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Full Length Article

The effect of injection parameters and boost pressure on diesel-propane dual fuel low temperature combustion in a single-cylinder research engine

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ABSTRACT

Diesel-ignited propane dual fuel low temperature combustion was characterized in a single-cylinder research engine (SCRE) at constant values of indicated mean effective pressure (IMEP of 5.1 bar), engine speed (1500 rpm), and propane energy substitution (PES = 80%). The effects of three important engine parameters (start of injection (SOI) of diesel fuel, common-rail pressure (P_{rail}) for diesel injection, and boost pressure (P_{in})) on engine performance, combustion, and emissions were examined. As SOI was advanced from 355 absolute crank angle degrees (CAD) (or 5° BTDC) to 280 CAD for constant P_{rail} = 500 bar and P_{in} = 1.5 bar, the apparent heat release rate (AHRR) profiles changed from a two-stage, "diesel-like" combustion process to a smooth, "Gaussian-like," single-stage combustion process, that was representative of more homogeneous combustion. In addition, with SOI advancement, the combustion phasing (CA50) was initially advanced but eventually occurred later for very early SOIs. Indicated-specific emissions of oxides of nitrogen (ISNOx) were reduced to about 0.12 g/kW h for SOIs advanced beyond 310 CAD while maintaining high indicated fuel conversion efficiencies (IFCEs). While smoke emissions were below 0.1 FSN for all conditions tested in this study, indicated-specific hydrocarbon (ISHC) and carbon monoxide (ISCO) emissions were high at both very early and very late SOIs. Efficiency-emissions tradeoffs indicated an "optimal" SOI of 310 CAD under these conditions, which was chosen for further studies at different P_{rail} and P_{in}. Decreasing P_{rail} from 1300 bar to 200 bar at P_{in} = 1.5 bar led to a steep increase in ISNOx emissions for P_{rail} below 400 bar; however IFCE and smoke were relatively invariant with P_{rail}. Boost pressure effects were then quantified at P_{rail} = 500 bar. As P_{in} was increased from 1.1 bar to 1.8 bar, the ignition delay decreased and the AHRR profiles continued to exhibit single-stage combustion, albeit with different rates and peak magnitudes. Moreover, with increasing P_{in}, the IFCE and ISCO increased while ISNOx and ISHC decreased slightly. Finally, the impact of SOI, P_{rail}, and P_{in} variations on engine stability (i.e., COV of IMEP), maximum pressure rise rates (MPRRs), and combustion duration were also characterized.

1. Introduction

Recent interest in improving the fuel conversion efficiency (FCE) and reducing the carbon dioxide (CO_2) emissions from internal combustion engines has refocused attention on advanced combustion strategies and alternative fuels. Advanced low temperature combustion (LTC) strategies have been proposed for compression ignition engines to simultaneously reduce engine-out emissions of oxides of nitrogen (NOx) and soot. It is well known that NOx formation through the thermal mechanism increases exponentially when local in-cylinder temperatures exceed a certain threshold value (~1900 K); LTC strategies reduce NOx emissions by decreasing local in-cylinder temperatures below this threshold. To reduce soot formation, locally fuel-rich regions must be avoided. This is accomplished in most partially premixed LTC strategies by improving

Abbreviations: AHRR, apparent heat release rate, J/deg; BDC, bottom dead center; BMEP, brake mean effective pressure, bar; BTDC, before top dead center; CA10-90, crank angle degrees between the locations of 10% and 90% cumulative heat release, CAD; CA5, crank angle at which 5% of cumulative heat release occurs, CAD; CA50, crank angle at which 50% of cumulative heat release occurs, CAD; CAD, crank angle degrees; CO, carbon monoxide, g/kW h; COV, coefficient of variation, %; EGR, exhaust gas recirculation; EOI, end of injection of diesel, CAD; FSN, filter smoke number; HC, unburned hydrocarbon, g/kW h; HCCI, homogeneous charge compression ignition; ID, ignition delay, CAD; IFCE, indicated fuel conversion efficiency, %; IMEP, indicated mean effective pressure, bar; LHV, lower heating value, MJ/kg; LTC, low temperature combustion; MPRR, maximum pressure rise rate, bar/CAD; NOx, oxides of nitrogen, g/kW h; PES, percent energy substitution, %; P_{in}, intake manifold (boost) pressure, bar; P_{rail}, rail pressure, bar; RCCI, reactivity controlled compression ignition; SOC, start of combustion, CAD; SOI, start of injection of diesel, CAD; TDC, top dead center; η_{comb}, combustion efficiency, %.

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fuel-air mixing rates and/or by increasing the time available for mixing (i.e., residence time) before the onset of combustion. Consequently, a primary goal of many LTC strategies is to achieve some separation between the fuel injection and combustion events by increasing ignition delay, which increases the residence time and affords better fuel-air mixing, thereby reducing local equivalence ratios below the soot formation threshold and local temperatures below the NOx formation threshold. Some LTC strategies include, for example, homogeneous charge compression ignition (HCCI) [1], partially premixed combustion [2,3], gasoline compression ignition combustion [4,5], as well as various dual fuel LTC strategies [6–10]. Each of these strategies has its own set of advantages and challenges but generally most LTC strategies are accompanied by high unburned hydrocarbon (HC) and carbon monoxide (CO) emissions.

Dual fuel engines have been pursued for several decades [11–22], particularly with natural gas as the primary fuel, with the main intention of improving exhaust emissions while maintaining diesel-like FCEs. In dual fuel combustion, an easily auto-ignitable high-cetane fuel (e.g., diesel) is used to ignite an autoignition-resistant low-cetane primary fuel (e.g., methane). Before discussing the scope of the present work and how it fits with the existing literature, it is perhaps useful to examine well-established trends for performance and emissions in dual fuel combustion. For example, it is well known that both NOx and soot emissions in dual fuel combustion decrease with increasing percent energy substitution (PES) of the primary fuel [23–26]. According to Dec's conceptual model of diesel combustion [27], NOx is formed in the high temperature regions near the periphery of the diesel jet where the diffusion flame exists while soot is formed in fuel-rich areas, especially in the head vortex region. In dual fuel combustion, since the primary fuel-air mixture is lean and nearly homogeneous, it engenders very little NOx or soot formation; therefore, both NOx and soot are formed within the diesel jet. Consequently, as the size of the diesel jet decreases with increasing PES of the primary fuel, both NOx and soot decrease but usually at the expense of higher HC and CO emissions, especially at low loads.

Of particular interest to the present work are dual fuel LTC strategies that target high FCEs and low engine-out NOx and soot emissions. Reviewing past literature, it is evident that dual fuel LTC is a logical outgrowth from conventional dual fuel combustion with emphasis on achieving LTC using modern engine control hardware and software. With precise gaseous fuel injection, electronic control over diesel injection timing and quantity, boost pressure, exhaust gas recirculation (EGR), etc., conventional dual fuel combustion has been extended to LTC regimes [6,7,28–32]. Since the overall reactivity of the fuels is "stratified" between the high-cetane and low-cetane fuels within the combustion chamber, dual fuel LTC is also known more recently as reactivity controlled compression ignition (RCCI) combustion [33].

Dual fuel LTC has been demonstrated with diesel as the high-cetane fuel and a variety of primary, low-cetane fuels such as methane or natural gas [34,35], gasoline [10,33,36], and ethanol [37]. Among gaseous primary fuels for dual fuel LTC, methane (or natural gas) has been investigated quite extensively. On the other hand, while conventional diesel-ignited propane dual fuel combustion has been studied by several researchers [38–43], very few studies have focused on propane as the primary fuel for dual fuel LTC (e.g., [44,45]). The present effort is an attempt to fill this gap. Building on previous research efforts on dual fuel LTC at Mississippi State University (MSU) [34–36,44,45], this paper presents experimental results for diesel-ignited propane dual fuel LTC on a single-cylinder research engine (SCRE). Considering the well-established infrastructure for propane production and distribution within the United States, it is attractive as the primary fuel for dual fuel LTC. Moreover, propane has a higher lower heating value (LHV) compared to diesel, is easier to store (in the liquefied phase) compared to methane (natural gas), and exhibits a relatively high resistance to knock (RON ~ 112, MON ~ 97). Consequently, it is well-suited as the primary fuel for dual fuel LTC.

2. Objective

The objective of the present work is to implement diesel-ignited propane dual fuel LTC on the MSU SCRE and assess the effects of start of (diesel) injection (SOI), diesel common-rail pressure (P_{rail}) and intake boost pressure (P_{in}) on engine performance, combustion, and exhaust emissions.

3. Experimental setup

The experiments were performed on the SCRE, whose details are provided in Table 1. As shown in the schematic of the experimental setup (Fig. 1), the engine was coupled to a 250 HP Dyne Systems AC regenerative dynamometer, which was controlled by an Inter-Lock V controller that also provided torque and speed measurements.

Table 1
Single-cylinder research engine details.

Engine type	RSi-130 DV11 single-cylinder research engine, 4-stroke, compression-ignition
Bore × Stroke	128 mm × 142 mm
Connecting rod length	228 mm
Displaced volume	1827 cm^3
Compression ratio (nominal)	17.1:1
Valve train system	4 overhead valves with pushrod actuation
Intake valve open (CAD absolute)	32°
Intake valve close (CAD absolute)	198°
Exhaust valve open (CAD absolute)	532°
Exhaust valve close (CAD absolute)	14°
Diesel fuel injection system	Bosch CP3 common-rail
Injection nozzle hole diameter	0.197 mm
Number of nozzle holes	8
Gaseous (propane) fueling	Fumigation into intake manifold
Aspiration	Boosted intake (with external compressor)
Maximum engine speed	1900 rev/min

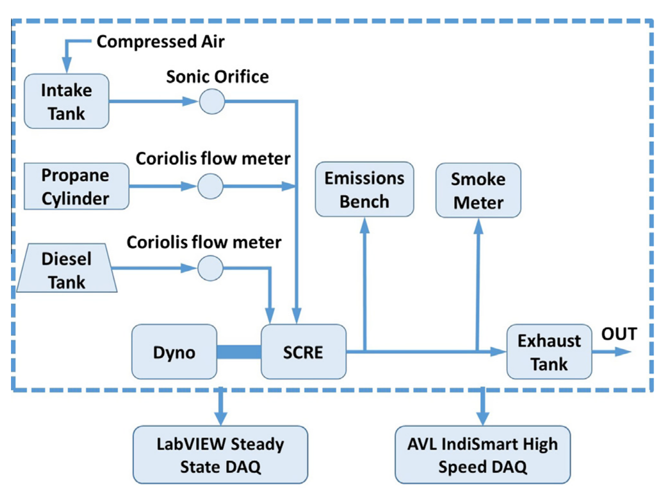

Fig. 1. Experimental setup of the single cylinder research engine.