EXPERIMENTAL STUDY OF THE EFFECT OF START OF INJECTION AND BLEND RATIO ON SINGLE FUEL REFORMATE RCCI

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ABSTRACT

A new concept of single fuel RCCI has been proposed through the catalytic partial oxidation reformation of diesel fuel. The reformed fuel mixture is then used as the low reactivity fuel and diesel itself is used as the high reactivity fuel. In this paper, two reformate mixtures from the reformation of diesel were selected for further analysis. Each reformate fuel mixture contained a significant fraction of inert gases (89% and 81%). The effects of the difference in the molar concentrations of the reformate mixtures were studied by experimenting with diesel as the direct injected fuel in RCCI over a varying start of injection timings and different blend ratios (i.e., the fraction of low and high reactivity fuels).

The reformate mixture with the lower inert gas concentration had earlier combustion phasing and shorter combustion duration at any given diesel start of injection timing. The higher reactivity separation between reformate mixture and diesel, compared with gasoline and diesel, causes the combustion phasing of reformate-diesel RCCI to be more sensitive to the start of injection timing. The maximum combustion efficiency was found at a CA50 before TDC, whereas the maximum thermal efficiency occurs at a CA50 after TDC. The range of energy-based blend ratios in which reformate-diesel RCCI is possible is between 25% and 45%, limited by ringing intensity (RI) at the low limit of blend ratios, and COV of IMEP and combustion efficiency at the high limit. Intake boosting becomes necessary due to the oxygen deficiency caused by the low energy density of the reformate mixtures as it displaces intake air.

Keywords: Single-fuel RCCI, reformation, blend ratio, start of injection

NOMENCLATURE

SI	spark ignition
CDC	conventional diesel combustion
THC	total unburned hydrocarbons
LTC	low temperature combustion
HCCI	homogeneous charge compression ignition
RCCI	reactivity-controlled compression ignition
DTBP	di-tert butyl peroxide
EHN	ethyl-hexyl nitrate
CPOX	catalytic partial oxidation
DR1	diesel reformate 1
DR2	diesel reformate 2
CAD	crank angle degree
SOI	start of injection
deg aTDC	degrees after top dead center
IMEPn	net indicated mean effective pressure
CAx	crank angle at which x% of mass burned
IS	indicated specific
COV	coefficient of variance
LTHR	low temperature heat release
RI	ringing intensity
CEff	combustion efficiency
TEff	thermal efficiency

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1. INTRODUCTION

There is an efficiency-emissions tradeoff with the conventional combustion modes, i.e., spark ignition (SI) and conventional diesel combustion (CDC). SI operates homogeneously and stoichiometrically, which provides an easy and inexpensive way to treat the harmful emissions that are produced from combustion, like NOx, CO, and total unburned hydrocarbons (THC), using a three-way catalyst. However, this strategy constitutes an efficiency compromise. CDC, on the other hand, operates heterogeneously and lean, offering much higher thermal efficiencies than SI at the cost of moderate NOx emissions that are difficult to treat, and soot emissions. To eliminate the efficiency-emissions tradeoff, advanced, low temperature combustion (LTC) concepts have been conceived to offer high efficiency engine operation with low harmful emissions. The first widely researched LTC concept is homogeneous charge compression ignition (HCCI) [1-5].

HCCI operates homogeneously and lean, avoiding soot production from rich in-cylinder regions, while achieving high efficiency through lean, unthrottled operation with mid-range compression ratios. Additionally, the lean operation in HCCI keeps in-cylinder temperatures below the NO_x production threshold while simultaneously reducing heat transfer losses, further improving emissions characteristics and thermal efficiency. However, HCCI has a limited operating range due to the apparent lack of control over the heat release process. Researchers have therefore been searching for ways to control the combustion process in LTC, without sacrificing the emissions and efficiency benefits.

Thermally stratified compression ignition (TSCI) is a combustion mode that aims to control the heat release process in LTC by controlling the in-cylinder thermal stratification. TSCI uses the evaporative cooling of a compression stroke injection of a non-combustible liquid, like water [6-7], or a high latent heat of vaporization, low equivalence-ratio-sensitive fuel, like wet ethanol [8-10], to modify the thermal stratification profile in the combustion chamber. Contrarily, combustion modes like partial fuel stratification (PFS) [11-13], gasoline compression ignition (GCI) [14-15], and premixed charge compression ignition (PCCI) [16-18] use a compression stroke injection of an equivalence-ratio-sensitive fuel to create an equivalence ratio stratification in the cylinder, where the rich regions will have a shorter ignition delay than the lean regions, staging the heat release process. These combustion modes all use a single fuel and a single fuel injection system.

Reactivity-controlled compression ignition (RCCI) is a combustion mode that aims to control the heat release process in LTC by introducing a reactivity gradient in the cylinder [19-21]. Whereas combustion modes like PFS take advantage of a fuels' equivalence-ratio-sensitive ignition delay, RCCI uses two distinct fuels with differing reactivities, i.e. differing *effective octane number*. Traditionally, RCCI uses two injection systems; one injection system is used to premix the low-reactivity fuel with the incoming air, which is inducted into the cylinder during the intake stroke, and the second injection system is used to direct inject the high-reactivity fuel into the combustion chamber midway through the compression stroke. The injection timing is early enough so that the combustion is kinetically controlled, rather than mixing-controlled. RCCI, using gasoline as the low-reactivity fuel and diesel as the high-reactivity fuel, has been shown to provide excellent control over the combustion process in LTC [22 – 25].

One potential drawback of traditional RCCI is the need for two distinct fuels and injection systems. This has created the need to develop *single fuel RCCI,* which could create a reactivity gradient in the combustion chamber without the need for two distinct fuels. Some groups have attempted to use a single, low-reactivity fuel with two injection systems, where some of the fuel is premixed with the air, as usual, and another portion of the fuel is diverted, mixed with a cetane improver, and direct injected into the cylinder during the compression stroke. Specifically, this concept has been shown to be effective with gasoline as the fuel and di-tert butyl peroxide (DTBP) as the cetane improver [26, 27], and ethyl-hexyl nitrate (EHN) as the cetane improver [28 – 30]. Although these results are promising, the fuel-bound NO_x group associated with EHN is a significant drawback. Additionally, this method is not strictly single fuel RCCI since there are two liquids involved that need to be refilled. However, the goal is that the cetane improver would have a sufficient range such that it could be refilled at oil-change intervals similar to diesel exhaust fluid.

To enable single fuel RCCI without the need for a cetane improver, a new concept has been proposed that uses an on-board fuel reformation process to enable single fuel RCCI [31]. In this concept, a fraction of a high-reactivity fuel is diverted through an on-board fuel reformer that generates *reformate*, a mixture of H_2, CO, and partially reacted hydrocarbons, to serve as the low-reactivity fuel. Other researchers have used *syngas* (a mixture of CO and H_2) with diesel in RCCI and showed that the heat release process can be effectively controlled [32 - 34]. In that study, the effect of H_2 and CO concentration on combustion characteristics and thermal efficiency were quantified [33]. External catalytic reforming can be done through 1) steam reforming (SR) or steam methane reforming (SMR), 2) catalytic partial oxidation (CPOX), or 3) autothermal reforming (ATR). In this paper, the specific reformation process that is studied to enable single fuel RCCI with reformate and diesel is catalytic partial oxidation (CPOX) reformation. CPOX reformation is an exothermic reformation process, which means it can be self-sustaining at the cost of global fuel efficiency, since there is energy release during the reformation process. Alternatively, steam reforming requires a high-temperature heat source, since the process is endothermic, and a long startup time. Therefore, steam reforming would be considerably more challenging in an engine application. Autothermal reforming could also be used. However, due to simplicity and cost, the CPOX method has been chosen in this study. Future studies could evaluate other reforming methods. The authors have shown that out of three potential parent fuels (gasoline, diesel, and natural gas), diesel is the best candidate to enable single fuel RCCI [35].

To assess the viability of a diesel's reformate mixture as a low-reactivity fuel in single fuel RCCI, the combustion characteristics of two diesel reformate mixtures were studied in HCCI combustion [35]. The speciation of diesel reformate-1 (DR1) and diesel reformate-2 (DR2), respectively, were found to have a relatively low reactivity – the *effective octane numbers* of both reformate mixtures studied are higher than gasoline. This is advantageous for RCCI, where a larger difference in the reactivity between the low and high reactivity fuels is desired. However, the high concentration of inert gases in the reformate mixture that results from the CPOX process of reacting fuel with air does have its drawbacks, namely the low energy density, i.e. lower heating value, of the fuel. Replacing a high energy density liquid fuel with a gaseous low energy density fuel is detrimental to engine power density; therefore, the engine requires elevated intake pressures to compensate. It will also be beneficial to use low blend ratios, i.e., the fraction of the total energy in the cylinder that came from the premixed, low reactivity fuel.

A previous study compared combustion characteristics of reformate-diesel RCCI to that of the conventional gasoline-diesel RCCI [36]. This study takes a more in-depth look at the behavior of reformate-diesel RCCI. Specifically, the effect of diesel injection timing during the compression stroke on the combustion process is studied. Then, the effects of blend ratio on the combustion characteristics are studied, taking into account the large reactivity difference between the fuels and the high concentration of inert gases in the reformate mixtures.

2. EXPERIMENTAL SETUP

Experiments were conducted using selected diesel reformate fuel mixtures as the low reactivity fuel with the parent fuel (diesel) as the direct injected high reactivity fuel on a single cylinder research engine. The engine uses a production light-duty 4-cylinder 1.7L GM engine head on a single cylinder Ricardo Hydra research engine block. The remaining three cylinders are deactivated. The engine parameters are presented in Table 1 and the schematic of the engine test cell is presented in Figure 1

Table 1 : Ricardo Hydra engine properties

Bore	79 mm
Stroke	86 mm
Connecting Rod Length	160 mm
Piston pin offset	0.6 mm
Compression ratio	15.5
Optical Shaft Encoder's Resolutions	0.1 Crank Angle Degrees (CAD)
Intake Valve Opening (IVO)	-354° deg aTDC
Intake Valve Closing (IVC)	-146° deg aTDC
Exhaust Valve Opening (EVO)	122° deg aTDC
Exhaust Valve Closing (EVC)	366° deg aTDC

The engine's intake, exhaust, fuel, coolant, and oil systems are custom-made. The intake system consists of a 5kW intake air heater, a mass flow controller to control the intake pressure and flow rate, and an intake plenum. The exhaust system has a valve to control the exhaust pressure and an ECM lambda sensor to measure the oxygen concentration in the exhaust, from which the air-fuel ratio was then calculated, and a plenum, from which exhaust gas is sampled and sent to an emissions analyzer. The plenums in the intake and exhaust system are used to dampen pressure fluctuations during the gas exchange process. Four Kistler high-speed pressure transducers are used in the engine setup: intake, exhaust, fuel rail, and cylinder.

The coolant and oil system have an electric heater each and a radiator to maintain temperature. During this experiment, the coolant and oil temperatures were maintained at 353 K and 343 K, respectively. The fuel system consists of a "fuel cart", which is a portable fuel system that can supply two liquid fuels simultaneously, for both port fuel injection and direct injection. Both of the fuel systems have a MicroMotion Coriolis mass flow meter to measure the mass flow rate of fuel. The port fuel injection system uses an axial pump to pressurize the fuel to 35 psi. The direct injection system is a common rail system and has a low-pressure pump (lift pump) followed by a Bosch CP3 pump to pressurize the fuel up to 2000 bar. In this current study, the direct injection pressure was kept constant at 700 bar. The engine is also capable of running gaseous fuels, where the fuel will be controlled using a pressure regulator and is directly introduced into the intake plenum through a mass flow meter/controller, which is used to control the mass flow rate of the gaseous fuel.

Emissions, such as CO, CO_2, O_2, total unburned hydrocarbons (THC), and NO_x, are measured using a Horiba MEXA7100 D-EGR. Emissions values were used to calculate the air-fuel ratio of the mixture using the Brettschnieder air-fuel ratio equation [37] and combustion efficiency. A Kistler optical shaft encoder, with 0.1 crank angle degree (CAD) resolution, is coupled to the crankshaft, measuring CAD and signaling the high-speed pressure transducers to record data measurements. The low-speed measurements were recorded every 2 seconds. A custom LabVIEW code is used for data acquisition and engine test cell control, including temperature and pressure PIDs. A 30hp DC electric motor is used as the dynamometer. In this current study, the engine speed was kept constant at 1200rpm. Data is collected for 200 consecutive cycles and post-processed using MATLAB.

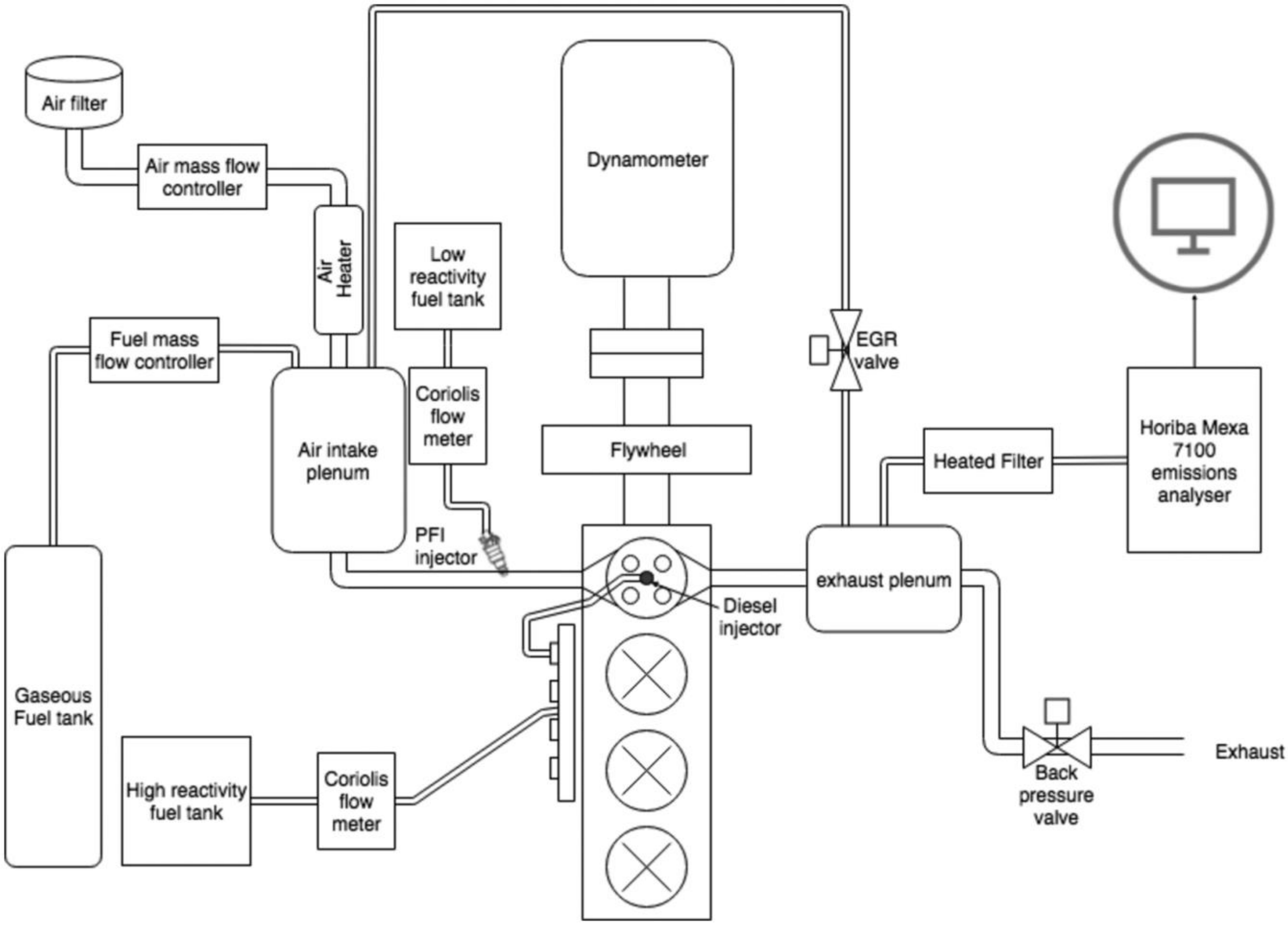

Figure 1: Schematic of the ricardo hydra engine test-cell

In this study, two reformate mixtures of diesel, named diesel reformate-1 (DR1) and diesel reformate-2 (DR2), were used as the premixed, low-reactivity fuel in RCCI, while the parent fuel, diesel, was used as the direct injected, high-reactivity fuel. The reformate mixtures were produced from a catalytic partial oxidation (CPOX) reformation process of diesel fuel. Initially, the fuel was oxidized at various equivalence ratios and pressures to study their effect on the reformate products' concentrations, which were determined using gas chromatography-mass spectrometry (GCMS) [35]. Following that, gas bottles were procured and used for the experimental study with a reformate composition that matched the GCMS-determined results as closely as possible. Due to practical constraints, the exact reformate mixture composition that exited the fuel reformer could not be contained in gas bottles. Therefore, an approximation of the species concentrations was made and was validated in a previous study [36]. More details on the reformation process and the reformate's combustion characteristics were presented in earlier studies [35, 36]. In this study, the effect of the start of injection (SOI) timing of diesel and the effect of the blend ratio of the low reactivity fuel was studied for both of the reformate fuel mixtures.

Table 2 : Molar concentration of the components of both the diesel reformate fuel mixtures, along with their fuel density and lower heating value

			Diesel reformate 1 (DR1)	Diesel reformate 2 (DR2)
Molar concentration of various components	Acetylene	C_2H_2	0.05%	0.20%
	Methane	CH_4	1.35%	2.38%
	Ethylene	C_2H_4	2.90%	3.45%
	Carbon dioxide	CO_2	11.09%	8.49%
	Carbon monoxide	CO	3.40%	8.25%
	Hydrogen	H_2	3.07%	5.61%
	Nitrogen	N_2	78.15%	71.63%
Fuel Density (kg/m3)			1.19	1.15
Lower heating value (MJ/kg)			2.32	3.77
Effective octane number			~105	~102

3. RESULTS AND DISCUSSIONS

Previous work with these two reformate mixtures (DR1 and DR2) found that the reactivity, i.e., the *effective octane number,* of both reformate fuels are similar [35]. Additionally, their heat release rates were comparable, as they both had single-stage heat release with no low temperature heat release, even though their parent fuel, diesel, does exhibit low temperature heat release [35]. Another study compared the combustion characteristics of reformate-diesel RCCI with conventional gasoline-diesel RCCI [36].

To gain a more fundamental understanding of reformate-diesel RCCI, the start of injection timing was varied from -49 to -40 deg aTDC in increments of 3 degrees for DR1-diesel and -55 to -49 deg aTDC in increments of 2 degrees for DR2-diesel. These experiments were conducted with a constant intake temperature of 340K and a constant energy-based blend ratio of 43% (i.e., 43% of the fuel energy in the cylinder was contributed by the premixed fuel). CA10, CA50, and CA90 vs. start of injection timing for both DR1-diesel and DR2-diesel are shown in Figure 2.

The biggest difference between the two reformate mixtures is the difference in the molar concentration of inert species, such as CO_2 and N_2, in the fuel. DR1 has approximately 8 percentage points of inert species higher than DR2, which changes the combustion duration. Thus, the CA10, CA50, and CA90 of the DR2 were advanced compared with DR1, at a start of injection of -49 deg aTDC. Regardless of the reformate mixture, the combustion phasing is generally very advanced for the reformate-diesel RCCI. This is due to the low combustion efficiencies that are observed on this engine in RCCI. The early combustion phasing helps to maintain the highest possible combustion efficiencies; however, it results in higher heat transfer losses and lower thermal efficiencies. Additionally, the combustion duration of DR1 at any constant CA50 is longer than the combustion duration with DR2, due to the increased diluents. Since the combustion process of DR1-diesel RCCI and DR2-diesel RCCI are comparable, a detailed study of the effects of the start of injection timing and the blend ratio on the combustion characteristics of DR2-diesel RCCI is presented in the following sections. DR1-diesel RCCI had similar results, with minor quantitative differences due to the difference in the molar concentrations and energy density of the reformate fuel mixtures.

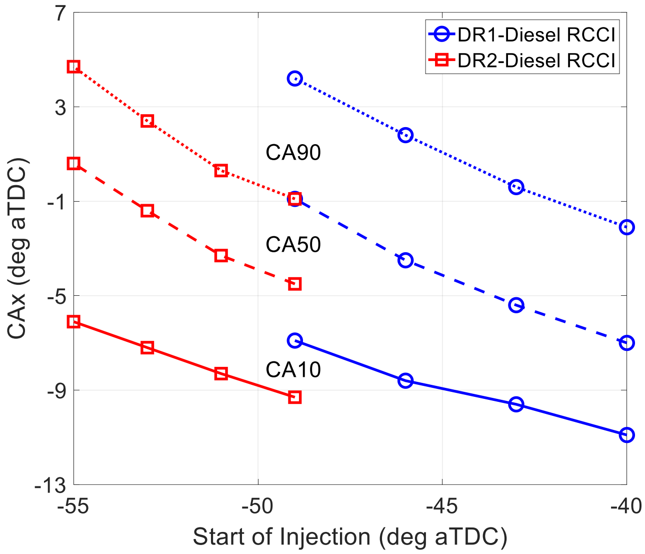

Figure 2: CA10, CA50, and CA90 of DR1-diesel RCCI compared with DR2-diesel RCCI over a range of start of injection of diesel

Additionally, the combustion phasing of both of the reformate RCCI pairs (DR1-diesel and DR2-diesel) were highly sensitive to changes in the start of injection of diesel compared with conventional gasoline-diesel RCCI. Figure 3 shows a comparison of the CA50 of reformate RCCI and conventional RCCI over a wide range of start of injection timings. Reformate RCCI has a steeper slope than conventional RCCI, as conventional RCCI has a slope of -0.3 CA50 degrees per SOI degree, while the reformate RCCI has a slope of -1 CA50 degree per SOI degree. The steeper slope of the reformate RCCI data shows that reformate RCCI has a higher sensitivity of CA50 to SOI timing.

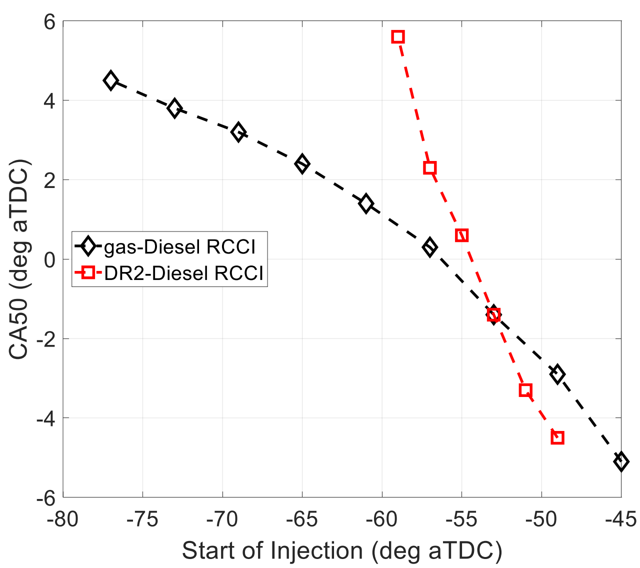

Figure 3: Comparison of the sensitivity of combustion phasing of DR2-diesel RCCI and conventional gasoline-diesel RCCI to the start of injection of diesel

The start of injection timing was swept from -66 deg aTDC to -58 deg aTDC, in increments of 2 degrees. The intake temperature and pressure were maintained at 350 K and 1.4 bar, respectively, while the equivalence ratio was maintained at 0.5, with an energy-based blend ratio of 44%. No external EGR has been used, but, due to the inert species in the reformate fuel, the effective EGR has been calculated and it was constant at approximately 15% since the equivalence ratio and blend ratio were constant. Advancing the start of injection timing further than -66 deg aTDC, under these operating conditions, led to low combustion efficiency and a high COV of IMEPn. Retarding the start of injection any further than -58 deg aTDC under these operating conditions led to an excessively high ringing intensity. The calculated ringing intensity is reported in Table 3. The cylinder pressure and gross heat release rate traces for each case are shown in Figure 4a and 4b, respectively.

As the start of injection is advanced, the combustion phasing retards and the peak heat release rate decreases, as is typically seen in RCCI. Additionally, the reformate mixture does not possess any low temperature heat release, even with an intake boost level of 1.4 bar, resulting in a low peak of LTHR, which was produced only from the direct injected diesel fuel. Interestingly, the sensitivity of combustion phasing to the start of injection timing was higher than with conventional gasoline-diesel RCCI combustion. This agrees with previous results that attribute this higher sensitivity of combustion phasing to SOI timing to a larger difference in the reactivity separation between the low and high reactivity fuels in RCCI combustion. Since the *effective octane rating* of the reformate fuel is higher than gasoline [35], the reactivity separation between the reformate mixture and diesel was higher than that of gasoline and diesel, which causes the higher sensitivity of combustion phasing to the SOI timing. This change in combustion phasing has a considerable effect on the combustion efficiency, gross thermal efficiency, and net indicated mean effective pressure (IMEPn), shown in Figure 5a, 5b, and 5c, respectively.

Table 3: Combustion characteristics of the SOI sweep of DR2-diesel RCCI

SOI	RI
deg aTDC	MW/m2
-58	4.8
-60	4.6
-62	3.4
-64	1.7
-66	0.6

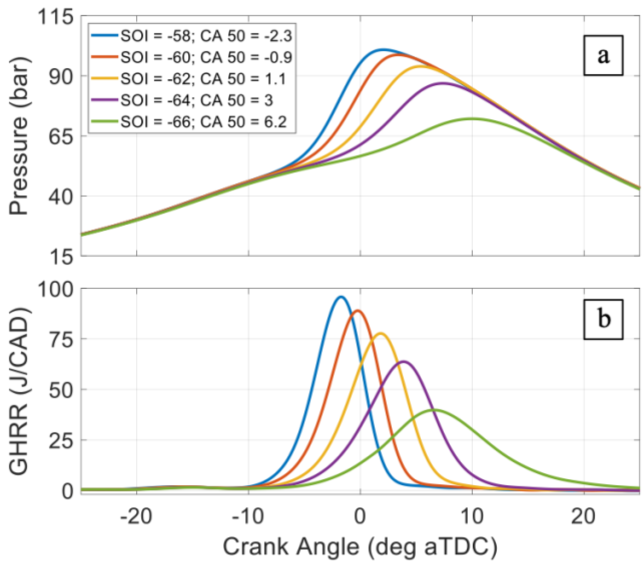

Figure 4: a) Cylinder pressure and b) Gross heat release rate of the DR2-diesel RCCI over a range of start of injection of diesel

Although the mass of fuel and air were kept constant, the IMEPn changed as CA50 retarded, first increasing to a maximum of 5.7 bar at a CA50 of 1.1 deg aTDC, before decreasing. IMEPn first increased with retarding CA50 because the high energy release rates and in-cylinder temperatures near TDC associated with early CA50s resulted in low thermal efficiency. Retarding CA50 therefore increased thermal efficiency. While thermal efficiency continued to increase as CA50 was retarded past TDC, IMEPn decreases due to the decrease in combustion efficiency. The latest possible combustion phasing is limited by the combustion efficiency becoming excessively low and the COV of IMEPn exceeding 5% (almost reaching 7%). This is a trade-off that has been seen with RCCI on this engine with any fuel pair; the combustion efficiency for RCCI peaks before TDC whereas gross thermal efficiency peaks after TDC due to heat transfer losses which increase as combustion phasing is advanced.

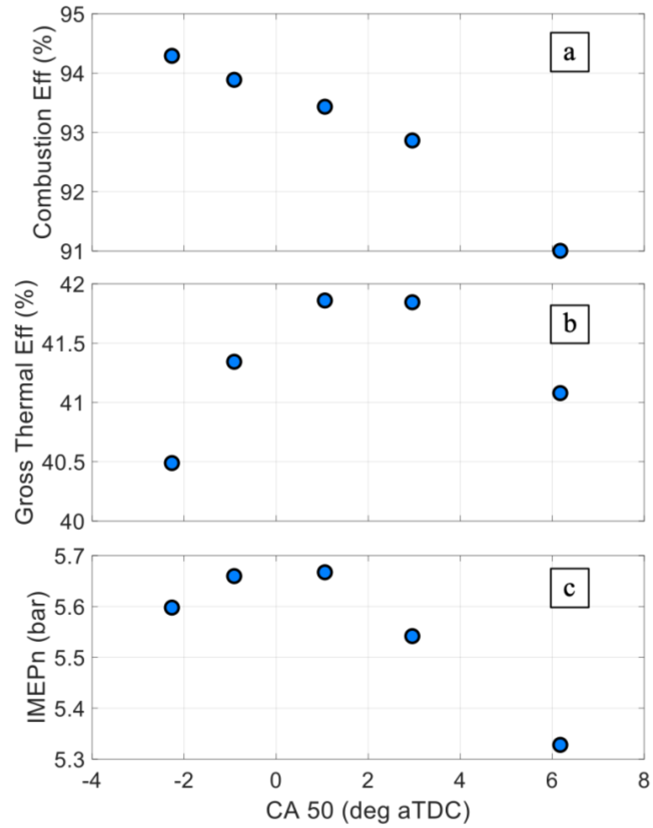

Figure 5: a) Combustion efficiency, b) Gross thermal efficiency, and c) IMEPn of the DR2-diesel RCCI over a range of start of injection of diesel

The maximum bulk temperature, burn duration (CA10 to CA90), and cumulative heat loss are shown in Figure 6a, 6b, and 6c, respectively. After a CA50 of ~3 deg aTDC, the burn duration begins to increase rapidly. If the burn duration becomes excessively long, the effective expansion ratio of the cycle is reduced, which is detrimental to thermal efficiency. Therefore, after a CA50 of ~3 deg aTDC, the thermal efficiency begins to decrease with retarding CA50 due to an over-elongated combustion process, further lowering IMEPn.

The peak bulk temperature has the same trend as the combustion efficiency, because the two are related. The combustion efficiency, specifically the conversion of CO to CO_2, mainly depends on the peak bulk temperature [38]. As the start of injection advances, the start of combustion retards because there are fewer locally diesel-rich areas to facilitate early combustion due to an increase in mixing time, thereby retarding combustion phasing and elongating the burn duration. This retarded and elongated combustion process, and its corresponding lower heat release rate, results in the low bulk temperatures observed. While this is detrimental to combustion efficiency, it does decrease heat transfer losses during the cycle. The cumulative heat loss of the cycle decreases with retarding CA50 with diminishing returns, which explains why the thermal efficiency first increased with retarding CA50 up to a CA50 of ~3 deg aTDC, and then subsequently began to decrease.

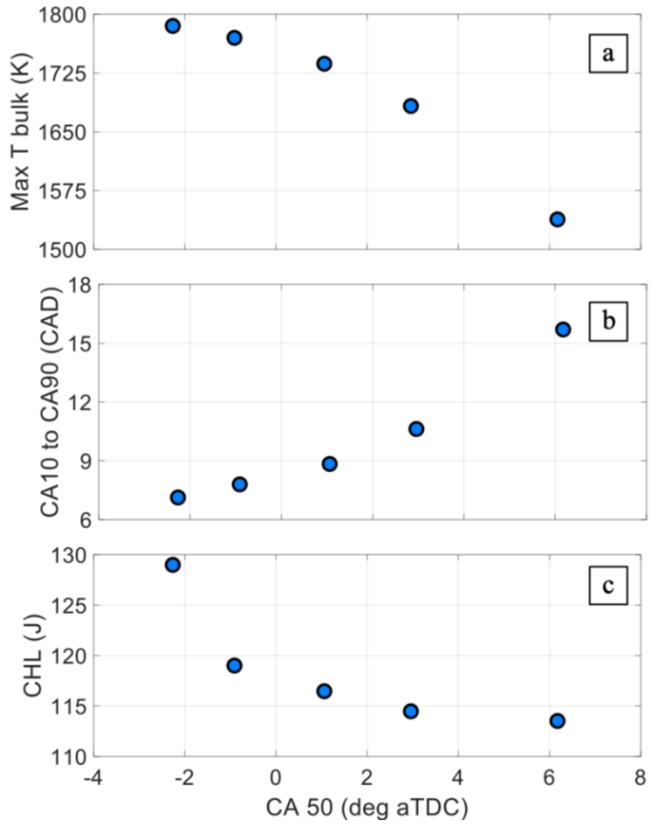

Figure 6: a) Maximum bulk temperature, b) Combustion duration (CA10 to CA90), and c) Cumulative heat loss of DR2-diesel RCCI over a range of diesel start of injection timing

The indicated specific (IS) emissions produced during this start of injection timing sweep are shown in Figure 7a (IS THC and IS NOx) and 7b (IS CO and IS CO2), respectively. Indicated specific emissions were chosen over emissions index because of the large amount of inert species (~93% by mass) contained in the reformate mixture. This large amount of inert species would result in seemingly low emissions index values when compared to the literature. To provide a fairer comparison, indicated specific emissions are reported.

In-cylinder bulk temperature is the main factor that dictates NO_x formation. Therefore, the IS NO_x emissions decreases steadily with retarding combustion phasing, as the peak bulk temperature decreased. IS THC, on the other hand, increases as the combustion phasing retards, due to a slowing of the progression of sequential autoignition, preventing complete combustion in the colder and leaner regions of the cylinder. Additionally, since the included angle of the injector is 150 degrees, the fuel spray tends to wet the walls at RCCI injection timings. When the start of injection advances during the compression stroke, the pressure inside the cylinder during injection decreases, resulting in an increase in spray penetration length, allowing comparatively more mass to wet the wall. Even though the start of injection was not advanced substantially, this may have a minor effect on the total hydrocarbon emission.

For the same reason as IS THC, IS CO increases as combustion retards. CO to CO_2 conversion is dictated by the local temperature and to undergo complete oxidation, the local temperatures need to be above ~1500 K [39]. Since the later CA50 is the result of earlier injection timing, there is more time for mixing of diesel fuel with the homogenous mixture of air and reformate which decreases the rich pockets of fuel and increases the homogeneity of the mixture. Even though the peak bulk temperature stays above 1500 K (refer to Figure 6a), later combustion phasings, especially with the longer burn durations that exist with RCCI combustion, always result in higher CO emissions in LTC. IS CO2 decreased as the combustion phasing was retarded due to the decrease in oxidation of CO. In general, the values of IS CO_2 are higher than the values typically seen for this equivalence ratio. This is due to the high concentration of CO_2 in the reformate fuel, which was formed during the partial oxidation of the parent fuel, diesel. In other words, all of the carbon content ultimately came from the parent fuel, diesel, which has an unfavorable H/C ratio, resulting in higher CO_2 emissions.

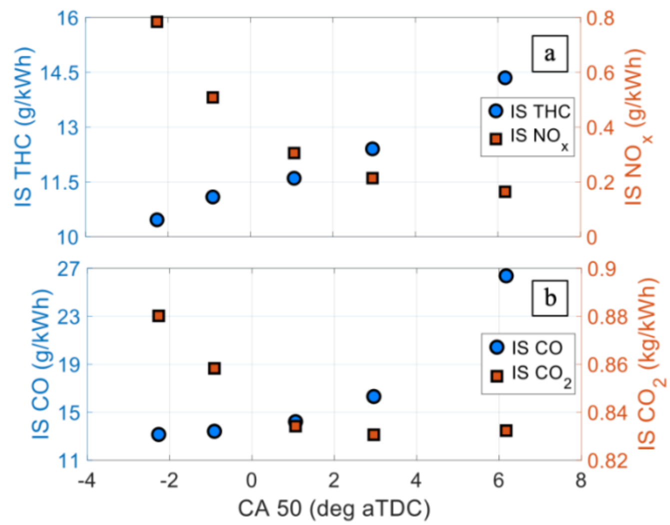

Figure 7: a) IS THC and IS NO_x and b) IS CO and IS CO_2 of the DR2-diesel RCCI over a range of start of injection of diesel

Blend ratio sweep – DR2-diesel

Since the reformate fuel mixtures have a high concentration of inert gases, such as CO_2 and N_2, their lower heating value is ~20% of the parent fuel, diesel. Although the energy-based blend ratios used in these experiments appear low, they correspond to a mass-based blend ratio of ~91%, which is relatively high.

Since the inert gases in the reformate mixtures act similarly to EGR, the maximum blend ratio that can be achieved with the current operating conditions (340 K intake temperature, 1.4 bar intake pressure) is 45%. The effective EGR values were calculated and reported in Table 4. Increasing the blend ratio higher than 45% results in low combustion efficiency and a high COV of IMEPn. This is due to the large amount of inert species in the combustion chamber which 1) keeps in-cylinder temperatures low by acting as a heat sink and 2) displaces fresh intake air, causing an oxygen deficiency. Increasing the intake boost level beyond 1.4 bar may increase the maximum possible blend ratio further by reducing the global equivalence ratio and compensating for the oxygen deficiency. However, this only exacerbates the issue of low in-cylinder temperatures because the excess air serves as a heat sink, and a required boost level of more than 1.4 at an

IMEPg of ~4.7 bar is excessive. The boosting requirements of single fuel RCCI, due to the inert species in the reformate mixture with catalytic partial oxidation, are a limitation of the proposed strategy. Reducing the blend ratio below 25% results in very early combustion phasing and excessive energy release rates, surpassing the ringing intensity (RI) limit of 5 MW/m_2. In order to prevent this, the start of injection timing must be retarded further, which results in injection timings that are no longer in the RCCI regime.

The operating range of reformate-diesel RCCI is very limited in terms of blend ratio, as the energy-based blend ratio ranges between 25% and 45%. In addition, the values are considerably lower compared to the conventional gasoline-diesel RCCI, where the nominal blend ratio ranges between 50% and 90%. In reformate-diesel RCCI, although the blend ratio values are limited to a lower range, there are advantages to this approach. During the CPOX reformation of diesel, a fraction of chemical energy in the fuel is released in the reaction to produce the reformate mixtures. By operating on a lower blend ratio, the fraction of reformate mixture in the overall energy input is lower. Therefore, the efficiency penalty associated with the energy released during reformation is minimized.

Blend ratio comparison at a constant SOI

To compare the combustion characteristics of different blend ratios at the same operating conditions, two distinct energy-based blend ratios, 30% and 42%, were compared against each other, both with a start of injection timing of -60 deg aTDC, an intake temperature of 340K, and an intake boost level of 1.4 bar. The equivalence ratio of both cases is approximately 0.46. The cylinder pressure and gross heat release rate traces of both blend ratios are shown in Figure 8 and their other combustion characteristics are tabulated in Table 4.

Increasing the energy-based blend ratio from 30% to 42% with constant operating conditions resulted in a retardation of CA50 by 8.3 degrees, which is mainly due to a decrease in the overall reactivity of the aggregate fuel. Additionally, the increase in the reformate mixture corresponds to an increase in the inert gas concentration in the combustion chamber, which also serves to retard the start of combustion as can be seen in Table 4. CA10 is retarded by approximately 3 CAD. This retarded start of combustion also affects the burn duration, along with an increase in the inert gas in the cylinder. The burn duration increases by approximately 63%, from 10.7 CAD to 17.4 CAD. Thus, the CA50 retarded significantly.

Another thing to consider with increasing inert gas content is the corresponding decrease in oxygen content associated with it. Since the total energy input to the cylinder remains constant, increasing the inert gas content serves to increase the global equivalence ratio. Being a partially premixed combustion mode, the RCCI injection strategy intentionally creates in-cylinder equivalence ratio inhomogeneity. With a higher global equivalence ratio, the likelihood that there are locally rich areas increases. While this is offset in part by the decrease in the amount of diesel injected during the compression stroke associated with increasing the blend ratio, there is still a higher likelihood of incomplete combustion and soot formation in locally rich regions. This, along with the retarded combustion phasing are detrimental to combustion efficiency. As such, combustion efficiency decreases from 92% to 87% when increasing the energy-based blend ratio from 30% to 42%.

With the retarded combustion phasing, the peak temperature decreases and so do the heat transfer losses, which helps to increase the thermal efficiency by two percentage points (refer to Table 4). The amount of LTHR also decreases with increasing blend ratio, since diesel is the source of the LTHR.

Since the effects of changing blend ratio is convoluted by the effects of changing combustion phasing, the following section shows a comparison at constant combustion phasing with different blend ratios by changing the diesel start of injection timing.

Table 4 : Combustion characteristics of blend ratio sweep of DR2-diesel RCCI at constant SOI

SOI	IMEPg	BRe	TEff	CEff	Effective EGR	CA10	CA50	CA90	CA10to90
deg aTDC	bar	%	%	%	%	deg aTDC	deg aTDC	deg aTDC	CAD
-60	4.8	30	37	92	10	-8.3	-2.7	2.4	10.7
-59	4.6	42	39	87	14	-5.2	5.6	12.2	17.4

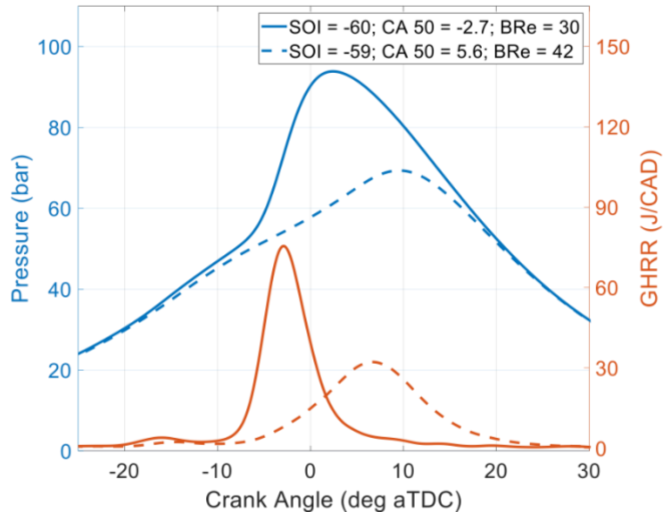

Figure 8: Effect of blend ratio on the cylinder pressure and gross heat release rate of DR2-diesel RCCI at a constant start of injection of diesel

Blend ratio comparison at a constant CA50

To more fundamentally compare the combustion characteristics of different blend ratios, the combustion phasing of both energy-based blend ratio cases, 30% and 42%, are kept constant by adjusting the diesel start of injection timing. The intake temperature and pressure remain at 340 K and 1.4 bar, respectively. To achieve a CA50 of -1.5 deg aTDC, the start of injection timing for the 30% blend ratio case is -62 deg aTDC, while that of the 42% blend ratio case is -53 deg aTDC. The cylinder pressure and gross heat release rate traces for both blend ratios are shown in Figure 9 and other combustion characteristics are tabulated in Table 5.

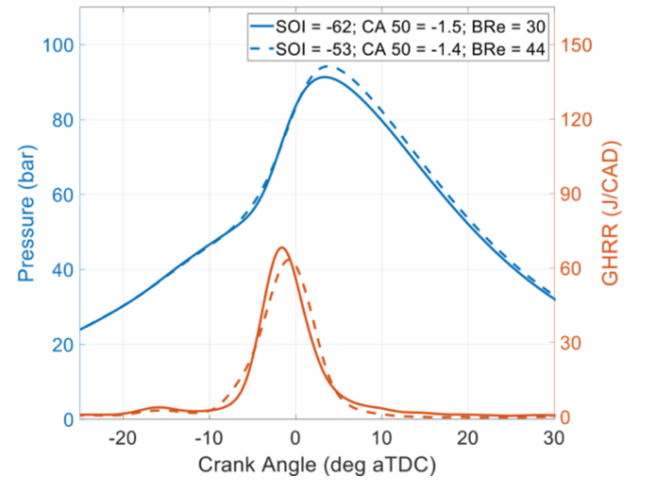

Figure 9: Effect of blend ratio on the cylinder pressure and gross heat release rate of DR2-diesel RCCI at a constant combustion phasing

Considering the injection timing sweep discussed earlier, the change of injection timing from -62 deg aTDC to -53 deg aTDC is significant and will also affect some of the results. This large change is necessary to account for the retardation of combustion phasing seen in the previous section. Now that the combustion phasing is constant, it can be noticed that the combustion duration does not change significantly compared with the cases in Figure 8, since the combustion duration changed by 18% with the increase in blend ratio at constant combustion phasing, compared with 63% at varying combustion phasing. The decrease in burn duration by 18% also corresponds to an increase in IMEP and combustion efficiency. This shows the later combustion phasing has a bigger influence on increasing the combustion duration than the change in blend ratio or increment in the inert species concentration. Additionally, the thermal efficiency for this case is the highest observed in these results at 41%. Even though the slightly higher combustion efficiency and IMEP helped improve efficiency, the main factor is the combustion duration.

Table 5 : Combustion characteristics of blend ratio sweep of DR2-diesel RCCI at constant CA50

SOI	IMEPg	BRe	TEff	CEff	Effective EGR	CA10	CA50	CA90	CA10to90
deg aTDC	bar	%	%	%	%	deg aTDC	deg aTDC	deg aTDC	CAD
-62	4.8	30	37	91	10	-8.1	-1.5	3.6	11.7
-53	5.1	44	41	93	14	-7.2	-1.4	2.4	9.6

4. CONCLUSIONS

Reformate mixtures generated from a CPOX reformation process with diesel fuel were used as the low reactivity fuel in RCCI, while the parent fuel, diesel, was used as the high reactivity fuel to enable *single fuel RCCI*. In this study, the effects of the start of injection timing of the high-reactivity fuel, diesel, on the combustion characteristics of single fuel RCCI were studied in detail. Following that, the effects of blend ratio on the combustion characteristics were studied. From detailed analysis of the results, the following conclusions can be drawn:

1. The lower reactivity, i.e. higher *effective octane number*, of the reformate mixture compared with gasoline, made reformate-diesel RCCI combustion more sensitive to the start of injection timing than gasoline-diesel RCCI. This phenomenon was noticed with both reformate mixtures studied, which had similar effective octane numbers.
2. Even with no external exhaust gas recirculation (EGR) and low internal EGR, the combustion could not be retarded significantly without a significant penalty in combustion efficiency, due to the high molar concentration of inert gases, such as N_2 and CO_2, in the reformate fuel, which behaves like EGR. The reformate-diesel RCCI blend ratio operating range is limited to 25% to 45% under the operating conditions studied in this set of experiments (340 K intake temperature, 1.4 bar intake pressure). The lowest blend ratios were limited by high ringing intensity while the highest blend ratios were limited by low combustion efficiency and high COV of IMEPn, which is due to the large amount of inert gas associated with the reformate mixtures displacing incoming air.
3. While the reformate-diesel RCCI blend ratio operating range is considerably lower than the conventional gasoline-diesel RCCI blend ratio operating range, this is beneficial because it decreases the impact of the energy loss incurred on the reformate mixtures during the CPOX reformation process, which is detrimental to the global efficiency of the CPOX reforming, single fuel RCCI system

5. ACKNOWLEDGEMENTS

The authors wish to gratefully acknowledge the financial support of the Department of Energy under award number DE-EE0007216.

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