Applied Energy 230 (2018) 1205–1217

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Flame development analysis in a diesel optical engine converted to spark ignition natural gas operation

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HIGHLIGHTS

- In-cylinder pressure trace and flame images correlated well with each other.
- Normal cycle-to-cycle variations and no knocking phenomena at medium load.
- Strong wrinkling of the turbulent flame and fast flame propagation.
- Use of natural gas in diesel engines without complex engine modification or control strategies.

ARTICLE INFO

Keywords:
Optical compression ignition engine
Natural gas
Spark ignition
Piston-shape effects

ABSTRACT

The conversion of heavy-duty diesel engines to spark-ignition natural gas operation has the potential to decrease the use of conventional petroleum-based fuels and reduce greenhouse gas emissions. A better understanding of the fundamentals such as early natural gas flame development in re-entrant bowl combustion chambers can accelerate this conversion. This paper details an optical investigation of flame luminosity inside a conventional heavy-duty diesel engine converted to spark-ignition natural gas operation by replacing the diesel fuel injector with a spark plug and adding a port-fuel gas injector in the intake manifold. Knock-free lean-burn experiments were performed at medium engine load using methane as fuel. Combustion images confirmed that kernel inception played an important role in the subsequent flame propagation. In addition, flame luminosity images of individual engine cycles showed strong flame wrinkling and counterclockwise rotation due to increased turbulence inside the re-entrant bowl. However, the flame front for the mean cycle was relatively circular. Flame luminosity also suggested a thick flame and a high turbulent flame speed for early inside-the-bowl flame propagation, at the operating conditions investigated. Higher surface-to-volume ratio in the squish region increased the heat transfer to the surroundings and reduced flame propagation, which increased the late combustion period. The separation of the combustion process into two distinct zones (i.e., inside and outside the piston bowl) created a secondary peak or "bump" in the heat release of individual cycles. The data suggests that the combustion strategy should optimize the mass of fuel that burns inside the squish region. In addition, the moderate rate of pressure-rise and lack of knocking showed promise for heavy-duty diesel engines converted to spark-ignition natural gas operation.

1. Introduction

The conversion of existing heavy-duty compression ignition (CI) internal combustion engines (ICE) to natural gas NG operation has the potential to reduce the dependence on petroleum imports in the transportation sector [1]. More, the use of NG in such engines reduces PM emissions by avoiding the creation of fuel-rich regions inside the cylinder [2]. The higher hydrogen-to-carbon (H/C) ratio of NG compared to conventional petroleum-based fuels can lower engine-out CO_2 emissions at similar power output [3]. The wider flammability limits of NG allow leaner operation, which can reduce both carbon monoxide (CO) and unburned hydrocarbon (HC) emissions [4]. Further, leaner combustion reduces combustion temperature, which lowers the formation of nitrogen oxides (NO_x) [5].

NG can generally replace conventional diesel fuel in heavy-duty CI engines without the need of major engine modifications. But NG's higher autoignition temperature compared to diesel requires an additional ignition source to initiate combustion such as a spark plug [6] or

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https://doi.org/10.1016/j.apenergy.2018.09.059
Received 3 June 2018; Received in revised form 4 September 2018; Accepted 6 September 2018
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a pilot of diesel fuel (i.e., dual-fuel strategies) [7]. In a cost driven market as the U.S. market, the replacement of the diesel injector with a spark plug and the addition of a gas injector in the intake manifold is the most economical way to convert a CI engine to SI NG operation, despite the reduction in peak torque and power (especially at low speeds) due to the lower volumetric efficiency and air-fuel ratio of NG compared to the diesel fuel [8].

Despite NG's higher octane-number compared to gasoline, knocking is a main concern in CI engines converted to NG operation [2]. The reason is that in addition to the choice of compression ratio (CR), in-cylinder flow motion in a CI engine is designed to improve the air–fuel mixing and accelerate the mixing-controlled combustion rather than flame propagation characteristic of dedicated SI NG or dual fuel engines [9]. As a result, it is paramount to understand how the different flow motion affects the operation, efficiency, and emissions of heavy-duty IC engines converted to NG. Johansson et al. [10] and Olsson et al. [11] showed that a benefit of the re-entrant bowl and flat head found in most CI engines is the increased turbulence compared to the conventional roof-type head combustion chamber in SI engines. Higher turbulence increases flame propagation and decreases knocking propensity, but high local velocities at the spark plug location can increase the probability of delayed or slower flame kernel formation. This would increase the cycle-to-cycle variation and combustion duration, which can affect thermal efficiency and combustion stability, and can increase the CO and HC emissions [12]. More, higher turbulence increases the heat transfer to the walls and reduces engine efficiency [5]. As lean mixtures are more difficult to ignite and the maximum NG laminar flame speed is around stoichiometry, most ICE converted to SI NG run at stoichiometric conditions [13]. Another benefit for operating at stoichiometric conditions is the possibility of using cost-effective solutions for emission control such as the three-way catalyst. However, even if the flame propagates faster, stoichiometric NG engines are knock sensitive at high load, particularly for low methane-number fuels, which limits their operating range, efficiency, and power density [12]. Therefore, lean burn is the solution to decrease knocking, especially in highly-turbulent re-entrant bowl combustion chamber, if the ignition process is robust. More, the higher ratio of specific heats for lean mixtures can result in close-to-diesel efficiencies when a higher compression ratio is used [14]. But lean-burn NG engines may require more complex aftertreatment systems (e.g., SCR to control NO_x emissions) despite producing lower in-cylinder emissions levels than stoichiometric SI engines [12].

This study used in-cylinder visualization to investigate the fundamentals of the NG flame propagation inside a re-entrant flat bowl combustion chamber. The goal was to study the fundamentals of kernel growth and flame propagation under lean burn conditions in a heavy-duty CI engine converted to NG SI operation. The reason for the limited number of papers in the literature is that most fundamental investigations on the topic were performed in experimental setups that were either not representative of ICE geometry such as constant-volume combustion vessels [15] or rapid-compression machines [16], non-representative combustion chamber geometry (i.e., flat pistons instead of re-entrant bowls) [17,18], or the combustion strategies were different (direct fuel injection [19,20], and/or dual fuel strategies [21,22]). When engine operation was investigated in such retrofitted engines, the fuel was not NG, but propane [23] or butane [24]. Further, the efficiency of existing emissions aftertreatment systems in heavy-duty CI engines converted to NG SI operation is of concern. Chiu et al. [25] found that a class 8 heavy-duty truck operating stoichiometric with EGR met U.S. 2010 standard emissions with NG but not with gasoline. Einewall et al. [26] concluded that the efficiency of EGR and a three-way catalyst in curtailing emissions of a NG engine will decrease when engine operation will change from stoichiometric to lean-burn. Recently, Zhang et al. [26] observed that the combination of stoichiometric NG combustion, EGR, and a three-way catalyst met Europe's EURO VI emissions standards for heavy-duty NG vehicles. As the market potential of heavy-duty CI engines converted to NG SI operation or new high-compression lean-burn SI NG engines is tremendous, other research focused on identifying the main issues related to converting CI engines to NG SI operation [27], fuel consumption and engine power [28], cycle-to-cycle variations [29], and NG compositions effects [30] were also investigated. More, the limited experimental data for retrofitted CI engines is also reflected in the reduced number of 3D CFD investigations of CI engines converted to SI NG operation compared to, for example, the amount of investigations on gasoline and/or dual-fuel diesel-NG applications. For example, Donateo et al. [31] evaluated several design alternatives in the conversion of a diesel engine to either CNG-dedicated or dual fuel engines. They found that the cost of converting an existing diesel engine can be negligible compared with the case of completely overhauling the combustion chamber for NG operation. Overall, the gap in the fundamentals of lean burn NG combustion in re-entrant bowl geometry (particularly on flame inception and subsequent flame propagation) has the potential to delay conversion of existing heavy-duty diesel engines to NG operation or the development of dedicated lean-burn NG engines. This is extremely relevant for practical applications as a recent assessment by the U.S. Department of Energy (DOE) suggested that the number of NG vehicles can increase up to 20% of new heavy-duty vehicles by 2025 [32]. Consequently, the results presented here can guide and/or complement the design/optimization directions for lean-burn high-compression NG SI engines, which would enhance the U.S. energy security. In addition, the combustion visualization contained in this study can contribute to the development and validation of combustion models that simulate the physics of turbulent flames in such environments.

2. Experimental setup

2.1. Engine and fuel system

Experiments were performed in an optically-accessible single-cylinder research engine (Ricardo/Cussons, U.K., Model Proteus). The engine is based on a commercial heavy-duty diesel engine (Volvo, Sweden, Model TD120). The original cylinder block was replaced with an extended version, which allows the visualization of the combustion chamber from below through a "Bowditch" piston whose combustion bowl has a flat bottom and vertical walls. In-cylinder pressure trace was measured by a piezo-electric pressure transducer (Kistler, Model 6011) that was installed in the glow plug location and connected to a charge amplifier (Kistler, Model 5010). The original diesel injector was replaced by a spark plug (Stitt, USA, Model S-RSGN40XLBEX8.4-2). As a result, a low-pressure solenoid-controlled gas injector delivered the fuel. The gas injector was installed in the intake system at a distance of 55 mm from the intake valve. The fuel was added to the intake manifold immediately after the intake valve opened (IVO) using a single 18-ms long injection event. Table 1 shows the primary specifications of this research engine.

Skip-fired control strategy (one fuel injection event every 5 engine cycles) helped protecting the optical window from thermal and mechanical stresses in the experiments. At the same time, the cylinder head needed to be removed each time the window needed cleaning, which reduced the number of engine cycles and operating conditions that could be recorded before the image quality was affected. As a result, the analysis presented next is based on combustion visualization of only twenty-one engine cycles at one operating condition. An aftermarket engine management system (Megasquirt, Model 3X) controlled engine operation conditions such as fuel injection and spark timing. An in-house-built data acquisition software (Scimitar) collected operating data such as engine speed, torque, air, coolant, and oil temperature, and air mass flow. The fuel was chemically pure methane (99.5 vol%). Table 2 shows the engine operating conditions. Fig. 1 shows the experimental setup of the research engine in its optical-access configuration.

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