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Impact of propane energy fraction on diesel-ignited propane dual fuel low temperature combustion

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ABSTRACT

This paper focuses on quantifying the effects of percent energy substitution of propane on Diesel-ignited Propane Dual Fuel Low Temperature Combustion (DPDFLTC) performed in a single cylinder research engine (SCRE). All the experiments were performed with the engine load and speed held constant at 1500 rev/min and 3.3 bar BMEP, respectively. The intake pressure and temperature were held constant at 150 kPa and 30 °C, respectively, the diesel injection timing and injection pressure were maintained at 310 CAD (50 deg. BTDC) and 500 bar, while the propane energy fraction (PEF) was varied throughout the experiment. The results indicate that the maximum PEF was limited by to 90% due to high cyclic combustion variability (COV imep ~ 11%), and the minimum PEF was limited to 53% due to onset of engine knock (MPRR ~ 10.5 bar/deg). Additionally, the engine-out unburned hydrocarbon emissions decreased from nearly 40 g/kWh at 90%PEF to about 10 g/kWh at 53% PEF, the engine-out carbon monoxide emissions decreased from nearly 30 g/kWh 90% PEF to about 5 g/kWh at 53% PEF and the engine-out nitrogen oxide emissions increased from 0.1 g/kWh 90% PEF to 1.5 g/kWh at 53% PEF; whereas, engine-out smoke emissions remained low throughout the experimental program.

1. Introduction

With the new cafe 2020 standards set in motion now more than ever there is a large push for advanced combustion technologies that employ a variety of alternatives to diesel fuel that are abundantly available through a vast network of well established pipelines in the continental United States e.g., natural gas, LPG or propane, and gasoline-like fuels, e.g. naphtha, and other minimally refined gasolines to achieve superior fuel economy and defeating the nitrogen oxides (NOx) – soot trade-off in conventional heavy-duty diesel engines [1–7]. Dual fuel engines exploit the inherent resistance to auto-ignition of fuels to achieve stable combustion. Natural gas - a fuel that exhibits very high resistance to auto-ignition, is introduced into the combustion chamber either via fumigation through the intake manifold or direct injection. It is then compressed along with air to high pressures and temperatures to form a nearly homogeneous lean mixture and ignited using diesel – a fuel that is readily auto-ignited. The classical diesel-ignited natural gas dual fuel combustion is believed to occur in three stages, viz., combustion of the diesel pilot fuel, combustion of the entrained natural gas – air mixture in the vicinity of the combusting diesel pilot, and combustion of the pre-dominantly lean natural gas – air mixture farther away from the diesel pilot via flame propagation [8]. Due to the smaller fraction of combustion heat release occurring in stages 1 and 2 as described, the engine-out nitrogen oxide (NOx) emissions are lower than from conventional diesel combustion while the engine-out particulate matter (PM) emissions are lower than from conventional diesel combustion due to the pre-dominantly lean natural gas combustion occurring in stage 3 (as described). On the other hand, dual fuel engines have lower thermal efficiencies and higher un-burned hydrocarbon (UHC) and carbon monoxide (CO) emissions than their diesel counterparts; particularly, at low engine loads [9,10]. This is attributed to the inability of the flame to propagate through the lean natural gas-air mixture, which results in

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

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flame quench, and due to crevice hydrocarbons. This also impacts combustion in the subsequent cycles by changing the composition of the residual gas fraction from one cycle to another; thereby leading to high cycle-to-cycle combustion variations [11,12].

Over the last decade research has focused on advanced combustion dual fuel technologies to simultaneously reduce NOx and PM emissions [13–19]. Earlier attempts focused on micro-pilot ignited natural gas combustion [20–22]. These attempts, while extremely successful in reducing engine-out NOx and PM, resulted in exceedingly high UHC and CO emissions and excessive cyclic variations. However, some efforts, such as uncooled EGR were demonstrated to extend LTC combustion regime and reduce HC and CO emissions and cyclic variations [23,11]. Later studies focused on utilizing a stock common rail diesel pump and injector combination to investigate parametric effects on DFLTC with methane, propane and gasoline as primary fuels in both single and multi cylinder heavy-duty engines [24–28]. These studies further corroborated the fact that very low NOx and PM emissions were possible with advancement in diesel SOI; but with an accompanying UHC and CO emissions penalty. A previously published research effort by this group [29] reported a comprehensive experimental program that investigated the impact of diesel SOI, boost pressure, and diesel injection pressure at a constant PEF of 80% on diesel-ignited propane DFLTC. It was found that the lowest engine-out NOx emissions were achieved at 50 BDTC or 310 CAD; however, at this condition, the engine-out UHC and CO emissions were high. This paper is a follow-up study to Krishnan et al. [29] that reports on the management of propane energy fraction (PEF) with the diesel SOI and rail pressure fixed at 50 BTDC and 500 bar, respectively, as a viable strategy to achieve significant UHC and CO emissions reduction with minimal impact on engine-out NOx and PM emissions from diesel-ignited propane DFLTC in a SCRE operated at a constant intake boost pressure of 1.5 bar and intake temperature maintained at 35 deg. C, at a constant engine speed of 1500 rev/min producing 3.3 bar BMEP. Additionally, it is also found that the PEF could be varied between a minimum of 53% to a maximum of 90% as these establish the knock and mis-fire envelope for this engine operating condition.

2. 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

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

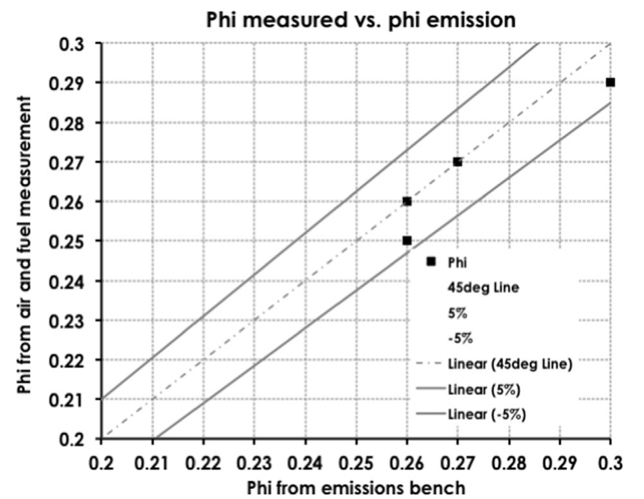

Fig. 1. Comparison of fuel-air equivalence ratios from air and fuel measurements with fuel-air equivalence ratios obtained from engine-out raw emissions for data acquired in this experimental investigation.

regenerative dynamometer, which was controlled by an Inter-Lock V controller that also provided torque and speed measurements.

2.1. Data acquisition

Both crank-resolved data and steady-state data were acquired in the experiments discussed in this paper. Intake, exhaust, coolant, and oil temperatures were measured using Omega Type-K thermocouples. Gaseous and exhaust emissions were measured downstream of the exhaust manifold using an emissions sampling trolley and an integrated emissions bench (EGAS 2M) manufactured by Altech Environment S.A. The EGAS 2M bench measured total hydrocarbons (THC) with a heated flame ionization detector, NOx emissions with a chemiluminescence detector, carbon dioxide (CO_2) and carbon monoxide (CO) emissions with a non-dispersive infrared analyzer, and oxygen (O2) with a paramagnetic detector. Smoke was measured in filter smoke number (FSN) units using an AVL 415S variable sampling smoke meter. Mass flow rates of diesel and propane were measured with Micro Motion (Model CMF025M319N2BAEZZZ) coriolis mass flow meters with 0.35% and 0.56% accuracies (of reading), respectively. A Bosch CP3 common-rail fuel injection pump and injector (maximum P_{rail} of ~1500 bar) were used for diesel injection. Diesel injection parameters were controlled by a National Instruments stand-alone diesel injection (SADI) driver coupled with CALVIEW software. An electronically controlled needle valve (HANBAY Model MCM-050AB) was used to control the flow rate of propane, which was fumigated in the intake manifold. In-cylinder pressure was measured using a Kistler model 6052C pressure sensor and a Kistler Type 5010B charge amplifier. The diesel injector was instrumented with a Wolff Hall effect sensor to obtain needle lift data. Both sensors were phased with respect to crank angle using a BEI incremental shaft encoder with a resolution of 0.1 crank angle degree (CAD), which was coupled to the engine crankshaft. Cylinder pressure and needle lift data were recorded and averaged over 1000 consecutive cycles, and the intake manifold pressure was used to peg the cylinder pressure data at bottom dead center (BDC). It is well known from the literature that dual fuel combustion, utilizing diesel as the ignition source and any low cetane fuel as the primary fuel, tends to exhibit significant cyclic combustion variations depending on the concentration of primary fuel and engine operating parameters. In the present study, cyclic combustion variations over 1000 consecutive cycles were quantified as the coefficient of variation (COV) of *net* indicated mean effective pressure (IMEP), which is the ratio of the standard deviation in net IMEP to the arithmetic mean of the net IMEP expressed as a percentage. To provide compressed air in the intake manifold, an Atlas