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Effects of different cetane number enhancement strategies on HCCI combustion and emissions

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Abstract: Cetane number is the accepted indicator for quantifying the autoignition characteristics of diesel fuels in compression ignition engines. Diesel fuel specifications typically require a minimum cetane number to achieve satisfactory combustion behaviour in conventional diesel engines. In contrast, a high cetane number fuel may not be beneficial for implementing high efficiency, clean combustion strategies such as homogeneous charge compression ignition (HCCI). The purpose of this study was to investigate cetane number effects on HCCI combustion and emissions. The experiments were conducted in a single-cylinder, variable compression ratio, cooperative fuel research engine operated in HCCI combustion mode. The fuels were finely atomized and partially vaporized in the intake manifold. The base fuel was a low cetane refining stream derived from oil sands sources. Three different methods were employed to increase the base fuel cetane number, namely hydroprocessing, cetane improver addition, and blending with a renewable fuel component. Results show that the three methods of cetane number enhancement produce significantly different HCCI combustion behaviour. The hydroprocessed fuels exhibited more stable and complete combustion than the base fuel, which resulted in a wider operating region, reduced carbon monoxide, unburned hydrocarbon, and nitrogen oxide (NO_x) emissions, and lower indicated specific fuel consumption (ISFC). The main disadvantages of the hydroprocessed fuels were the higher exhaust gas recirculation rates required to retard the combustion phasing, which limits the maximum indicated mean effective pressure for a given intake pressure, and increased knock intensity due to a faster combustion process. In comparison, the other two methods of fuel cetane enhancement increased ISFC compared to the base fuel. The addition of nitrate cetane improver resulted in higher NO_x emissions, while blending with a renewable fuel component increased hydrocarbon emissions. The experimental data provide evidence that the magnitude and phasing of low temperature heat release, as well as fuel volatility, play important roles in HCCI combustion.

Keywords: homogeneous charge compression ignition (HCCI) combustion, cetane number, hydroprocessing

1 INTRODUCTION

Cetane number (CN) provides a measure of the ignition characteristics of diesel fuels in compression ignition engines. It is commonly measured using three methods: ASTM D613 (Cooperative Fuel Research Engine) [1], ASTM D6890 (Ignition Quality Tester) [2], and ASTM D7170 (Fuel Ignition Tester) [3]. In North America,

ASTM D975 specifies a minimum CN of 40 for grade 1-D and 2-D diesel fuels. The most established method, applicable for the entire CN scale from 0 to 100 but typically in the range of 40 to 55, is ASTM D613 using a cooperative fuel research (CFR) engine. The CFR engine has a variable compression ratio and is equipped with a combustion pre-chamber and mechanical fuel injector. It is operated at constant conditions of 900 r/min with fuel injection timing set at 13°CA_{bTDC} (crank angle, before top dead centre). The ignition delay, defined as the delay between the start of fuel injection and the start of combustion pressure rise, is held constant at 13°CA by

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varying the compression ratio of the engine. The CN is determined by comparing the autoignition quality of the test fuel to blends of two reference fuels, normal cetane (*n*-cetane, CN = 100) and 2,2,4,4,6,8,8-heptamethylnonane (HMN, CN = 15). The CN is calculated as follows: $CN = (\text{vol.\% } n\text{-cetane}) + 0.15 (\text{vol.\% HMN})$, knowing the volume percentages of a blend of *n*-cetane and HMN which matches the ignition quality of the test fuel. The relationship between the autoignition behaviour of fuels in a CFR engine and their performance in commercial, direct injection diesel engines operated at variable speed and load conditions is not completely understood.

In 2003, ASTM D6890 was approved as another method for rating diesel fuels [4–7]. The technique, which is based on using a constant volume combustion bomb, measures ignition delay at constant initial pressure and temperature. The apparatus is called the Ignition Quality Tester (IQTTM) and the measurement is referred to as a derived cetane number (DCN). An empirical equation relating DCN measured by the IQT and CN measured by the CFR engine has been established. More recently, a second method using a combustion bomb (ASTM D7170) was approved. The major difference between the constant volume combustion methods and the CFR method is that with the latter, the compression ratio is changed to obtain a constant ignition delay, whereas in the former the ignition delay is measured with the fuel being exposed to constant pressure and temperature.

None of the aforementioned ASTM methods for measuring the autoignition quality of diesel fuels examine the test fuel over a range of temperatures and pressures, nor do they take into account the presence of EGR or AFR variations. Hence, CN derived from any of the three methods may not provide enough information to assess the suitability of a test fuel for use in low-temperature combustion strategies.

While conventional diesel combustion process is primarily controlled by the fuel injection rate and subsequent diffusion flame, homogeneous charge compression ignition (HCCI) combustion is mainly governed by chemical kinetics. Hence, standardized methods that are capable of rating fuels for conventional diesel combustion technology may not be suitable for HCCI combustion fuel quality rating. The phenomena that strongly relate to chemical kinetics may have a much more pronounced effect on HCCI combustion characteristics, and may not be captured solely by CN determination. For example, the multi-stage autoignition behaviour of some hydrocarbons has a pronounced effect on HCCI combustion that may not be adequately characterized by CN. In addition,

fuel volatility may play a significant role in HCCI combustion that is not reflected by CN.

The multi-stage autoignition of hydrocarbons has been well known since the early 1950s. In this type of autoignition, as the pressure and/or temperature of the air–fuel mixture is increased, reaction rates increase with temperature according to the classical exponential Arrhenius rate equation [8]. A small amount of heat is released in the temperature range of 760–880 K, which is referred to as low-temperature heat release (LTHR). Then, the reaction rates of some hydrocarbons do not increase as temperatures rise above 880 K. This is referred to as the negative temperature coefficient (NTC) period. After the NTC period, reaction rates quickly increase with increasing temperature, the main combustion stage occurs and most of the energy is released. LTHR is strongly influenced by fuel chemistry and the engine operating condition. It plays a significant role in HCCI combustion by providing heat and a radical pool to help initiate the main combustion stage. Generally, *n*-paraffins exhibit strong LTHR behaviour and aromatics do not show a dual-stage autoignition under typical engine operating conditions. Diesel-like fuels exhibit dual-stage autoignition behaviour under HCCI operating conditions whereas gasoline-like fuels exhibit a single-stage autoignition.

The effects of fuel chemistry on HCCI combustion phasing have been studied before. Risberg *et al.* [9] correlated CN with CA₅₀ (the crank angle cycle where 50 per cent of the total heat is released) for mixtures of *n*-heptane, iso-octane, and toluene. Aroonsrisopon *et al.* [10] investigated fuels with identical research octane numbers but different fuel chemistries. It was found that HCCI combustion is a strong function of fuel composition and cannot be predicted by octane number. Several other studies were performed using diesel fuels. In a series of studies by Shibata *et al.* [11–14], the effect of fuel composition on HCCI combustion characteristics was investigated. It was demonstrated that fuel chemistry directly affected LTHR and the subsequent main combustion stage. They also found that *n*-paraffins had the highest LTHR, followed by isoparaffins, olefins, cycloparaffins, and aromatics. Aromatics, some cycloparaffins, and olefins were found to reduce LTHR. Examining a matrix of 11 fuels, an attempt was made to develop a new index of fuel suitability for HCCI combustion based on LTHR and LTHR inhibition effects, such as those of aromatics [12]. In the studies of Bunting *et al.* [15, 16], the effect of CN on HCCI combustion was examined. It was found that high cetane fuels have stronger LTHR behaviour and require a lower intake temperature for

autoignition. In the same reference, statistical analyses of HCCI combustion with a variety of diesel fuels showed that fuel conversion efficiency was primarily a function of density and energy content, whereas the ignition characteristics were mainly controlled by CN.

More recently, the effect of CN on premixed charge compression ignition (PCCI) combustion was investigated by Cho *et al.* [17] using the Coordinating Research Council's Fuels for Advanced Combustion Engines (FACE) fuel matrix. These fuels cover a range of CN from 30 to 55. Performing experiments with constant initial conditions and with varying fuel injection timing, it was found that the low CN fuels produce less soot emissions, more hydrocarbon (HC) and carbon monoxide (CO) emissions, and slightly less combustion noise. Using the same CRC FACE fuel matrix, Bunting *et al.* [18] reported that low CN fuels are more desirable for pure HCCI combustion. Hildingsson *et al.* [19] investigated PCCI combustion of high octane gasoline with commercial diesel fuel in a diesel engine and found that gasoline with an octane number between 75 and 85 produced significantly lower smoke and NO_x emissions than commercial diesel fuel.

Martin *et al.* [20] studied fuel volatility and vaporization effects on PCCI combustion and emissions in an optical engine. They showed that fuel film condensation may occur on top of the piston and in the piston bowl for early injection timings when the in-cylinder temperature is not hot enough, under some conditions, pool fires contributed significantly to overall engine emissions. In a follow-up study by Cheng *et al.* [21], it was found that a larger fuel heating value increased the fuel vaporization rate, thereby reducing liquid-fuel impingement and reducing HC emissions. Although these two later studies were conducted using direct fuel injection with very advanced injection timing, the results may be applicable to HCCI experiments in which air and fuel are pre-mixed prior to entering the combustion chamber.

The purpose of this paper is to investigate the HCCI combustion characteristics of fuels with similar CN but achieved in different manners. CN enhancement of HCCI fuels is of interest because conventional diesel engines require a higher CN, and it would be cost effective to be able to use the same base fuel for HCCI and conventional diesel engines. The fuels were derived from a base diesel fuel with a relatively low CN using hydroprocessing, cetane improver addition and blending with a renewable diesel fuel component. The HCCI combustion characteristics were compared using two different sets of experiments: controlled initial (AFR-EGR)

conditions and controlled engine outputs (speed-load) conditions.

2 EXPERIMENTAL SET-UP

Figure 1 is a schematic diagram of the HCCI combustion research facility. The CFR engine used for this study was a single-cylinder, four-stroke, variable compression ratio engine. This engine was selected because of its variable compression ratio and its wide use in industry for rating gasoline and diesel fuels. Table 1 provides the basic engine specifications.

The engine was coupled to an eddy current dynamometer for measuring engine load and controlling engine speed. A variable speed AC motor, coupled to an over-drive clutch, was used to motor the engine before initiating HCCI combustion and to maintain engine speed when combustion was unstable or the power produced was not sufficient to maintain the desired engine speed. The engine set-up was modified from the standard CFR configuration by the addition of an air-assist port fuel injection system and hardware to control critical engine parameters such as intake temperature, air/fuel ratio, intake and exhaust pressures, and exhaust gas recirculation.

A port fuel injector was used to atomize the fuels just upstream of the intake port. Compressed air, taken from the intake air after the mass flow meter, was used as blast air to improve the atomization process. For this study, the fuel and air-blast pressures were maintained at 500 and 200 kPa, respectively. The timing and duration of the air blast relative to the fuel injection was optimized to minimize emissions. Experimental data provided by Southwest Research Institute suggest that this fuel injector produces droplets with approximately 15 µm Sauter mean diameter under the conditions used in this study.

A heated section was added directly downstream of the fuel injector to increase the fuel spray temperature and partially vaporize the diesel fuels before they entered the combustion chamber. This helped to improve the fuel-air mixing process during the compression stroke. The exit temperature of the fuel vaporizer was maintained at a constant temperature in these experiments. Figure 2 is a schematic of the fuel injector/vaporizer unit.

The intake mixture temperature (T_{mix}) was measured in the intake port downstream of the fuel vaporizer. The intake air was provided from a pressurized dry air source. The intake air flow was measured by a mass flow meter before entering the intake surge tank, where the air was mixed with recycled exhaust gases (when desired). The EGR and air mixture then passed through

Fig. 1 Schematic of HCCI engine research facility

a lengthy intake system, which provided additional time to achieve a homogeneous mixture of air and EGR. One of the elements of the intake system was a heat exchanger to cool the EGR and air. The heat exchanger coolant was heated to just below the intake air temperature to avoid water vapour condensation. The heat exchanger was sized appropriately to compensate for the small temperature difference. An intake heater was used to maintain the intake air and EGR at the desired temperature.

The air/fuel ratio was calculated based on the mass flowrate of air to the engine measured upstream of the intake surge tank and the measured fuel flowrate. The air blast used in the fuel atomizer was taken from the measured air stream. The stoichiometric air/fuel ratio was calculated based on the measured H/C ratio of each fuel.

Table 1 CFR engine technical specifications

Engine	Waukesha CFR
Combustion chamber	Flat top piston, pancake
Compression ratio	Variable, 6:1 to 16:1
Bore × stroke	82.55 mm × 114.3 mm
Displacement	611.7 cm ³
Intake valve open	10 °CA, aTDC (after top dead centre)
Intake valve close	34 °CA, aBDC (after bottom dead centre)
Exhaust valve open	40 °CA, bBDC (before bottom dead centre)
Exhaust valve close	15 °CA, aTDC
Fuel system	Air-blast port fuel injection

The engine exhaust was routed through an exhaust surge tank equipped with a safety rupture disk. A back pressure valve was used to maintain the exhaust pressure slightly above the intake pressure to provide the pressure differential needed to recycle exhaust gases to the intake stream. The EGR rate was calculated using the ratio of the intake and exhaust carbon dioxide (CO₂) volume concentrations. The internal exhaust gas residual can be up to 8 per cent for the CFR engine. Since the difference between the intake and exhaust pressures was held constant, it was expected that the internal exhaust gas residual was relatively constant for all data points.

An engine data acquisition and control system (Sakor Technologies Inc., DynoLab™) was used to acquire temperatures, pressures, and flowrates. Exhaust gas composition (NO_x, HC, CO, CO₂, O₂) was measured using emission analysers (California Analytical Instruments, 600 series). Indicated specific emissions were calculated using direct exhaust emissions measurement, assuming equal mass flowrates of intake and exhaust, and compensating for water removal from the exhaust samples.

A water-cooled pressure transducer (Kistler Corp., model 6041A) flush-mounted in the cylinder head was used to measure cylinder pressure. A real-time combustion analysis system (AVL LIST GmbH, IndiModule) was used to collect cylinder pressure data at each test condition for 300 consecutive

Fig. 2 Schematic of the enhanced fuel injector/vaporizer

engine cycles with 0.2°CA resolution. AVL's library function (Thermodynamics1) for fast heat release calculation was used to determine CA50. The model is based on a single zone, zero-dimensional, well-stirred reactor with air as working fluid. The model was used to calculate LTHR energy and $\text{LTHR}_{\text{max,time}}$. All combustion-related parameters such as indicated mean effective pressure (IMEP), COV_{IMEP} , and $(dP/d\theta)_{\text{max}}$ were calculated for individual cycles and subsequently averaged for 300 cycles of data.

3 FUELS

The base diesel fuel for this study was a refinery stream derived from oil sands sources with a 36 CN (OS-CN36). Further properties of the base fuel are provided in Appendix 2. Three different methods were used to increase the CN of the base diesel fuel, namely hydroprocessing, cetane improver addition, and blending with a renewable diesel blending component. Although similar CN values were obtained using the three methods, the chemical compositions of the resultant fuels were significantly different.

The first method used to increase the CN of the base fuel was hydroprocessing. Hydroprocessing is used extensively in the petroleum industry to change the chemical properties of a feedstock by reacting it with hydrogen at elevated temperature and pressure. The process is known to increase the H/C ratio of the feedstock and reduce the sulfur content. Depending on the processing severity, it may increase the CN, produce lower molecular weight HCs, and alter the distillation curve toward lower temperatures [22].

In this study, the base fuel was subjected to two hydroprocessing severities using a commercial CoMo ULSD hydro-treating catalyst at the National Centre for Upgrading Technology (NCUT), Devon, Alberta,

Canada. The CNs of the resultant fuels were 39 (OS-CN39) and 41 (OS-CN41). The main chemical property changes in the less severely hydroprocessed fuel compared to the base fuel were saturation of some of the aromatics, leading to a reduction in the aromatic content from 27.6 to 17.1 per cent and a corresponding increase in the total cycloparaffins from 46.8 to 54.8 per cent. Sulfur content was reduced from 54 to 38 then 8 mg/L. In the more severely hydroprocessed fuel, the aromatics content was further reduced from 17.1 to 2.7 per cent. In addition, the cycloparaffin content was reduced from 54.8 to 49.6 per cent, which indicates that some of the ring structures were opened. It is also significant to note that the temperature at which 90 per cent of the fuel is recovered, as measured by ASTM D2887, was reduced from 291°C for the base fuel to 286 and 255°C for fuels OS-CN39 and OS-41CN, respectively. Note that, abundance of cycloalkanes in oil sands-derived diesel fuel should motivate further research on the combustion characteristics of this relatively less-studied class of compounds.

The second method used to increase the CN was the addition of 2-ethyl-hexyl-nitrate (2EHN), a commercial cetane improver. Two fuels with 40 (2EHN-CN40) and 44 CN (2EHN-CN44) were produced by adding 0.05 per cent, (500 ppmv) and 0.23 per cent, (2300 ppmv) by volume of 2EHN to the base fuel, respectively. The two fuels containing cetane improver had enhanced autoignition behaviour in comparison with the base fuel, but other fuel properties such as aromatics content and volatility were not changed.

The third method used to increase the CN was blending SupercetaneTM, a renewable diesel blending component, with the base fuel. The Supercetane fuel was produced by hydrotreating mustard seed oil at CanmetENERGY, a Research Centre of Natural Resources Canada. This renewable fuel blending

component consisted primarily of C_{15} to C_{20} n -paraffins and had a DCN (as measured by ASTM D6890) of 109. More than 80 per cent of the SupercetaneTM is composed of two n -paraffins, n - $C_{17}H_{36}$ (heptadecane) and n - $C_{18}H_{38}$ (octadecane). The Supercetane was blended at 5 and 10 per cent volume fraction into the base fuel, which produced fuels with CN of 39.6 (SCRD-CN39) and 41.9 (SCRD-CN42), respectively. It should be noted that the volatilities of the two Supercetane fuel blends was significantly lower than those of the other fuels.

4 EXPERIMENTAL PROCEDURE

It is challenging to devise a suitable experiment for comparing candidate HCCI fuels as each fuel requires different initial conditions (compression ratio, intake mixture temperature and boost pressure, EGR, AFR) to achieve optimal combustion behaviour (power, efficiency, emissions). Each HCCI fuel requires a different compression ratio and intake temperature to achieve timely autoignition, a range of AFR to achieve the desired power level, and varying EGR levels to control the combustion phasing, peak rates of pressure rise and cyclic variations in IMEP. In this study, two sets of steady-state experiments were devised to evaluate each test fuel: one set employed controlled input conditions (AFR-EGR), whereas the other set employed controlled engine outputs (speed, load).

Since a common base fuel was used and the range of CNs was 36 to 45, it was possible to fix the compression ratio at 13:1 for all experiments. In addition, preliminary tests were done to establish the minimum vaporizer temperature required to achieve HCCI combustion with near-zero soot emissions [23]. As a result, the heated section of the fuel vaporizer was operated at a fixed temperature of 220°C in this study. The intake mixture temperature was maintained at 75°C as this was the minimum temperature needed to prevent water condensation from the EGR in the intake mixture and to achieve near-zero soot emissions.

4.1 Experiment with controlled engine input conditions

In the first experiment, two of the input conditions, namely AFR and EGR, were varied and the resultant engine combustion behaviour (power, efficiency, emissions) was measured. The experiment was conducted by controlling AFR, but the results are

presented in terms of λ because the H/C ratios of the fuels were slightly different. No control was placed on the engine output. Other initial conditions were fixed for this experiment, as shown in Table 2.

It is generally known that HCCI combustion is more efficient when the fuel-air mixture is heavily diluted with EGR and the AFR approaches stoichiometry ($\lambda = 1$). The low and high λ limits of operation were established by determining the operating region where the maximum rate of pressure rise was less than 10 bar/°CA and the COV_{IMEP} was below 5 per cent, respectively. The EGR rate was then reduced in equal steps of 5 per cent for each fuel, and the low and high λ limits of operation were determined at each EGR rate. Experimental data were not collected at low EGR levels as fuel conversion efficiency was found to deteriorate and emissions increased substantially as EGR was reduced.

4.2 Experiment with controlled engine outputs

Although an experiment with controlled inputs is useful to compare the AFR-EGR operating range for various fuels, other experimental results are difficult to compare because the engine output and combustion phasing are different for each fuel. Therefore, a second experiment was devised to investigate HCCI combustion at fixed speed-load operating conditions while maintaining a constant combustion phasing.

A preliminary test demonstrated that a load of 6 bar IMEP was achievable with HCCI combustion in this engine employing 2 bar intake manifold absolute pressure (MAP). On the low load side, engine operation below 2 bar IMEP was not possible due to the high internal friction of the CFR engine. Based on this information, a matrix of nine speed-load operating conditions (three IMEP levels, three engine speeds) was defined for this experiment, as shown in Fig. 3(a). The intake MAP was fixed at 1, 1.5, and 2 bar MAP for the low (2 bar), medium (4 bar), and high (6 bar) IMEP conditions, respectively. The three engine speeds selected were 900, 1250, and 1600 r/min. Other initial conditions were fixed for this experiment, as shown in Table 3.

Table 2 Initial conditions for engine experiments with controlled input conditions

Fuel vaporizer temperature (T_{vap} , °C)	220
Intake mixture temperature (T_{mix} , °C)	75
Compression ratio	13:1
Engine speed (r/min)	900
MAP (kPa)	200

Fig. 3 (a) Graphical representation of the operating conditions and (b) flowchart of engine tuning strategy for controlled engine output experiment

Figure 3(b) shows the flowchart of the engine tuning strategy.

Several combinations of AFR and EGR rate could be used to achieve each desired operating condition (hereafter called a mode) with the base fuel. As a result, a systematic approach was followed to reach each operating condition, knowing that maximum efficiency is achieved with high EGR rates and close-to-stoichiometric AFR for a fixed compression ratio and intake mixture temperature. At each mode, the EGR rate was increased until the combustion phasing (CA50) was retarded to TDC. Then, the AFR was automatically adjusted to achieve the required IMEP. If the combustion phasing was affected by the AFR change, then the EGR rate was re-adjusted to maintain TDC combustion phasing. The maximum rate of cylinder pressure rise was also monitored and limited to 10 bar/°CA. If the maximum rate of pressure rise exceeded this value, then the EGR rate was increased and the AFR was re-adjusted. Concentrations of NO_x were also moni-

tored and limited to 10 ppm. If CO and HC emissions were excessive, the EGR rate was reduced and the AFR was adjusted accordingly. At each engine operating mode, the combustion cyclic variation was monitored and controlled ($\text{COV}_{\text{IMEP}} \leq 5\%$) except at the three modes with 2 bar IMEP.

5 RESULTS AND DISCUSSION

5.1 Experiment with controlled input conditions

5.1.1 HCCI combustion characteristics

Figure 4 shows how the λ -EGR operating region for HCCI combustion was affected by the three methods for increasing CN, namely hydroprocessing (Fig. 4(a)), cetane improver addition (Fig. 4(b)), and blending with Supercetane (Fig. 4(c)). The low and high λ limits of operation denoted in the figure correspond to a maximum rate of cylinder pressure rise of 10 bar/°CA and COV_{IMEP} equal to 5 per cent, respectively. The observed trend was towards higher EGR rates for all fuels as λ decreased in order to retard the combustion phasing.

The three methods for increasing CN all affected the λ -EGR operating region for HCCI combustion. In Fig. 4(a), it is evident that the high λ limit of operation was shifted towards leaner air-fuel mixtures for the

Table 3 Initial conditions for engine experiments with controlled output conditions

Fuel vaporizer temperature (T_{vap} , °C)	220
Intake mixture temperature (T_{mix} , °C)	75
Compression ratio	13:1

Fig. 4 λ -EGR operating regions for the three cetane enhancement methods: a. hydroprocessing; b. cetane improver addition; and c. blending with Supercetane renewable diesel. Controlled engine input experiment: $N = 900$ r/min, $CR = 13:1$, $MAP = 200$ kPa, $T_{mix} = 75$ °C, $T_{vap} = 220$ °C

less severely hydroprocessed fuel (OS-CN39) compared to the base fuel (OS-CN36). In comparison, more severe hydroprocessing (OS-CN41) shifted the entire λ -EGR operating region for HCCI combustion toward leaner mixtures and significantly expanded the operating region. This operating region expansion should make it easier for engine designers to control HCCI combustion, but the operating region shift towards leaner air-fuel mixtures makes it more difficult to achieve higher engine loads. The effects of the other two methods for increasing CN, namely cetane improver addition and blending with Supercetane, are shown in Figs 4(b) and 4(c). In both cases, the high λ limit of operation was shifted towards leaner air-fuel mixtures as CN increased, but there was little effect on the low λ limit of operation. The high λ limit of operation was significantly shifted by 500 ppm of cetane improver addition (2EHN-CN40), but increasing cetane improver addition to 2300 ppm (2EHN-CN44) only had a small incremental effect. On the other hand, the high λ limit of operation seemed to shift linearly with CN for the Supercetane blends.

Figures 5(a) and 5(b) provide direct comparisons of the λ -EGR operating regions for the three CN enhancement methods at 39.5 and 42.5 CN, respectively. In Fig. 5(a), the λ -EGR operating region was found to be similar for all three methods of CN enhancement and reflects a modest expansion of the high λ limit of operation compared to the base fuel (OS-36CN), while maintaining the same low λ limit of operation. Comparing Figs 5(a) and 5(b), the λ -EGR operating region has been expanded for all three methods of CN enhancement at 42.5 CN compared to 39.5 CN. However, a distinct shift is evident in the λ -EGR operating region towards leaner mixtures for the severely hydroprocessed fuel (OS-41CN) compared with the other two fuels. This suggests that cetane enhancement additives and high-cetane blending components can be used to expand the λ -EGR operating region by shifting the high λ limit of operation towards leaner air-fuel mixtures. However, alterations to the molecular structure of the base fuel by severe hydroprocessing (OS-CN41) shifted the entire λ -EGR operating region towards leaner air-fuel mixtures.

In order to better understand the influence of different CN enhancement methods on HCCI combustion and emissions, the experimental data collected with similar EGR levels of 60 ± 2 per cent were investigated in detail. Figure 6 shows typical cylinder pressure and heat release data for the 42.5 CN fuels at $\lambda = 2$. The combustion phasing was advanced from optimal conditions for all three fuels as the peak rate of heat release occurred before TDC. The

Fig. 5 Comparing λ -EGR operating regions for two sets of similar CN fuels: a. CN = 39.5 ± 0.5 ; and b. CN = 42.5 ± 1.5 . Controlled engine input experiment: $N = 900$ r/min, CR = 13:1, MAP = 200 kPa, $T_{\text{mix}} = 75^\circ\text{C}$, $T_{\text{vap}} = 220^\circ\text{C}$

LTHR phasing was advanced slightly for the cetane improved fuel (2EHN-CN44), whereas the magnitude of the LTHR was higher for the severely hydroprocessed (OS-CN41) fuel and the fuel containing Supercetane renewable diesel blending component (SCRD-CN42). The phasing of the main combustion stage for the two fuels with enhanced LTHR was slightly advanced relative to the cetane improved fuel.

Figure 7 is a graph of IMEP produced by the different fuels between the low and high λ limits of operation with 60 per cent EGR. Since increasing fuel CN advanced the combustion phasing further beyond optimal values, the CN-enhanced fuels might be expected to produce lower IMEP. Compared to the base fuel, only the two hydroprocessed fuels (OS-CN39

Fig. 6 (a) Cylinder pressure and (b) heat release data for the three cetane enhancement methods at $\lambda = 2$ and 60 per cent EGR. Controlled engine input experiment: $N = 900$ r/min, CR = 13:1, MAP = 200 kPa, $T_{\text{mix}} = 75^\circ\text{C}$, $T_{\text{vap}} = 220^\circ\text{C}$

and OS-CN41) produced higher IMEP. The other two methods used to increase CN, namely cetane improver addition and blending with Supercetane, produced

Fig. 7 Effect of CN enhancement method on IMEP as a function of λ . Controlled engine input experiment: $N = 900$ r/min, CR = 13:1, MAP = 200 kPa, $T_{\text{mix}} = 75^\circ\text{C}$, $T_{\text{vap}} = 220^\circ\text{C}$

similar or reduced IMEP compared to the base fuel. The higher IMEP produced by the hydroprocessed fuels was primarily due to improved combustion efficiency as demonstrated by significantly lower HC and CO emissions, as will be shown later. The reduced IMEP of the fuels containing Supercetane renewable diesel may be related to the poor volatility of the renewable diesel blending components. These fuels showed a large sensitivity to EGR rate which is symptomatic of marginal combustion performance. It is possible that fuel condensation and pool boiling may occur with these fuels if the EGR rate is too high. This would be expected to lead to reduced combustion efficiency and IMEP, as discussed in references [20] and [21]. Cetane improver addition did not seem to have a significant effect on IMEP in this experiment.

In general, the three methods employed to enhance CN reduced COV_{IMEP} compared to the base fuel, as shown in Fig. 8. This figure shows that the lean limit of operation (highest λ) was higher for the CN enhanced fuels for a given COV_{IMEP} . Alternatively, lower cyclic variations in IMEP were obtained for the higher CN fuels at a given λ . Both hydroprocessed fuels had significantly reduced COV_{IMEP} compared to the base fuel with the most severely hydroprocessed fuel (OS-CN41) demonstrating the most stable combustion behaviour. The authors do not have an explanation for the high COV_{IMEP} for 2EHN-CN40 at $\lambda = 2$.

Figure 9 shows that the energy released during LTHR increased for all three CN enhancement methods compared to the base fuel. The addition of cetane improver provided the smallest increase in LTHR of the three methods. On the other hand, the largest increase in LTHR energy release was recorded

Fig. 8 Effect of CN enhancement method on COV_{IMEP} as a function of λ . Controlled engine input experiment: $N = 900$ r/min, $CR = 13:1$, $MAP = 200$ kPa, $T_{mix} = 75$ °C, $T_{vap} = 220$ °C

Fig. 9 Effect of CN enhancement method on energy released during the LTHR stage as a function of λ . Controlled engine input experiment: $N = 900$ r/min, $CR = 13:1$, $MAP = 200$ kPa, $T_{mix} = 75$ °C, $T_{vap} = 220$ °C

for SCRD-CN42, which was due to the addition of long-chain *n*-paraffins that make up Supercetane.

Figure 10 illustrates that the crank angle position of peak LTHR was advanced for all methods of CN enhancement compared to the base fuel. The nitrate cetane improver provided the largest advance in the LTHR combustion phasing, while blending with Supercetane and hydroprocessing the base fuel provided progressively smaller advances in peak LTHR phasing.

Figure 11 illustrates that the CA50 combustion phasing, defined as the crank angle corresponding to 50 per cent heat release, was advanced by at least 2°CA for all CN enhanced fuels compared to the base

Fig. 10 Effect of CN enhancement method on LTHR combustion phasing as a function of λ . Controlled engine input experiment: $N = 900$ r/min, $CR = 13:1$, $MAP = 200$ kPa, $T_{mix} = 75$ °C, $T_{vap} = 220$ °C

Fig. 11 Effect of CN enhancement method on CA50 combustion phasing as a function of λ . Controlled engine input experiment: $N = 900$ r/min, $CR = 13:1$, $MAP = 200$ kPa, $T_{mix} = 75^\circ\text{C}$, $T_{vap} = 220^\circ\text{C}$

fuel. The severely hydroprocessed fuel (OS-CN41) had the most advanced combustion phasing. In general, the CA50 combustion phasing for the different fuels tended to group according to CN.

In 2003, Tanaka *et al.* [24] demonstrated that the knocking intensity (KI) for HCCI combustion increased linearly with the fuel burn rate in a rapid compression machine. In this study, knocking intensity values were calculated by integrating the low-pass filtered cylinder pressure for 300 combustion cycles over a crank angle range of -45 to $+45^\circ\text{CA}_a\text{TDC}$ and then averaging the result. Figure 12 shows that KI decreased as λ increased for all fuels due to reduced engine load and more retarded combustion phasing. Hydroprocessing was the only CN enhancement method that significantly increased KI compared to the base fuel. Perhaps it is not surprising that hydroprocessing was the only CN enhancement method that significantly altered the fuel burn rate since it was the only method that changed the molecular structure of the base fuel. The increased burn rate for the hydroprocessed fuels may improve HCCI combustion performance under low load operating conditions; however, it may also reduce the upper load limit for HCCI combustion as a result of higher rates of pressure rise, as indicated in Fig. 5.

5.1.2 Regulated emissions and ISFC

Indicated specific CO, HC, and NO_x emissions are plotted as a function of λ in Figures 13 to 15,

Fig. 12 Effect of CN enhancement method on knocking intensity (KI) as a function of λ . Controlled engine input experiment: $N = 900$ r/min, $CR = 13:1$, $MAP = 200$ kPa, $T_{mix} = 75^\circ\text{C}$, $T_{vap} = 220^\circ\text{C}$

respectively. Figure 13 illustrates that isCO emissions increased with increasing λ for all fuels. Since the CA50 combustion phasing occurred before TDC in this experiment, there was plenty of time for CO oxidation to occur early in the expansion stroke if temperatures were sufficiently high. The main reason for the rapidly increasing CO emissions as λ increased were insufficient temperatures inside the combustion chamber due to the effects of reduced heat release as the AFR increased and the combined dilution due to 60 per cent EGR and a lean AFR. Compared to the base fuel, all three methods of CN enhancement generally reduced isCO emissions.

Fig. 13 Effect of CN enhancement method on indicated specific CO (isCO) emissions as a function of λ . Controlled engine input experiment: $N = 900$ r/min, $CR = 13:1$, $MAP = 200$ kPa, $T_{mix} = 75^\circ\text{C}$, $T_{vap} = 220^\circ\text{C}$

Fig. 14 Effect of CN enhancement method on indicated specific HC (isHC) emissions as a function of λ . Controlled engine input experiment: $N = 900$ r/min, $CR = 13:1$, $MAP = 200$ kPa, $T_{mix} = 75^\circ\text{C}$, $T_{vap} = 220^\circ\text{C}$

Two of the CN enhancement methods, namely hydroprocessing and cetane improver addition, showed a trend of decreasing isCO emissions with increasing CN. This is due to further advancement of the CA50 combustion phasing with increasing CN, which increased the combustion temperatures and increased CO oxidation. It is interesting to note that the fuel containing 10 per cent Supercetane (SCRD-CN42) had higher isCO emissions than the fuel with 5 per cent Supercetane (SCRD-CN39) at $\lambda = 2.2$. The relatively poor volatility of Supercetane was clearly problematic when the combustion process was heavily diluted with 60 per cent EGR and a lean

Fig. 15 Effect of CN enhancement method on indicated specific NO_x (isNO_x) emissions as a function of λ . Controlled engine input experiment: $N = 900$ r/min, $CR = 13:1$, $MAP = 200$ kPa, $T_{mix} = 75^\circ\text{C}$, $T_{vap} = 220^\circ\text{C}$

AFR. Thus, there appears to be a tradeoff between increased LTHR provided by Supercetane, which advanced the combustion phasing, and slower fuel preparation and CO oxidation of the long-chain *n*-paraffins when the combustion process was heavily diluted.

Figure 14 shows that the three different methods of CN enhancement significantly influenced the indicated specific HC (isHC) emissions. The two cetane improved fuels (2EHN-CN40 and 2EHN-CN44) had similar isHC emissions to the base fuel (OS-CN36), whereas the two hydroprocessed fuels generated lower isHC emissions than the base fuel. Hydroprocessing increased the fuel volatility, as well as reduced the aromatic content. On the other hand, the two Supercetane fuel blends had significantly higher isHC emissions than the base fuel. A recent study [25] using the same engine and a fuel matrix specifically designed to investigate the effects of CN, aromatics, and T_{90} distillation temperature on HCCI combustion and emissions provided evidence that the combination of high CN and low T_{90} distillation temperature reduced isHC emissions. The current results show that a higher T_{90} distillation temperature at a fixed CN increased isHC emissions.

Figure 15 shows that the indicated specific NO_x emissions (isNO_x) were below 0.02 g/kW-h for all fuels except the two fuels that contained nitrate cetane improver. There are at least two other studies which have observed a similar correlation between nitrate cetane improver addition and increased NO_x emissions from HCCI [16] and PCCI combustion [26]. The only CN enhancement method that reduced NO_x emissions was hydroprocessing.

Figure 16 shows the indicated specific fuel consumption (ISFC) for the three methods of CN enhancement as a function of λ . Note that the IMEPs were not similar for all fuels as discussed previously. The two fuels that were produced by hydroprocessing the base fuel, namely OS-CN39 and OS-CN41, achieved a lower ISFC as a result of higher IMEP. The two Supercetane fuel blends (SCRD-CN39 and SCRD-CN42) produced higher ISFC, partially due to the relatively high HC emissions compared to the other fuels. In addition, fuel SCRD-CN42 generated lower IMEP than the base fuel, which also contributed to the higher ISFC. The two fuels with cetane improver (2EHN-CN40 and 2EHN-CN44) had slightly higher ISFC due to a combustion phasing which was further advanced from optimal conditions compared to the base fuel.

Although the soot emissions were not measurable with an AVL smoke meter (model 415) in this

Fig. 16 Effect of CN enhancement method on indicated specific fuel consumption (ISFC) as a function of λ . Controlled engine input experiment: $N = 900$ r/min, $CR = 13:1$, $MAP = 200$ kPa, $T_{mix} = 75^\circ\text{C}$, $T_{vap} = 220^\circ\text{C}$

experiment, it is not known if the Supercetane blending component was completely vaporized prior to the early stages of autoignition.

5.2 Experiment with controlled output conditions

In the previous section, the λ -EGR operating regions for HCCI combustion were compared for several fuels under controlled input conditions. Since the engine load and combustion phasing were not controlled in that experiment, some of the observed effects between fuels were due to the engine load and combustion phasing differences. Furthermore, the experiments were performed at a single engine speed. In order to address these issues, a second experiment was designed to investigate HCCI combustion at nine different speed-load conditions. The input conditions were allowed to vary between fuels in this experiment to maintain a constant combustion phasing.

5.2.1 Required input conditions (AFR and EGR)

The objective of this experiment was to attain the optimal fuel conversion efficiency (minimum ISFC) for each fuel at nine different speed-load conditions (called modes) subject to the requirement of acceptable HCCI combustion and emissions behaviour, as discussed in the experimental procedure. Since optimal ISFC occurs with CA50 combustion phasing near TDC, EGR rates were adjusted to achieve this combustion phasing for all fuels.

Figures 17 and 18 show the final AFR and EGR rates selected at the nine modes in an attempt to achieve the desired speed-load operating conditions. The AFR and EGR rates were determined at each mode by following the engine tuning strategy described previously and depicted in Fig. 3. The AFR was restricted to stoichiometric or leaner conditions ($\lambda \geq 1$) to avoid excessive HC and CO emissions. Likewise, the EGR rate under high load operating conditions was restricted to avoid water condensation in the intake system.

The following general trends for AFR and EGR rate may be observed for the engine control strategy utilized. First, the required EGR rate was found to decrease and AFR increased slightly as engine speed increased at any given engine load. This is due to the fact that increasing engine speed significantly retards the combustion phasing of diesel fuels that exhibit dual-stage autoignition behaviour [27]. Second, AFR was increased to reduce the IMEP at any given engine speed with a corresponding decrease in EGR to avoid excessive air-fuel mixture dilution and incomplete combustion. For modes 6 and 9, the combustion phasing (CA50) was excessively retarded even with 0 per cent EGR. This was corrected by increasing the compression ratio until CA50 occurred at TDC for fuels OS-CN39, 2EHN-CN40, and SCRD-CN39 at mode 9 to 13.7:1, 13.33:1, and 13.53:1, respectively. Lastly, the EGR rate required to maintain the CA50 combustion phasing at TDC increased as fuel CN increased.

The EGR requirement at a given CN was affected by the CN enhancement method. Blending with Supercetane renewable diesel increased LTHR and deteriorated the fuel volatility considerably. More EGR was needed to stabilize the combustion phasing at TDC. Blending with cetane improver had the smallest effect on LTHR and did not change fuel volatility, hence a moderate increase in EGR rate was required. Hydroprocessing improved both LTHR and fuel volatility, but had a reduced requirement for EGR to adjust the CA50 combustion phasing compared to the other two CN enhancement methods. These results show that both fuel volatility and CN influence HCCI combustion behaviour. In this study, the fuels were only partially vaporized in the intake manifold by the fuel vaporizer. Vaporization of the heavier fuel components occurred during the compression stroke, which may have contributed to the AFR and EGR requirements shown in Figs 17 and 18.

Despite our best effort, it was not possible to achieve all of the desired engine output conditions. Figure 19 demonstrates that it was not possible to achieve 6 bar IMEP with 200 kPa MAP for all fuels. For the cases where

Fig. 17 Effect of CN and CN enhancement method on AFR to control combustion timing (CA50 = TDC) and maximum rate of pressure rise $(dP/d\theta)_{\max} \leq 10 \text{ bar/}^\circ\text{CA}$. Controlled engine output experiment: CR = 13:1, $T_{\text{mix}} = 75^\circ\text{C}$, $T_{\text{vap}} = 220^\circ\text{C}$

the target IMEP could not be achieved, the procedure used was to reduce the fuelling rate (and IMEP) and then adjust the EGR rate to maintain combustion phasing (CA50) at TDC. In particular, it was more difficult to achieve 6 bar IMEP at the lowest engine speed (mode 1). This is due to the relatively strong influence of LTHR at low engine speeds, which results in advanced combustion phasing. In order to maintain CA50 combustion phasing at TDC, the EGR rate was increased, which effectively limited IMEP once stoichiometric AFR was reached. The fuel blends containing Supercetane (SCRD-CN39 and SCRD-CN42) exhibited the greatest IMEP shortfall, followed by the fuels containing the nitrate cetane improver (2EHN-CN40 and 2EHN-CN44). In addition, excessive cyclic variations ($\text{COV}_{\text{IMEP}} > 5\%$) were observed at most of the 2 bar IMEP operating conditions (modes 3, 6, and 9). As a result, only the experimental data obtained at modes 2, 5, and 8 will be presented in this paper.

5.2.2 Regulated emissions and ISFC

The isCO emissions data at modes 2, 5, and 8 are presented in Fig. 20. The general trend was towards lower

isCO emissions as engine speed increased. No conclusive CN effect is evident for the three operating conditions investigated, but isCO emissions were reduced as CN increased at the highest engine speed investigated (mode 8) for all three CN enhancement methods.

Figure 21 is a graph of the isHC emissions at modes 2, 5, and 8. Two of the three methods of CN enhancement decreased isHC emissions. The only exception was the fuel blend with 10 per cent Supercetane, where the low volatility of the Supercetane was problematic. Note that combustion phasing was maintained constant and the resultant reduction in isHC emissions may be attributed to the influence of higher CN. The hydroprocessed fuels produced the lowest isHC emissions followed by the fuels containing nitrate cetane improver.

Figure 22 shows that the isNO_x emissions were below 0.02 g/kW-h at all three modes, except for the fuels containing nitrate cetane improver (2EHN-CN40 and 2EHN-CN44). Schwab *et al.* [28] investigated the effects of nitrate- and peroxide-type cetane improvers on conventional diesel combustion. Their conclusion was that both types of cetane improvers decreased NO_x emissions and that the nitrogen

Fig. 18 Effect of CN and CN enhancement method on EGR to control combustion timing ($CA_{50} = TDC$) and maximum rate of pressure rise $(dP/d\theta)_{max} \leq 10 \text{ bar}/^\circ\text{CA}$). Controlled engine output experiment: $CR = 13:1$, $T_{mix} = 75^\circ\text{C}$, $T_{vap} = 220^\circ\text{C}$

Fig. 19 Maximum IMEP as a function of cetane number for modes 1, 4, and 7. The rest of the modes met the target IMEP. Controlled engine output experiment: $CR = 13:1$, $T_{mix} = 75^\circ\text{C}$, $T_{vap} = 220^\circ\text{C}$

introduced by nitrate-type cetane improvers does not contribute to higher NO_x emissions. As the combustion temperatures are significantly lower in HCCI combustion, the thermal route for NO_x formation that dominates in conventional diesel combustion is not as important. Thus, the presence of nitrate radicals in the HC-rich environment during HCCI combustion may have caused the increase in

is NO_x emissions for the fuels containing the 2EHN additive.

Figure 23 shows the ISFC data for modes 2, 5, and 8. This figure shows similar trends to those observed previously in Fig. 15, but in this case the operating (speed-load) conditions and combustion phasing were fixed. Each of the three methods used to increase CN affected ISFC differently. First, the

Fig. 20 Indicated specific CO emissions as a function of cetane number for modes 2, 5, and 8. Controlled engine output experiment: CR = 13:1, $T_{\text{mix}} = 75^\circ\text{C}$, $T_{\text{vap}} = 220^\circ\text{C}$

Fig. 21 Indicated specific HC emissions as a function of cetane number for modes 2, 5, and 8. Controlled engine output experiment: CR = 13:1, $T_{\text{mix}} = 75^\circ\text{C}$, $T_{\text{vap}} = 220^\circ\text{C}$

Fig. 22 Indicated specific NO_x emissions as a function of cetane number for modes 2, 5, and 8. Controlled engine output experiment: CR = 13:1, $T_{\text{mix}} = 75^\circ\text{C}$, $T_{\text{vap}} = 220^\circ\text{C}$

severely hydroprocessing fuel had reduced ISFC for all three modes. On the other hand, blending with Supercetane fuel deteriorated ISFC for all three modes. Lastly, ISFC was relatively unaffected by cetane improver addition. Thus, ISFC appears to not be correlated with CN for pure HCCI combustion. The differences in ISFC at each mode are primarily

due to fuel chemistry and volatility effects as the combustion phasing was held constant using appropriate combinations of AFR and EGR, while all other initial conditions were fixed.

It is believed that Fig. 23 illustrates the important role played by fuel volatility in HCCI combustion. The increased volatility of the severely hydropro-

Fig. 23 Indicated specific fuel consumption as a function of cetane number for modes 2, 5, and 8. Controlled engine output experiment: CR = 13:1, $T_{\text{mix}} = 75^\circ\text{C}$, $T_{\text{vap}} = 220^\circ\text{C}$

cessed fuel, as well as its faster burn rate, improved ISFC. The reduced volatility of fuels containing Supercetane, on the other hand, had higher ISFC. The poorer volatility of Supercetane increased the energy required for fuel vaporization during the compression stroke.

6 SUMMARY AND CONCLUSIONS

In this study, CN effects on HCCI combustion were investigated in a CFR engine using an air-assist port fuel injector and subsequent heated section to deliver partially vaporized fuel into the intake manifold. The base fuel was a low CN refining stream derived from oil sands sources. Three different methods were employed to increase the CN of the base fuel, namely hydroprocessing the base fuel, cetane improver addition, and blending with a high CN renewable diesel blending component (Supercetane) derived from mustard seed oil. A total of seven fuels were examined in two sets of experiments: controlled input conditions, which covered a wide range of air-to-fuel ratios (AFR) and exhaust gas recirculation (EGR) rates; and controlled engine outputs, which covered a matrix of nine speed-load conditions.

Based on an analysis of the experimental data collected, the following conclusions may be drawn.

1. In general, increasing the fuel CN expanded the λ -EGR operating region for HCCI combustion to higher λ (leaner mixtures) and reduced cyclic variations of IMEP. Severe hydroprocessing of the base fuel was the only CN enhancement method that shifted the lower λ limit of the λ -EGR operating region to higher λ (leaner mixtures). Higher EGR rates were required to effectively utilize the

higher CN fuels. This led to a significant decrease in the maximum IMEP produced for some of the higher CN fuels while maintaining a fixed boost pressure.

2. Comparing the different methods for increasing CN, it was found that the hydroprocessed fuels had more stable and complete HCCI combustion than the base fuel, which resulted in lower ISFC, as well as reduced CO, HC, and NO_x emissions. The main disadvantages of hydroprocessing were the higher EGR rates required to retard the combustion phasing near the low λ limit and increased knocking intensity due to the faster combustion process. In comparison, the other two methods of CN enhancement produced lower combustion cyclic variations and lower CO emissions than the base fuel, but had specific disadvantages compared to hydroprocessing. The nitrate cetane improver additive increased ISFC and produced substantially higher NO_x emissions on a relative basis, but the absolute emissions were still low. Blending 10 per cent by volume of a high-cetane, renewable diesel component (Supercetane) with relatively poor volatility increased both ISFC and HC emissions, presumably due to the challenge of vaporizing and burning long chain n -paraffins that comprise the renewable diesel using a low-temperature combustion strategy.
3. The three CN enhancement methods produced fuels with similar CNs but with significantly different low-temperature combustion characteristics. Hydroprocessing the base fuel and blending Supercetane with the base fuel both increased the magnitude of LTHR and advanced LTHR phasing. The nitrate cetane improver provided a larger advance in LTHR phasing, but had only a relatively modest effect on the magnitude of

LTHR. As a result, different air–fuel ratios (AFR) and exhaust gas recirculation (EGR) rates were required to control the HCCI combustion process for different fuels.

In conclusion, this study shows that fuels with similar CNs may have significantly different HCCI combustion characteristics and emissions. The experimental data suggest that the magnitude and phasing of the LTHR stage, as well as fuel volatility, play important roles in HCCI combustion of diesel fuels.

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REFERENCES

- 1 **ASTM (American Society for Testing and Materials)** *ASTM D0613-08, Standard test method for cetane number of diesel fuel oil*. ASTM International, West Conshohocken, PA. DOI: 10.1520/D0613-10, 2008.
- 2 **ASTM (American Society for Testing and Materials)**, *ASTM D6890-10a, Standard test method for determination of ignition delay and derived cetane number (DCN) of diesel fuel oils by combustion in a constant volume chamber*. ASTM International, West Conshohocken, PA. DOI: 10.1520/D6890-10A, 2010.
- 3 **ASTM (American Society for Testing and Materials)** *ASTM D7170-10, Standard test method for determination of derived cetane number (DCN) of diesel fuel oils—fixed range injection period, constant volume combustion chamber method*. ASTM International, West Conshohocken, PA. DOI: 10.1520/D7170-10, 2010.
- 4 **Allard, L. N., Webster, G. D., Hole, N. J., Ryan, T. W., Ott, D., and Fairbridge, C. W.** Diesel fuel ignition quality as determined in the ignition quality tester (IQTTM). SAE paper 961182, 1996.
- 5 **Allard, L. N., Hole, N. J., Webster, G. D., Ryan, T. W., Ott, D., Beregszaszy, A., Fairbridge, C. W., Cooley, J., Mitchell, K., Richardson, E. K., Elliot, N. G., and Rickeard, D. J.** Diesel fuel ignition quality as determined in the ignition quality tester (IQTTM) – Part II. SAE paper 971636, 1997.
- 6 **Allard, L. N., Webster, G. D., Ryan, T. W., Baker, G., Beregszaszy, A., Fairbridge, C. W., Ecker, A., and Rath, J.** Analysis of the ignition behaviour of the ASTM D-613 primary reference fuels and full boiling range diesel fuels in the ignition quality tester (IQTTM) – Part III. SAE paper 1999-01-3591, 1999.
- 7 **Allard, L. N., Webster, G. D., Ryan, T. W., Matheaus, A. C., Baker, G., Beregszaszy, A., Read, H., Mortimer, K., and Jones, J.** Diesel fuel ignition quality as determined in the ignition quality tester (IQTTM) – Part IV. SAE paper 2001-01-3527, 2001.
- 8 **Turns, S. R.** *An introduction to combustion*, 2nd edn, 2000 (McGraw-Hill, New York).
- 9 **Risberg, P., Kalghatgi, G., Ångström, H.-E., and Wåhlin, F.** Auto-ignition quality of diesel-like fuels in HCCI engines. SAE paper 2005-01-2127, 2005.
- 10 **Aroonsrisopon, T., Foster, D., Morikawa, T., and Iida, M.** Comparison of HCCI operating ranges for combinations of intake temperature, engine speed and fuel composition. SAE paper 2002-01-1924, 2002.
- 11 **Shibata, G., Oyama, K., Urushihara, T., and Nakano, T.** The effect of fuel properties on low and high temperature heat release and resulting performance of an HCCI engine. SAE paper 2004-01-0553, 2004.
- 12 **Shibata, G., Oyama, K., Urushihara, T., and Nakano, T.** Correlation of low temperature heat release with fuel composition and HCCI engine combustion. SAE paper 2005-01-0138, 2005.
- 13 **Shibata, G. and Urushihara, T.** Dual-phase, high-temperature heat release combustion. SAE paper 2008-01-0007, 2008.
- 14 **Shibata, G. and Urushihara, T.** Auto-ignition characteristics of hydrocarbons and development of HCCI fuel index. SAE paper 2007-01-0220, 2007.
- 15 **Bunting, B., Wildman, C., Szybist, J., Lewis, S., and Storey, J.** Fuel chemistry and cetane effects on diesel homogeneous charge compression ignition performance, combustion, and emissions. *Int. J. Engine Res.*, 2007, **8**(1), 15–27.
- 16 **Bunting, B. G., Crawford, R. W., Wolf, L. R., and Xu, Y.** The relationships of diesel fuel properties, chemistry, and HCCI engine performance as determined by principal component analysis. SAE paper 2007-01-4059, 2007.
- 17 **Cho, K., Han, M., Sluder, C. S., Wagner, R. M., and Lilik, G. K.** Experimental investigation of the effects of fuel characteristics on high efficiency clean combustion in a light-duty diesel engine. SAE paper 2009-01-2669, 2009.
- 18 **Bunting, B. G., Eaton, S. J., and Crawford, R. W.** Performance evaluation and optimization of diesel fuel properties and chemistry in an HCCI engine. SAE paper 2009-01-2645, 2009.
- 19 **Hildingsson, L., Kalghatgi, G., Tait, N., Johansson, B., and Harrison, A.** Fuel octane effects in the partially premixed combustion regime in compression ignition engines. SAE paper 2009-01-2648, 2009.

- 20 **Martin, G. C., Mueller, C. J., Milam, D. M., Radovanovic, M. S., and Gehrke, C. R.** Early direct-injection, low-temperature combustion of diesel fuel in an optical engine utilizing a 15-hole, dual-row, narrow-included-angle nozzle. SAE paper 2008-01-2400, 2008.
- 21 **Cheng, A. S., Fisher, B. T., Martin, G. C., and Mueller, C. J.** Effects of fuel volatility on early direct-injection, low-temperature combustion in an optical diesel engine. *Energy & Fuels*, 2010, **24**(3), 1538–1551.
- 22 **Yui, S.** Athabasca oilsands produce quality diesel and jet fuels. *Oil & Gas J.*, 2000, **98**(47), 58–66.
- 23 **Hosseini, V., Neill, W. S., Thomson, K. A., and Chippior, W. L.** Effect of initial and operating conditions on soot emissions from an HCCI engine. In Proceedings of Combustion Institute/Canadian Section, Spring Technical Meeting, Montreal, Quebec, 2009, pp. 151–157.
- 24 **Tanaka, S., Ayala, F., Keck, J. C., and Heywood, J. B.** Two-stage ignition in HCCI combustion and HCCI control by fuels and additives. *Combust. Flame*, 2003, **132**, 219–239.
- 25 **Hosseini, V., Neill, W. S., Guo, H., Dumitrescu, C. E., Chippior, W. L., Fairbridge, C., and Mitchell, K.** Effects of cetane number, aromatic content and 90% distillation temperature on HCCI combustion of diesel fuels. SAE paper 2010-01-2168, 2010.
- 26 **Ickes, A. M.** *Fuel property impact on a premixed diesel combustion mode*. PhD Thesis, University of Michigan, Ann Arbor, 2009.
- 27 **Hosseini, V., Neill, W. S., and Chippior, W. L.** Influence of engine speed on HCCI combustion characteristics using dual-stage autoignition fuel. SAE paper 2009-01-1107, 2009.
- 28 **Schwab, S. D., Guinther, G. H., Henly, T. J., and Miller, K. T.** The Effects of 2-ethylhexyl nitrate and di-tertiary-butyl peroxide on the exhaust emissions from a heavy-duty diesel engine. SAE paper 1999-01-1478, 1999.
- AFR air-to-fuel ratio
CAXX crank angle position in which XX% of net cumulative heat is released
CFR cooperative fuel research engine
CN cetane number
COV ratio of measurement standard deviation to mean
COV_{IMEP} COV of IMEP
CR compression ratio
DCN derived cetane number
EGR exhaust gas recirculation
HCCI homogeneous charge compression ignition
IMEP indicated mean effective pressure
IQTTM ignition quality tester
isCO indicated specific CO emissions
ISFC indicated specific fuel consumption
isHC indicated specific HC emissions
isNO_x indicated specific NO_x emissions
KI knock integral
LTHR low-temperature heat release
LTHR_{max} maximum LTHR
LTHR_{max,Time} crank angle position of LTHR_{max}
MAP manifold absolute pressure
NTC negative temperature coefficient (period)
OS-CNXX test fuel with XX cetane number, produced by hydroprocessing the base fuel originating from oil sands sources
SCRD-CNXX test fuel with XX cetane number, produced by blending the base fuel with SupercetaneTM renewable diesel blending component
 T_{air} air and EGR mixture temperature before fuel vaporizer
 T_{mix} air, EGR, and fuel temperature measured in the intake manifold
 T_{vap} fuel vaporizer temperature measured at the exit of the heated section
TDC top dead centre (aTDC, after TDC; bTDC, before TDC)
ULSD ultra low sulfur diesel

APPENDIX 1

Notation

λ	relative air-to-fuel ratio; ratio of AFR to stoichiometric AFR
°CA	degrees crank angle (TDC = 0 °CA)
2EHN	2-ethylhexyl nitrate, a commercial cetane improver
2EHN-CNXX	test fuel with XX cetane number, produced by adding 2EHN to the base fuel

APPENDIX 2

Fuel properties

	Method	OS-CN36	OS-CN39	OS-CN41	SCRD-CN39	SCRD-CN42	2EHN-CN40	2EHN-CN44
Cetane number	ASTM D613	36.6	39.4	41.4	39.6	41.9	40	44.6
Cetane improver (ppmv)	ASTM D7467	0	0	0	0	0	500	2300
Cloud point (°C)		–	–	–	–28.2	–19.4	The same	The same
Carbon (wt%)	ASTM D5291M	86.48	86.08	85.28	86.28	86.37	as for	as for
Hydrogen (wt%)	ASTM D5291M	13.34	13.87	14.44	13.33	13.50	OS-	OS-
Sulfur (mg/L)	ASTM D5623	54	38	8	–	–	CN36	CN36
Density (g/mL)	ASTM D4052	0.8351	0.8248	0.7859	0.8327	0.8304		
Viscosity (cSt @ 40 °C)	ASTM D445	1.633	1.531	1.109	1.69	1.76		
Sim. distillation T_{10} (°C)	ASTM D2887	158	150	119	158	160		
Sim. distillation T_{50} (°C)	ASTM D2887	229	222	190	231	235		
Sim. distillation T_{90} (°C)	ASTM D2887	291	286	255	297	303		
Saturates (% m)	ASTM D5186	71.6	81.6	97.5	72.7	73.9		
Total aromatics (% m)	ASTM D5186	28.4	18.4	2.5	27.3	26.1		
Total paraffins (% m)	PIONA+SPE/GC – MS	25.3	27.7	46.8	26.7	29.9		
Total cycloparaffins (% m)	PIONA+SPE/GC – MS	46.8	54.8	49.6	43.2	41.3		
Total aromatics (% m)	PIONA+SPE/GC – MS	27.6	17.1	2.7	29.3	27.9		