of second injection.

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ABSTRACT

The effects of split pilot fuel injection on engine performance and PREmixed Mixture Ignition in the End Gas Region (PREMIER) combustion characteristics were investigated in a single-cylinder dual-fuel natural gas engine ignited with diesel fuel. In particular, the effect of second spray timing on combustion mode was examined. PREMIER combustion was observed in a wider range of operating conditions with split injection strategy compared to single injection strategy. We determined that it was possible to both decelerate heat release and suppress knocking to PREMIER combustion, and accelerate heat release and promote normal combustion to PREMIER combustion, with suitable second injection timing. The maximum of thermal efficiency of PREMIER combustion operation with split injection was close to the results obtained with knocking operation. In-cylinder images showed that split injection strategy advances or retards the progress of combustion by controlling the size and rate of growth of flame kernels, depending on the timing of the second injection. The combustion progress is earlier when the pilot fuel delivered during the first injection autoignites during the second injection. Kernel growth and the final size were adversely affected when the second injection was initiated after pilot fuel autoignition.

1. Introduction

The use of petroleum as an energy source is becoming less feasible due to the depletion of global oil reserves, its negative impact on the environment, and strict exhaust emission norms. This situation affects compression ignition (CI) engines in particular because of their role in transportation and electricity generation

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industries, emphasizing on the need for cleaner, more economical and reliable alternatives. Alternative fuels can solve these issues without significant compromise [1–4]. Natural gas is one such fuel, due to its abundance and clean combustion properties.

Natural gas is a mixture of mainly methane as the primary combustible gas, with traces of hydrocarbon gases and diluents, the fractions of which depend on the region of extraction and purification processes. Due to its methane-rich composition, natural gas is a clean-burning fuel and is globally becoming a more popular fuel source. Natural gas constituted 14% of total final consumption of world energy sources in 1973, which increased to 15.1% in 2013; the fraction used for transportation increased from 2.7% to 6.9% over this 40-year interval [5].

Use of natural gas in spark ignition (SI) engines and CI engines has been researched extensively. Especially, its use in dual-fuel CI has attracted much attention due to the high efficiency of such engines. Dual-fuel CI engines are suitable platforms for using gaseous fuels with high autoignition temperatures, one of which is natural gas. In this combustion mode, an air-gaseous fuel mixture is ignited by the pilot fuel. By its nature, autoignition of the pilot fuel creates a large zone of flames, the flame kernel. A profound improvement over SI, the CI configuration eliminates smoke emission and enables lean operation by reducing the risk of misfiring; however, increased unburned hydrocarbon (HC) and carbon monoxide (CO) emissions remain an issue [6,7]. Fundamental knowledge on the combustion of many gaseous fuel types, including natural gas, under dual-fuel operation conditions has been presented by Karim et al. [6–9]. These works report that the dual fuel operation range is limited by knocking at the higher load end and by misfiring at the lower load end. Moreover, exhaust emissions are a trade-off of CI versus SI processes, where soot and NO_x emissions are lower but CO and unburned hydrocarbon emissions are higher than those of direct-injection CI engines. Various researchers have addressed these problems by explaining the effects of use of alternative fuels as pilot fuel, pilot fuel quantity, fuel properties, injection timing, equivalence ratio, intake pressure, temperature and use of EGR [10–24]. Basic natural gas-diesel pilot injection dual fuel technology is currently used in public transportation buses, stationary engines used for power generation, and large-scale ships.

Another common interest in dual-fuel gas engine research is to minimise the pilot fuel injection quantity to reduce diesel fuel dependency while the gaseous fuel is functioning as the major energy source. In these systems, gaseous fuel is fed into the intake air and pilot fuel serves as the source of ignition. Several researchers have focused on this particular application [25–30]. Common observations in these studies include reduced exhaust emissions and improved thermal efficiency over direct injection CI engines [26–28]. Maximization of thermal efficiency is a common goal; however this goal can be achieved by increasing in-cylinder pressure. This high pressure is also the main reason for the increased temperature, which yields to knocking under borderline operating conditions [6–9,12]. This approach is especially beneficial because the fraction of unburned methane rejected in the exhaust gases, a phenomenon known as "methane slip," is reduced [26–27].

Conventional approaches to the use of gaseous fuels in CI engines have strict limitations; thus, more advanced combustion strategies are being investigated, such as Homogeneous Charge Compression Ignition (HCCI) and Reactivity Controlled Compression Ignition (RCCI) [31–36]. HCCI relies of autoignition of in-cylinder mixture, and is suitable for low load operation [31–33]. This strategy provides the foundation of RCCI combustion in terms of mixture preparation and presence of autoignition to a certain extent [34–36]. Currently these two concepts answer the need for low to high load range operation, but can't extend the load range [37].

Dual-fuel operation at high loads has been researched in the laboratory using dual-fuel gas engines with various fuels, including natural gas, and micro pilot fuel injection. Under heavy load conditions, two-stage combustion has been observed as a precursor to knocking with no sign of fluctuations or rapid increase in pressure [38–40]. The thermal efficiency of the engine shows noticeable improvements, with zero smoke emissions. From more recent studies, it is now understood that the end-gas region undergoes autoignition simultaneous with flame propagation; this phenomenon has been named "PREMIER" (PREmixed Mixture Ignition in the End Gas Region) combustion [41–44]. In PREMIER combustion mode, the end-gas region reaches autoignition conditions due to pressure and temperature build-up; simultaneous heat release from two different combustion modes causes more rapid heat release when the engine enters the expansion cycle. While attainable thermal efficiency in this combustion mode is superior to normal operation, the operation range is narrow, limited to the prior-to-knocking operating region. Currently PREMIER combustion is at an early stage of research, and new strategies that can extend its operation range are required in order to provide the tools and methodology required for future practical applications.

In this fundamental study on PREMIER combustion, split pilot fuel injection strategy was applied, and its feasibility as a method to extend the operating range of PREMIER combustion mode is assessed. Delivering the pilot fuel in two parts provided one of the means to control the flame kernels, their size, and the heat release from these sites.

2. Experimental set-up and data evaluation

2.1. Experimental procedure

Schematic diagrams of the performance test and visualization experimental set-ups are shown in Fig. 1. Experiments were conducted in a four-stroke, single-cylinder dual-fuel gas engine. This test engine can also be equipped with an extended piston with an imaging window and other auxiliary equipment for imaging. The engine had a 96-mm bore, a 108-mm stroke, and a compression ratio of 17.0:1 during both performance tests and visualization experiments. The engine is equipped with a shallow dish piston during performance tests. Technical details of the engine are listed in Table 1. Air pressure was stabilised at 101 kPa by a compressor and a surge tank. An air heater stabilised the intake temperature at 313 K, into which natural gas was delivered through a gas injector to prepare a homogeneous intake. This mixture was ignited by the pilot fuel delivered by a diesel fuel injector, equipped with a three-hole nozzle (hole diameter: 0.1 mm). This nozzle is purpose built in order to achieve low injection amounts; therefore its flowrate is restricted, making it unsuitable for 100% diesel fuel operation at medium and high load conditions. Fuel was pressurised by a high-pressure oil pump and sent to the injector through a common rail. The injection pressure was controlled by adjusting the spring inside common rail relief valve. The injection signal was formed from the crank angle (θ) signal obtained each 0.5° of crank angle (°CA), top dead centre (TDC), and cam full revolution signals. The signal duration versus injection amount was calibrated prior to the experiments.

Cylinder pressure was measured with a KISTLER type 6052C pressure transducer connected to a KISTLER type 5011 charge amplifier. In this engine, knocking triggers pressure oscillations at 6.5 kHz, 10.5 kHz and 14 kHz frequencies [41]. Digital filters applied to pressure history are designed based on this criterion. A 4–20 kHz band-pass filter is applied to pressure history for knock analysis. A 6.5 kHz low-pass filter is applied in order to obtain ROHR and performance characteristics. All performance results